THE CLINICAL VALUE OF TESTING SPEECH INTELLIGIBILITY IN NOISE M.J. MIDDELWEERD 1989

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Promotor : prof.dr.ir. R. Plomp

Copromotor : dr.ir. J.M. Festen

Referent : prof.dr.G.F. Smoorenburg

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CONTENTS

GENERAL INTRODUCTION

Hearing may be considered as one of the most important social skills of man. In early infancy acoustic stimuli, together with tactile stimuli, represent the main source of communication and sensation of well being. In the years that follow, an individual's hearing is a prerequisite for the development of communicative skills like speech and language. Therefore, we all know the tremendous sequelae of a hearing defect, especially when it occurs in early childhood. These consequences of hearing loss may range from being unable to speak and handle verbal communication to having difficulties with understanding speech only in unfavorable acoustic circumstances. This is of course largely depending on the time of onset and on the degree of hearing loss.

In functional examination of hearing, one of the first attempts to obtain a more or less objective insight into the degree and type of hearing loss was made by Weber in 1834. He introduced his well known tuning-fork test, by which in case of unilateral hearing loss a distinction between a sensorineural and a conductive impairment can be made in a simple way. In 1855 Rinne added his tuning-fork test, which also still takes an important place in the nowaday's otological examination in discriminating between a sensorineural and a conductive hearing inpairment by means of comparing bone-conduction with air-conduction. A more quantitative way of audiometric testing has received its main impetus from the research that was performed by Alexander Graham Bell and that eventually led to the development of the electrical telephone. In 1878, three years after the introduction of the telephone and making use of part of its technique, Hartmann presented his "Hörmesser" or "Acoumeter". From the otologists of those days there was only little interest for the apparatus because frequencies above 1 kHz could not be tested and the output intensity lacked a reference. It took until the early 1920's before the first clinically applicable electronic audiometer was introduced by Fowler and Wegel. They also were the first to call their hearing measuring results an "audiogram". Apart from the assessment of the pure-tone thresholds, a phonograph could be connected, by means of which recordings of spoken numbers could be presented simultaneously to multiple individuals via headphones. This method was used for the audiometric screening of large groups of school children in the framework of hearing-conservation programs and in this way a good impression of the hearing threshold could be obtained (1,2).

In audiological practice pure-tone audiometry has served quite well for a number of reasons, as the possibility of determining a frequency-specific and stable threshold, the ability to discriminate a conductive from a sensorineural hearing loss and because of the relative ease of handling the procedure. In other words, the pure-tone audiogram is a valuable and reliable diagnostic tool. However, the most important disadvantage of pure-tone audiometry is its lack of representing speech, the sound stimulus essential to man. Complaints about a hearing loss, and implicitly the handicap it causes, mostly concern a hearing loss for speech and although the pure-tone audiogram may provide an excellent picture for the threshold of hearing from 0.25 to 8 kHz, this is often insufficient in fully recognizing the hearing problem. An impression of speech hearing loss can be obtained by means of assessing the intelligibility for whispered speech on several distances, a procedure which has been used long before the introduction of pure-tone audiometry. Perhaps the only advantage of this method is its ready availability. The disadvantages are manifold: the test is not standardized and whispered speech has a spectrum essentially different from that of the normally uttered speech sound. Therefore, nowadays the method should be considered obsolete.

The simplest clinical version of standardized speech audiometry consists of word lists of monosyllables, presented in quiet. By this means, apart from the quantitative speech intelligibility threshold, an impression can be obtained of the quality of hearing of a patient. For example, a plateau in the intelligibilty score may be reached without any further increase of intelligibility with level, or scores may even go down with increasing level beyond some point (regression). A disadvantage of this kind of speech audiometry in quiet is its poor resemblance to everyday listening situations; these seldomly concern only monosyllabic words in quiet. On the contrary, hearing, as an outstanding social skill, has to serve us with the reception of speech in the presence of other people's conversation, music, street or machine noise and so on. Complaints about speech-hearing loss and the handicap that it brings about should, therefore, be evaluated based upon thresholds measured in the context of disturbing sounds like noise (i.e. signal-to-noise ratio).

In 1953 Simonton and Hedgecock (3) reported on a speech- intelligibility test employing interfering noise. They were searching for a method that could establish the practical hearing ability of airline pilots when working in a noisy cockpit. Discrimination of speech in noise was found to be disturbed in listeners with sensorineural hearing loss and undisturbed in those with a conductive hearing loss. This test provided valuable information in addition to the pure-tone audiogram. From papers by Palva (4) and by Cooper & Cutts (5) similar results are deductible. In The Netherlands, Groen (6) reported on the importance of speech intelligibility in noise in relation to the assessment of the social handicap due to hearing loss. As a sequel to this report, Lindeman (7) developed for industrial audiometry an instrument for the assessment of intelligibility of monosyllabic words in a noise with a spectrum equal to that of speech. In a group of 753 noise-exposed industrial workers the speech reception threshold for 4 different signal-to-noise ratios was measured. The difference in score with a reference group, called the discrimination loss for speech, could not be predicted sufficiently accurately from the pure-tone audiogram. In other words, test results closely related to the hearing handicap could not be reliably predicted by means of the easily assessible pure-tone hearing loss.

Recognizing that a hearing handicap represents in the first place a subjective social problem, Noble (8) has advocated the use of a questionnaire in which the subject is asked to answer several questions on common everyday hearing situations instead of performing pure-tone or speech audiometry. Although this method provides an original insight into the problem, it seems unreliable because of the following reasons: 1 especially in case of hearing loss that may be financially compensated for as occurs in some countries, exaggeration of a hearing handicap is easily provoked; 2 subjective estimation of one's own hearing loss may also render an unjustified favourable impression of hearing, as is often encountered in elderly people: due to only gradual deterioration of hearing in the case of presbyacusis loss, the defect is either not recognized or persons in close environment are blamed for having an indistinct pronunciation. Moreover, Diamant (9) reported on a much better subjective estimation of hearing than would be expected from pure-tone thresholds in a group of industrial workers with considerable noise-induced hearing loss.

Many studies have been performed to intercorrelate pure-tone thresholds and speech intelligibility scores in order to try to predict speech hearing loss from (interpretation of) the pure-tone audiogram. Fletcher (10) postulated the "Fletcher 0.8" method. Based upon the average spectrum of speech, he considered the pure-tone thresholds at 0.5, 1 and 2 kHz to be most important for speech intelligibility. Between 0 and 120 dB, every decibel average hearing loss should represent 0.8% of hearing impairment. This model, however, does not cover the effects on the intelligibility of speech caused by a high-frequency threshold shift, which is typical for elderly or noise-exposed people. A high-frequency hearing loss (>2 kHz) will obscure a part of high-frequency cues in the consonants and in this way some of the redundancy in everyday speech. This redundancy is especially important for the speech intelligibility in conditions with interfering noise, where part of the speech information is masked at any rate. In quiet, the high fequencies are apparently less important. Quiggle et al. (11) reported on a comparative study between the pure-tone thresholds and speech- reception thresholds for words in quiet in a group of young men with only mild hearing loss; an optimal prediction of the speech intelligibility scores (multiple correlation coefficient = 0.9) could be obtained by weighting of the 0.5-, 1- and 1.5-kHz thresholds. According to this study, pure-tone thresholds at 4 and 6 kHz did not have any significant influence on the predictability of speech hearing loss in quiet. More or less similar conclusions were drawn in a report of Harris et al.(12).

In a group of sensorineurally hearing-impaired soldiers, however, Kryter et al.(13) found a maximum multiple correlation coefficient of 0.81 between the 2, 3 and 4 kHz average thresholds and the speech intelligibility for words and sentences which were partially presented in noise. This indicated the importance of the high frequencies for speech reception under everyday listening conditions. Kryter (13) proposed, as a compromise between the studies of Quiggle et al.(11) and Harris et al.(12) to regard the average pure-tone thresholds at 1, 2 and 3 kHz as representative of speech intelligibility and speech-hearing loss. He suggested as a limit from which a hearing handicap starts a fence of 15 dB. This proposition has influenced the 1979 "Guide for evaluation of Hearing Handicap" of the American Academy of Otolaryngology, in which the average of the thresholds at 0.5, 1, 2 and 3 kHz is handled in the assessment of hearing impairment, with a fence of 25 dB. The addition of the 3-kHz threshold in the assessment of hearing impairment means an improvement as compared to using the Fletcher Index. For a group of patients this interpretation of the pure-tone audiogram provides an estimated hearing loss for speech with a high correlation to speech- reception thresholds in noise. However, when evaluating predictions for individual listeners we should look at prediction error instead of the correlation coefficient; even a high correlation coefficient of 0.8 accounts only for 0.8 x 0.8 = 64% of the variance, leaving 36% as unexplained or error variance. Lindeman (7) and also Young & Gibbons (14) concluded from multiple correlational analysis of pure-tone and speech-reception thresholds, performed in large groups of noise-induced hearing-impaired listeners, that there is an altogether insufficient base for predicting the speech intelligibility from an interpretation of the pure-tone audiogram.

Summarizing the just given overview of possible ways to determine the social consequences of an individual's hearing loss, the assessment of the speech intelligibility in noise renders the best approximation to performance in everyday listening situations. A remarkable problem of the earlier mentioned studies on speech intelligibility in noise, however, is the variety of speech and noise modalities that were used and the absence of a standard definition of the speech-reception threshold, which makes comparison of results among the different studies impossible. In pure-tone audiometry the just audible threshold per frequency is quantified, whereas on the contrary the assessment of intelligibility of speech in noise in most studies is performed at pre-fixed signal-to-noise ratios. As a consequence standard thresholds for normal hearing and hearing impairment were not readily available. In 1978 this has led Plomp (15) to propose the Speech-Reception Threshold to be represented by the signal-to-noise ratio for which 50% of speech is correctly understood. In this way for each listener a threshold can be determined for speech intelligibility analogous to the assessment of a pure-tone threshold. The definition of the Speech-Reception Threshold was part of the introduction of a descriptive model for the Speech-Reception Threshold as a function of the level of interfering noise by dividing a speech-hearing loss into two additive components: "A" for attenuation and "D" for distortion. The attenuation component acts on both speech and noise and can be fully corrected for by a sufficient amplification of the signal. This type of hearing loss corresponds, for instance, with a strictly conductive type of hearing impairment like in middle-ear pathology. The distortion component loss is due to a kind of deterioration of the signal which cannot be simply corrected for by means of a higher stimulus level. It represents a qualitative aspect of speech intelligibility in the presence of background noise and can only be compensated for by means of improving the signal-to-noise ratio of the speech signal. This type of hearing loss often occurs in case of a sensorineural hearing impairment. However, it is important to realize that this classification is only descriptive and hearing loss with a single pathological origin will usually contribute to both descriptive components.

For the assessment of the Speech-Reception Threshold in both quiet and noise, a speech intelligibility test was designed, representing everyday listening situations. The speech material consists of short meaningful Dutch sentences and the noise has a spectrum equal to the long-term average of the speech material. For normal-hearing listeners the Speech-Reception Threshold in quiet appears to be 16 dBA for this material. In critical situations a Speech-Reception Threshold in noise for these listeners is - 5 dB signal-to-noise ratio. An increase of 1 dB in speech-hearing loss in noise corresponds to a decrease of 18% in speech-intelligibility score (15). In accordance to Smoorenburg (16) the limit of Speech-Hearing Loss in Noise from which a hearing handicap starts was chosen at 2.5 dB, implicating a speech-intelligibility loss of approximately 45%. This 2.5 dB loss corresponds to the necessity of reduction of the inter-individual distance between two subjects while in conversation of 100 cm in normal-hearing listeners to 75 cm in case of hearing impairment of this size. A larger reduction of this distance seems generally socially undesirable. In addition, a Speech-Hearing Loss in noise of 2.5 dB was found by Plomp & Mimpen (17) in a group of non noise-exposed men of 60-70 years of age.

Using this speech material Plomp's model has been extensively tested for normal-hearing listeners and three categories of hearing-impaired listeners:

1 Plomp & Mimpen (17) and Duquesnoy (18) investigated a large group of elderly listeners with presbyacusis and found a correlation coefficient of 0.55 between SRT in quiet and in noise.

2 In a group of 147 listeners with inner ear hearing impairment not based upon presbyacusis, gathered from reports of Duquesnoy & Plomp (19), Festen & Plomp (20), Dreschler & Plomp (21,22) and De Laat & Plomp (23) the correlation coefficient between SRT in quiet and in noise was only 0.01.

The results of the different studies were reviewed by Plomp in 1986 (24).

3 In a more recent study, Smoorenburg (25) found a correlation coefficient of 0.45 between the Speech-Reception Threshold in quiet and in noise in a group of 200 noise-exposed listeners.

These findings in different categories of hearing impairment show that a Speech-Hearing Loss in Noise definitely is different from the Speech-Hearing Loss in Quiet. In general, the former is not predictable from the latter.

In daily clinical practice there is only a moderate awareness of the importance of speech intelligibility in background noise. A hearing impairment, however, often reveals first in noisy surroundings and routine audiometric testing might give a flattering impression of a patient's hearing handicap. This thesis deals with several clinical implications of Plomp's model for the Speech-Reception Threshold.

In Chapter II the results of the assessment of the Speech-Reception Threshold in quiet and in noise for a group of noise-exposed industrial workers are discussed. Their hearing handicap is expressed in terms of Speech Hearing Loss in Noise and is compared to pure-tone audiometric data. Pure-tone thresholds prove to be of only limited value in the assessment of hearing handicap due to noise-induced hearing loss.

Chapter III deals with a peri-operative study concerning the Speech-Reception Threshold in quiet and in noise before and after stapedectomy or revision stapes surgery.

In Chapter IV Speech-Reception Thresholds are analyzed for a group of patients with complaints about speech-hearing loss and yet a nearly normal pure-tone audiogram. This group of patients shows a significant Speech-

Hearing Loss in Noise as compared to a group of normal-hearing listeners, which objectifies their complaints not recognized in routine audiometry.

Finally, Chapter V describes the large beneficial effect, in terms of signal-to-noise ratio, obtained from speech reading for both elderly and young listeners in situations where speech is presented in background noise.

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THE ASSESSMENT OF HEARING HANDICAP IN A NOISE-EXPOSED POPULATION

M.J. Middelweerd, J.M. Festen, R. Plomp.

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ABSTRACT

In order to assess their handicap due to hearing impairment the Speech-Reception Threshold for sentences in noise was determined in a group of 183 noise-exposed sheet-metal workers. The results were compared to pure-tone audiometry. The Speech-Reception Threshold in Noise, which is known to give a good insight into intelligibility of speech in everyday listening situations, and implicitly hearing handicap, appeared to be insufficiently predictible from the pure-tone audiogram. Based upon the assessment of a hearing handicap by means of the Speech-Reception Threshold in noise, industrial audiometric recommendations are given.

INTRODUCTION

The effect of industrial noise upon human hearing has been the subject of extensive research over the last two decades. It is a kind of industrial pollution which can, at least partly, be prevented and with irreversible detrimental effect on hearing.

In a study on the prevalence of hearing impairment in England, Scotland and Wales, Wilkins (1) found that in 5% of the cases hearing loss was based upon industrial noise exposure. Ewertsen (2) performed a similar study for the Danish situation, which is in several respects comparable to the Dutch, and found an incidence of industrial noise-induced hearing loss of 23 per 100,000 inhabitants. This figure, corresponding to 6.6% of all hearing impaired, concerns people who complained of a hearing loss and applied for (free) audiologic help. 60% Of these individuals with hearing loss attributed to noise were 65 years of age or older and only 6% of them were female. It is important to realize that this incidence exceeds the nowaday's otosclerosis incidence by a threefold. Based upon their intelligibility score for speech (the author does not mention wether this test concerns intelligibility for words or sentences) he recognized 5 categories: normal hearing in spite of an audiometric loss (18%), slight impairment (46%), medium impairment (27%), severe impairment (7.2%) and deaf (2%). These data imply that more than one out of three individuals with noise-induced hearing loss suffer at least from medium hearing impairment.

The way in which noise damages cochlear hearing has been studied in animal models. From post-mortem analysis of the organ of Corti it appears that mainly the outer hair cells are destroyed. Regarding the cause of destruction, Bohne (3) distinguishes in a review of the literature four damaging mechanisms: 1 mechanical damage by direct acoustical trauma; 2 metabolic damage due to depletion of vital enzymes; 3 vascular changes causing ischaemia and 4 ionic damage due to the influx of endolymphe. Most probably the cochlear damage is caused by a combination of all four mechanisms. The main localisation of outer-hair-cell damage after prolonged exposure to white noise is situated at the end of the basal turn and in the beginning of the second turn of the cochlea as is demonstrated by Spoendlin (4). In the human ear this area corresponds to the pure-tone range from 3 to 6 kHz.

For a clinical diagnosis of noise-induced hearing loss in general the following three criteria have to be met: 1 history of industrial noise exposure, 2 normal findings on otoscopic and tuning fork examination, and 3 symmetrical perceptive pure-tone audiometric threshold shift in the range between 3 and 6 kHz with a predilection-site at 4 kHz. Recording of a pure-tone audiogram gives an excellent picture of the cochlear and middle-ear function of an individual. Moreover, periodical pure-tone audiometrical screening in industrial healthcare gives a reliable insight into onset and progress of cochlear deterioration and into the effect of preventive measures, like reduction of machine noise and the use of sound protectors at noisy work places. In other words, from a diagnostic point of view the pure-tone audiogram serves us quite well in case of noise-induced hearing loss.
However, deducing the degree of hearing handicap from a pure-tone audiogram of an individual with e.g. a symmetrical perceptive 40-dB loss at 4 kHz can be hazardous. We know that speech, being the most important communicative signal to man, contains most of its energy in the range of 0.5-2 kHz. Based upon the wide spectrum of speech, one might assume that an isolated pure-tone loss at 4 kHz will not be of any appreciable practical importance. However, intelligibility is not directly related to the overall signal energy; the consonants, being relatively faint, are an essential part of the speech signal and their character is mainly determined by the high frequencies. Therefore the weighting of speech energy related to intelligibility has a broad maximum in the region around 2 kHz [Kryter (5)]. This holds for audible speech both in quiet and in noise, but for noisy conditions the focus may shift further towards the high frequencies, because interfering noise, usually with most energy at the low frequencies, masks low-frequency elements in everyday speech. In such conditions the significance of the high-frequency acuity is even more vital for correct understanding of speech. In 1973 Kuzniarz (6) demonstrated the importance of pure-tone thresholds above 2 kHz by low-pass filtering in speech tests. For normal-hearing listeners speech intelligibility in quiet remained approximately normal, but in a white noise and especially in low-frequency background noise speech intelligibility deteriorated significantly.

The interpretation of the pure-tone audiogram in estimating an individual's hearing loss for speech has also altered as a result of correlational studies [Kryter (7), Smoorenburg (8)] between pure-tone thresholds and speech intelligibility scores. The accent on the low and mid-frequency range (Fletcher Index) has changed into one also including the 3- and 4-kHz thresholds. Additionally, in order to be able to evaluate a patient's complaint of hearing loss and to assess the degree of handicap that it represents, the intelligibility of speech should be tested.
As a diagnostic tool, speech audiometry is often performed with mono-syllabic or spondaic words, presented in quiet. Everyday listening situations, however, mostly concern speech in the presence of interfering noise. Because of the fact that in quiet our ear is far more sensitive than we need for speech reception, complaints about difficulties with speech understanding often appear first in noisy conditions like meetings, parties and so on. In spite of this, the intelligibility of speech presented in quiet has been proposed by the American Academy of Otolaryngology (9) to be the standard in calculating the degree of hearing impairment. Standardization of everyday noisy conditions was judged to be too difficult to incorporate into a hearing test.

The importance of considering the effect of interfering noise upon speech intelligibility has been recognized by several authors. Already in 1953 Simonton and Hedgecock (10) searched for a satisfactory procedure to evaluate the hearing of a group of airline pilots, because the existing criteria based on pure-tone thresholds appeared to be inadequate with regard to their practical listening situation. They found, on assessing the speech intelligibility for words and connected discourse, a discrepancy between the speech intelligibility in quiet and in noise. Additionally, sensorineural hearing loss appeared to cause a larger hearing loss for speech in noise than conductive loss did.

Groen (11) advocated the assessment of speech intelligibility of mono-syllabic words presented in "cocktail party noise" in order to estimate a patient's hearing handicap. Lindeman (12) applied this method to a group of 679 male noise-exposed industrial workers. From this study it was concluded that speech-hearing loss in noise gives a good evaluation of hearing in everyday listening situations and is insufficiently predictable from the pure-tone audiogram. The importance of speech intelligibility in noise was also demonstrated by Palva (13), Speaks and Karmen (14), Cooper and Cutts (15) and Tillman et al.(16). A problem with many of these reports is the variety of speech and noise modalities used, which makes it often impossible to compare the results among studies. In some cases even within the same study it is not possible to compare the speech- hearing loss in noise to speech hearing loss in quiet. Another problem in most of these studies is the handling of fixed signal-to-noise ratios for which the intelligibility score of each listener is determined; as a result a comparison of data is hampered because of a lacking standard assessment of the Speech-Reception Threshold in noise.

Plomp (17) recognized this problem and proposed to assess the Speech-Reception Threshold to be the sound level (in quiet) or signal-to-noise ratio (in noise) for which 50% of speech is understood. In other words, for a variable signal-to-noise ratio the standard performance (50% intelligibility) of a listener was determined instead of the other way around. This makes inter-individual comparison much easier. In the same paper Plomp introduced a descriptive model in which the hearing loss for speech is divided into two components, A and D, representing attenuation and distortion. An attenuation-type of hearing loss can be fully compensated for by sufficient amplification of the presented speech. This is not possible in case of a distortion-type of hearing loss, that concerns a deterioration of hearing of which the effect extends even far above absolute hearing threshold and which can only be compensated for by a better signal-to-noise ratio. The attenuation component is comparable with a purely conductive hearing loss; it causes hearing loss for speech in quiet, but for speech presented in noise normal signal-to-noise ratios for speech intelligibility are obtained. The distortion component often accompanies sensori-neural hearing loss; it acts as a distortion and causes elevated thresholds for speech reception both in quiet and in noise. It is important to realize that this classification is only descriptive and based upon speech-reception thresholds. Therefore, a hearing loss with a single pathological origin may contribute to both descriptive components. To determine the Speech-Reception Threshold (SRT) in quiet and in noise, Plomp and Mimpen (18) designed a test battery of sentences and a masking noise with a spectrum equal to the long-term average of the sentences. As stated earlier, the SRT was chosen to be represented by the level of speech for which 50% of the sentences was correctly reproduced by the listener. The SRT in noise is expressed as the signal-to-noise ratio at this threshold. For normal-hearing listeners the SRT in noise is found at a signal-to-noise ratio

of -5 dB. The difference in SRT in noise between a hearing-impaired listener and the average for normal hearing is called Speech-Hearing Loss in Noise (SHLN) and is used as a measure of hearing handicap. Every 1-dB difference in SHLN corresponds to a difference of approximately 18% in speech-intelligibility score for sentences. In accordance with Smoorenburg (19) we consider a beginning hearing handicap to be present at a SHLN of 2.5 dB; this degree of hearing loss corresponds to a reduction of 25% in the critical inter-individual distance in a two-person conversation in order to obtain intelligibility scores equal to the scores of normal-hearing listeners. Another argument for accepting the 2.5 dB limit is that this value is the average hearing loss in males of 60-70 years of age due to presbycusis only, according to Plomp and Mimpen (20). This 2.5 dB SHLN represents a speech-intelligibility loss of approximately 2.5x18% = 45% relative to a normal-hearing individual. The model was applied successfully to a variety of populations (21,22,23).

The goal of the present study is to give an insight into the hearing handicap of a group of noise-exposed individuals, who are protected against industrial noise according to the current Dutch standards. This insight is obtained by the assessment of the SRT for sentences in noise, together with the pure-tone audiogram. For a comparison of the speech-reception threshold in noise, and implicitly the hearing handicap, with an optimal interpretation of the pure-tone audiogram, an analysis of correlation between pure-tone thresholds and SRT is performed.

METHOD

In the period May 1986 until April 1987 185 sheet-metal workers were screened audiometrically. Their age ranged from 18 to 62 years with a median of 27 years and the median period in their current job (noise exposure) amounted 8 years. From earlier measurements at the workfloor the average noise level can be estimated to be 85-90 dB SPL. Peak noise levels amounted 114-120 dB SPL, measured at ear level of the employee when performing the noisiest part of his work (riveting). On the average approximately one hour per working day was spent on riveting. In these circumstances sound protectors were used.

Two employees were considered not eligible for the study; one because of a radical mastoidectomy in the past and the other because of a monaural deafness since childhood. So the study concerns 183 subjects or 366 ears.

A pure-tone air-conduction audiogram ranging from 0.25 to 8 kHz in one-third octave frequency steps was recorded for both ears of each subject (Peekel audiometer). Subsequently the Speech Reception Threshold (SRT) in quiet and at four noise levels (35, 50, 65 and 80 dBA) was determined for both ears.

The speech material consisted of short meaningful Dutch sentences of eight or nine syllables, representative of everyday conversation, as designed by Plomp and Mimpen (18). The noise had a spectrum equal to the long-term average spectrum of the speech material. For every subject 10 lists of 13 sentences each were available; there were five measuring conditions in every ear and for each condition one list of sentences was used. The speech material and noise were stored on a computer disc and the presentation of speech and noise was controlled by a mini-computer. The Speech Reception Threshold was determined by means of a simple up-and-down procedure (24) starting at a sub-threshold level. For each incorrect response the first sentence was repeated at a 4 dB higher level. After a correct reproduction of the full sentence by the subject the step size was reduced to 2 dB and in each subsequent trial a new sentence was presented. In case of correct reproduction of a full sentence the speech level was lowered by 2 dB, whereas incorrect response caused the speech level to be raised by 2 dB. The procedure stopped after the thirteenth sentence and the average level of the last ten sentences was taken as the SRT for 50% intelligibility.

The SRT in noise for-normal hearing listeners using our speech material and noise amounts -5 dB in signal-to-noise ratio. Speech- Hearing Loss in Noise is defined as the difference between this normal threshold and the actually obtained SRT in noise for the hearing-impaired listener; when the SRT in noise for a subject amounts e.g. -2 dB S/N ratio, the SHLN is 3 dB. For every ear the average SHLN is calculated from the SRT as a function of noise level according to the curve-fitting procedure described by Duquesnoy (23).

RESULTS

1 Pure-tone audiometry

The distribution of the pure-tone audiometric thresholds found for 366 ears is given in figure 1. Median values, and the 10, 25, 75 and 90 percentiles are plotted. There is, as expected, a marked threshold elevation at 4 kHz. Nevertheless 75 % of the ears have a threshold shift at this frequency of 20 dB or less. Only 15 % of the ears have at 4 kHz a hearing loss between 20 and 40 dB and 10% have a hearing loss in excess of 40 dB.

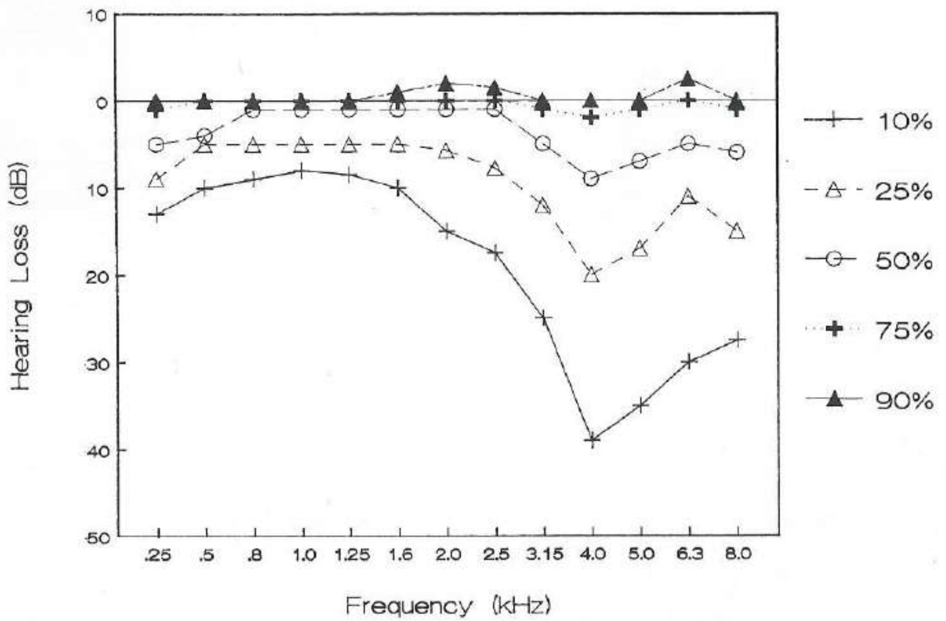

Fig.1 Distribution of audiograms in a group of 183 workers (366 ears) who were exposed to noise. Different curves show hearing losses that are exceeded for the indicated percentage of ears.

In figure 2 the average 2- and 4-kHz threshold of the tested population is compared with normative data on noise-exposed populations, as can be derived from the ISO/DIS 1999.2 standard (25); To obtain the average hearing loss at 2 and 4 kHz due to noise exposure, the audiometric thresholds as measured were corrected for the normal increase of hearing loss with age according to an estimate from the standard. We used the equation:

$$A = B - C/[1-(C/120)] \qquad (1)$$

where: A = age-corrected pure-tone average for 2 and 4 kHz (to be

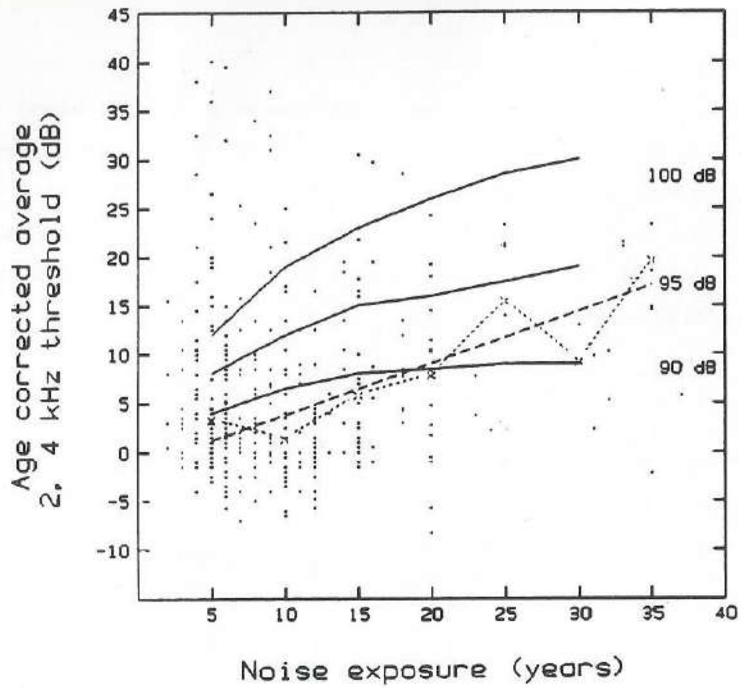

Fig.2 Age-corrected average hearing loss for 2 and 4 kHz plotted against the number of years of noise exposure, for 366 ears. The symbols represent the median hearing loss for the group in 5-year intervals and the dashed line is the best fitting straight-line approximation to the symbols. The solid lines represent the growth of average hearing loss for an 8-hour daily exposure to 90, 95, and 100 dBA noise, respectively (from ISO/DIS 1999.2).

calculated). B = measured pure-tone average for 2 and 4 kHz, and C = pure-tone average for 2 and 4 kHz according to age as given in the standard. The three solid curves are from he ISO standard and represent the average pure-tone threshold for 2 and 4 kHz as a function of time for 8-hours daily industrial noise exposure of 90, 95 and 100 dBA, respectively. The dotted curve represents the median thresholds for subsequent 5 year periods of noise exposure for our subjects. The dashed line is the best-fitting straight line through these medians. The 8-hour daily noise exposure for our subjects as estimated from this diagram is between 90 and 95 dBA.

2 Speech intelligibility

Figure 3 shows the median level and the 10 and 90 percentiles for the

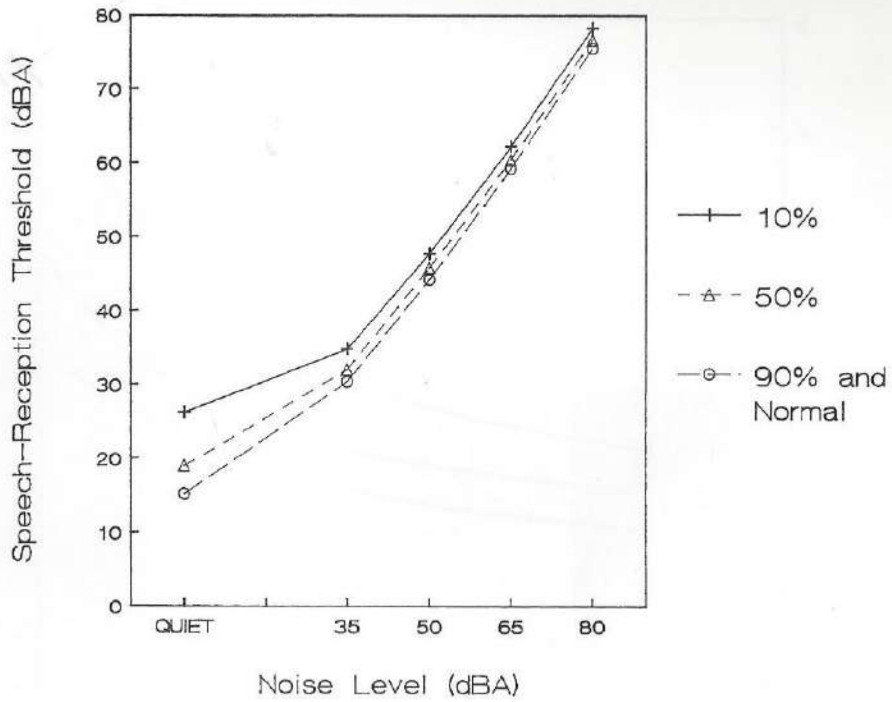

Fig.3 Distribution of the Speech Reception Thresholds measured as a function of noise level in 366 noise-exposed ears.
Different curves show thresholds exceeded for the indicated percentage of ears.

SRT as a function of the level of masking noise. The median SRT values for normal-hearing individuals overlap with the level that 90% of the tested employees exceed. The median SRT in quiet amounts 19 dB, which is 4 dB higher than for normal-hearing individuals. The median Speech Hearing Loss in Noise amounts 1 dB, with a 2.7-dB spread. The effect of age upon Speech Hearing Loss in Noise was investigated by Plomp and Mimpen (20). In figure 4 we plotted our SHLN data against age in order to separate the effect of noise from the effect of aging. The three solid curves represent the median values and 25 and 75 percentiles of SHLN for a non-noise exposed population (20). Roughly 50% of the tested ears have a SHLN higher than the worst 25% of the non-noise exposed population. This diagram clearly shows the detrimental effect of noise in terms of speech hearing loss, independent of the aging effect.

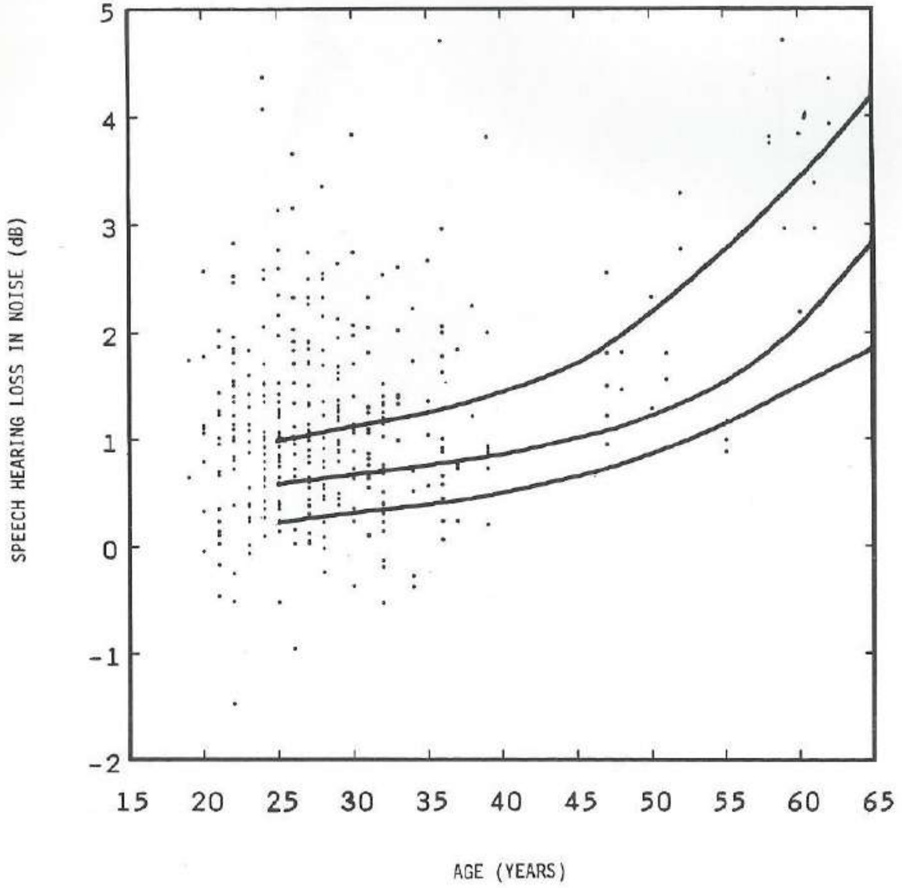

Fig.4 Speech-hearing loss in noise (SHLN) plotted against age for 366 noise-exposed ears.
Solid lines represent median and quartile boundaries for the distribution in a non noise-exposed population according to Plomp and Mimpen (20).

3 Hearing handicap

Table I shows the distribution of SHLN over all 366 ears. 10% Of the tested ears show an SHLN of 2.51 dB or more, which as pointed out in the introduction, represents at least a beginning hearing handicap. Table II shows several relevant data for the subgroup of subjects having one or two ears with an SHLN of 2.5 dB or more, compared to the overall group. As might be expected in case of hearing handicap due to industrial noise exposure, the

Table I.

Distribution of speech-hearing loss in noise for 366 noise-exposed ears. The thresholds shown are exceeded for the indicated percentage of ears.

SPEECH HEARING LOSS IN NOISE. 366 EARS (dB)	
10 %	2.51
25 %	1.72
50 %	1.07
75 %	0.64
90 %	0.23

Table II.
Comparison of audiologically relevant data between the overall group of noise-exposed ears and the subgroup with an SHLN greater than 2.5 dB. Mean data are given with standard deviation in parentheses.

EARS WITH A SHLN OF >2.5 dB
COMPARED WITH THE OVERALL GROUP

	SHLN >2.5*	OVERALL GROUP**
AGE (YRS)	37.2 (14.5)	29.2 (8.2)
NOISE EXPOSURE (YRS)	15.2 (11.1)	10.2 (7.2)
FLETCHER INDEX (dB) (0.5,1,2 kHZ)	7.5 (8.6)	3.9 (6.4)
PURETONETHRESHOLD(dB) (3,4,5 kHZ)	32.1 (25.8)	11.9 (15.7)
SRT QUIET (dB)	25.0 (7.6)	20.3 (5.4)

* = 38 ears, 29 employees
**= 366 ears, 183 employees

average number of years of working in noise is higher than in the overall group. Of course, the same holds for the average age. Considering age, a striking phenomenon can be observed: a group of employees with an average age of 37.2 years shows an SHLN equal to that of a man in the age interval between 60-70 years old without a history of industrial noise exposure. There is a considerable threshold elevation at 3, 4 and 5 kHz (32 dB) in spite of a low Fletcher Index and the relatively good SRT in quiet (25 dB).

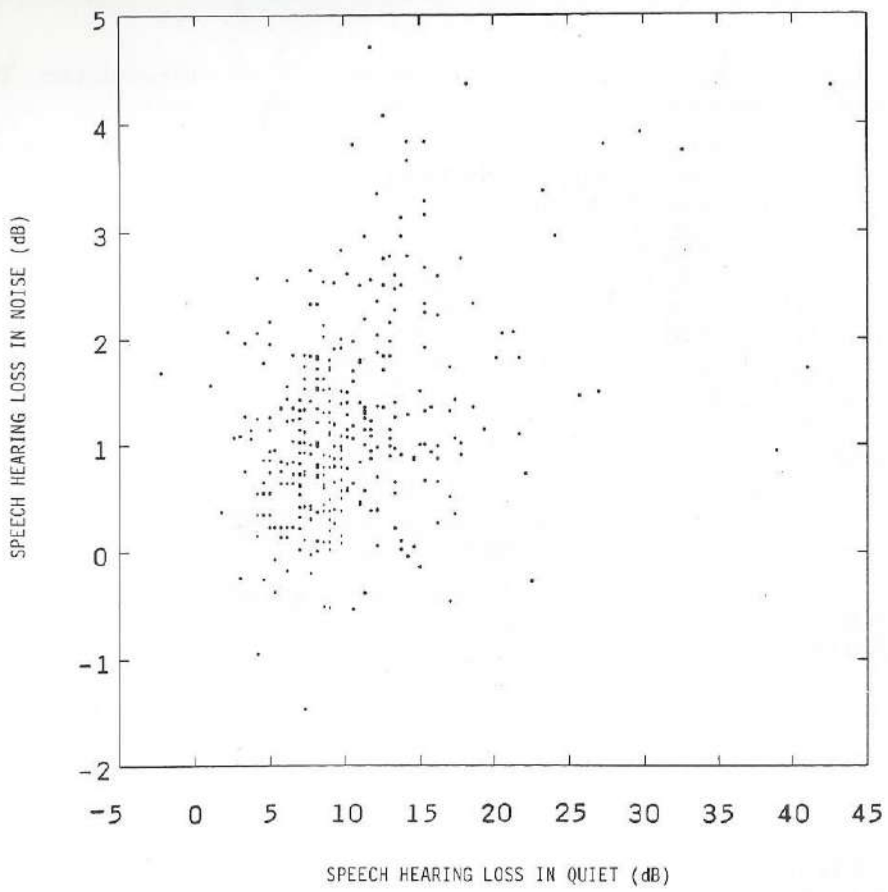

Fig.5 Scatter diagram of Speech-Hearing Loss in noise against the Speech-Hearing Loss in Quiet (r=0.35).

Figure 5 shows the poor relation between the Speech-Hearing Loss in quiet and Speech-Hearing Loss in Noise. The correlation coefficient is only 0.35. As is also clear from the diagram this low correlation coefficient implies that speech intelligibility in noise cannot be predicted from speech intelligibility in quiet.

RELATION BETWEEN PURE-TONE AUDIOMETRY AND SPEECH INTELLIGIBILITY

The audiometric data, giving an accurate picture of the cochlear function, are now compared to the SRTs in quiet and in noise, which are more representative of complaints of hearing handicap in everyday listening situations. In order to find pure-tone parameters optimally fitting to speech intelligibility in quiet and in noise, the data are processed by means of analysis of correlation: first simple correlations and secondly canonical correlations.

1 analysis of correlation

The overall group of sheet-metal workers was of relatively early age and, on the average, the number of years of work in a noisy environment was low. Therefore in the overall group the typical high-frequency threshold shift is only moderate. For a more clear-cut comparison between noise-induced high-frequency hearing loss and Speech Hearing Loss in quiet and in noise, two subgroups are distinguished in which pure-tone audiometric losses are more clearly present. The first subgroup contains 74 employees who worked in noise for 10 years or more and includes the second subgroup of 37 employees working in noise for 15 years or more.

Figure 6 shows for these two subgroups the median thresholds and 10 and 90 percentiles of the pure-tone audiograms. The two selected subgroups have a 4 kHz median threshold of 14 and 22 dB, respectively; these figures are higher than for the overall group. Figure 7 shows the correlation coefficient of Speech-Hearing Loss in Noise and the pure-tone thresholds as a function of frequency. Correlation coefficients are given for the overall group and the two subgroups. The three curves show comparable patterns; high frequency thresholds starting from about 2.5 kHz correlate best with SHLN. This pattern is most distinct in the subgroup of 15 years or more noise exposure and the highest correlations are obtained for 3, 4, and 5 kHz (0.73, 0.72, and 0.68, respectively). In a relatively simple way this finding demonstrates the importance of the high-frequencies regarding speech reception in noise. For the same groups figure 8 shows the correlation coefficient of the SRT in quiet and the pure-tone threshold as a function of frequency. This curve is completely different from figure 7; here the highest correlations are found in the lower frequency pure-tone thresholds up to about 2 kHz. Again, in the two selected subgroups this pattern is more distinct than in the overall group.

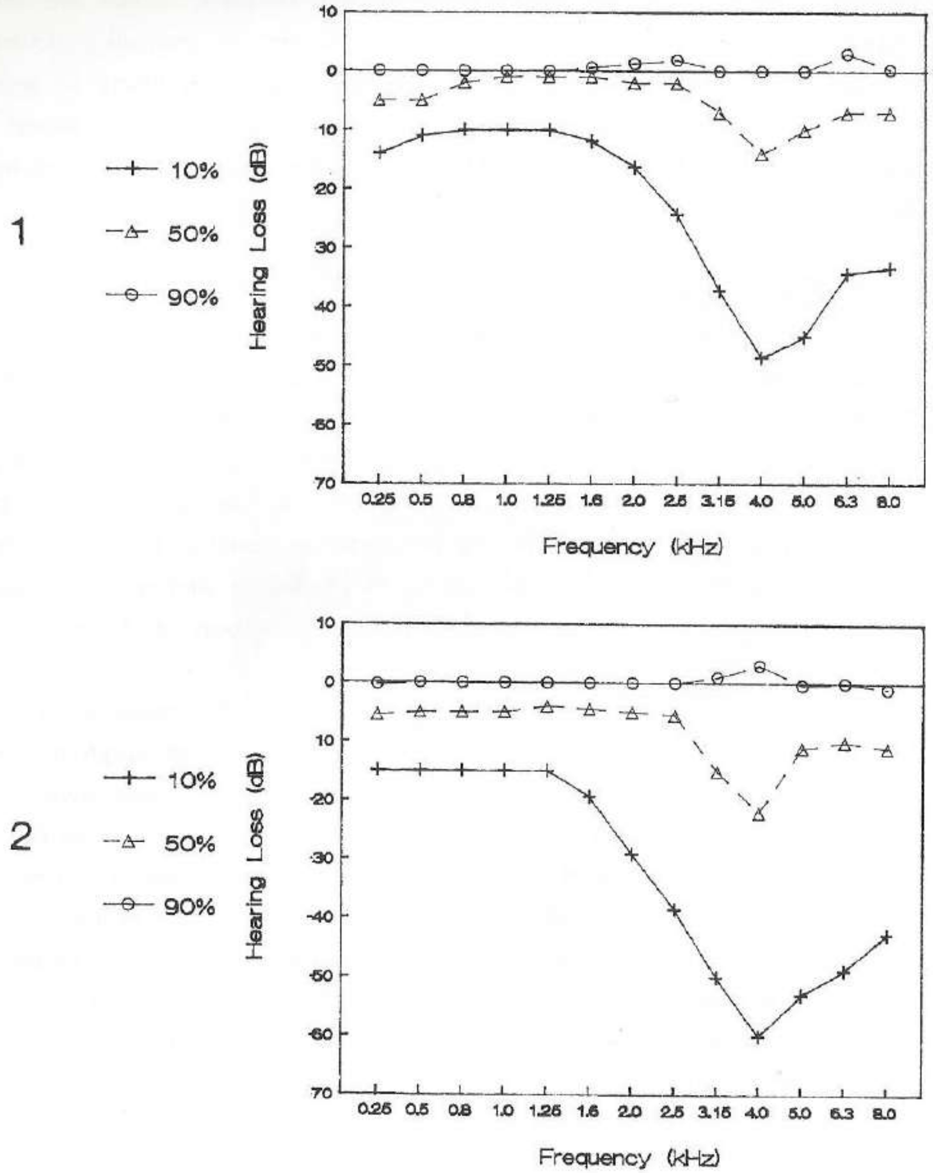

Fig.6 Distribution of the audiograms of the two subgroups. Different curves show hearing losses that are exceeded for the indicated percentage of ears. Panel 1 for the 10 years or more noise-exposed ears (148). Panel 2 for the 15 years or more noise-exposed ears (74).
1 10 years or more noise exposure. 74 subjects (148 ears)
2 15 years or more noise exposure. 37 subjects (74 ears)

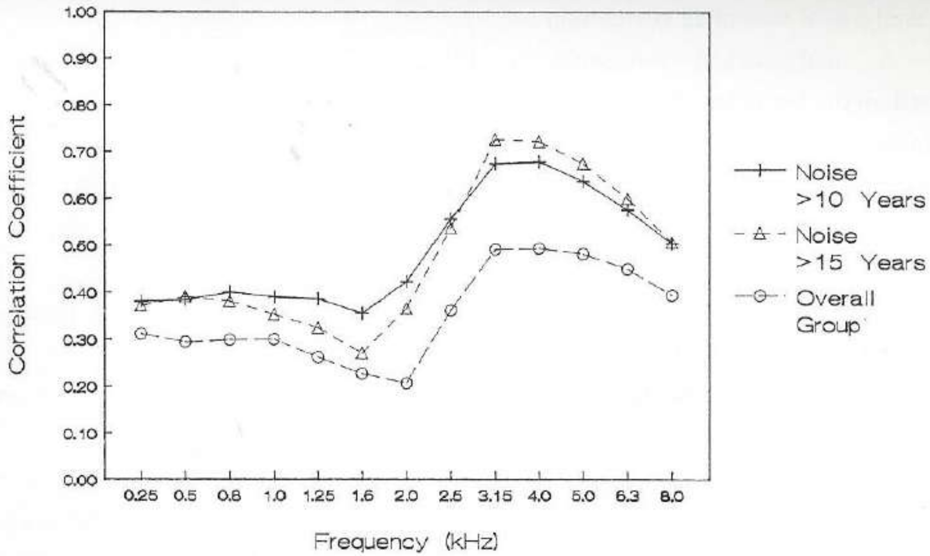

Fig.7 Correlation coefficients between Speech-Hearing Loss in Noise and pure-tone thresholds for individual frequencies. Different curves represent the overall group and two subgroups.

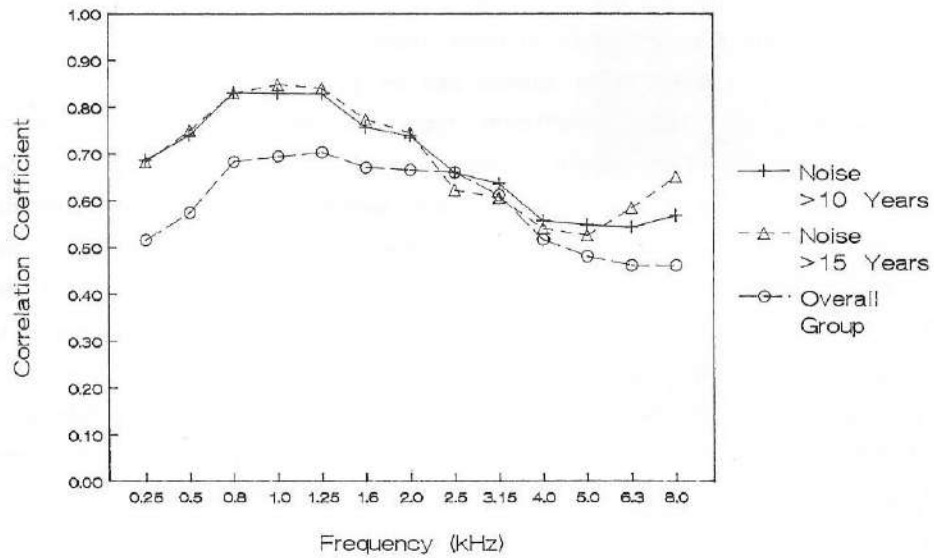

Fig.8 Correlation coefficients between Speech-Reception Threshold in quiet and pure-tone thresholds for individual frequencies. Different curves represent the overall group and two subgroups.

2 analysis of canonical correlation

A mathematical procedure to find the highest possible correlation coefficient between two sets of multiple variables is canonical correlation analysis. The procedure finds from each set of variables the linear combination that gives the highest mutual correlation correlation. Then, from each set all variance related to that dimension is extracted, and the procedure is repeated. In this way a series of linear combinations for the groups of variables is obtained that for each stage gives the highest possible correlation after the variance related to all previous stages is removed. We applied this procedure to the pure-tone thresholds and the speech-reception thresholds in quiet and noise. Details of the procedure and results are given in the appendix. Here, we will confine to the results for the group of employees working in noise for 15 years or more, representing the effects of noise-induced hearing loss most clearly. For this subgroup the canonical correlation coefficient between the SRTs in noise of 50, 65, and 80 dBA and the pure-tone thresholds amounts 0.88. What we really wish to know from the canonical correlation analysis applied to pure-tone thresholds and SRT in noise is: to what extent does information contained in pure-tone thresholds duplicates information in the SRTs in noise? In other words, to what extent is the information in the SRTs in noise redundant, given that the pure-tone thresholds are available? This answer can be given by redundancy analysis: The canonical correlation coefficient represents the relation, after having addressed an individual weight factor to each variable, between a linear combination of one set of variables and another. The squared canonical correlation coefficient represents the percentage of explained variance in the linear combination of the variables, which is only a certain fraction of the variance in the original variables. In order to calculate the redundancy in canonical correlation analysis we have to multiply the squared canonical correlation coefficient by this fraction. In case of the pure-tone thresholds and SRTs in noise for the 15 years or more noise-exposed subgroup this fraction is 0.62, which renders a redundancy percentage of only 48.

3 simple versus canonical correlation

Table III gives correlation coefficients between 4 different pure-tone threshold averages and Speech-Hearing Loss in Noise. The canonical-

Table III.
Correlations between simple pure-tone averages and the speech-hearing loss in noise for three groups of subjects. Also given is the canonical-correlation coefficient for all 13 pure-tone thresholds and the speech-reception thresholds (for 50, 65, and 80 dBA noise respectively).

PURE-TONE THRESHOLD AVERAGES CORRELATED TO SHLN, COMPARED WITH CANONICAL CORRELATION COEFFICIENTS OF PURE TONE THRESHOLDS WITH SRT(50-80 dB)

PTA/SHLN	OVERALL	NOISE>10YRS	NOISE>15YRS
2,4 kHz	0.45	0.66	0.67
2,3,4 kHz	0.48	0.68	0.71
3,4 kHZ	0.51	0.70	0.75
3,4,5 kHZ	0.52	0.70	0.74
CANON. CORR.	0.68	0.82	0.88

correlation coefficient, being the highest possible correlation, between pure-tone audiometry and the SRT in noise is 0.88 for the subgroup with 15 years or more noise exposure. The simple correlation coefficient in this group that approaches the canonical correlation most closely is 0.75, obtained for the average threshold at 3 and 4 kHz. The average of the thresholds at 2 and 4 kHz yields a correlation coefficient of 0.67. Again these results concern the 15 years or more noise-exposed group. For the other two groups the results are essentially equal, but the correlation coefficients are lower. Regarding the only small difference between simple- and canonical-correlation coefficient and the convenience of handling a simple instead of a canonically weighed pure-tone average, we believe that the average threshold of 3 and 4 kHz is the best compromise between simplicity and prediction strength.

DISCUSSION

IMPLICATIONS FOR INDUSTRIAL AUDIOMETRY

As appears from the analysis of simple-correlation, the average 3- and 4-kHz pure-tone thresholds are nearly optimally correlated to the SHLN. In

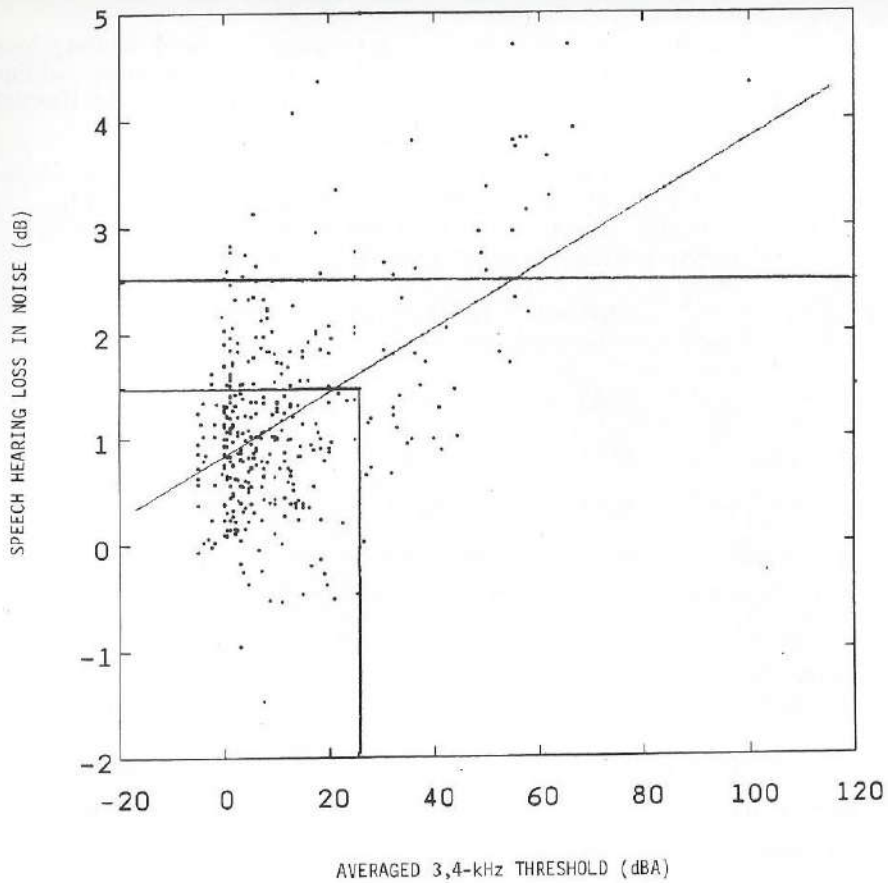

Fig.9 Scatter diagram of Speech-Hearing Loss in Noise against the averaged thresholds at 3 and 4 kHz (366 ears).

figure 9 this relation is shown grafically for the overall group. Here, the correlation coefficient is only 0.51 (see table III) and thus only about 25% of the variance in Speech-Hearing Loss in Noise can be accounted for by the pure-tone thresholds. The still considerable error of estimate is also apparent from the spread around the regression line predicting Speech-Hearing Loss in Noise. The standard deviation of this spread is 0.8 dB. This means that for over 20% of the individuals we make a prediction error in excess of 1 dB. On the contrary, the measurement error in the Speech-Reception Threshold averaged over three noise levels is only 0.5 dB. Moreover, we should be very careful with a regression on the overall group because of the skewed

distributions of both pure-tone thresholds, and speech-reception thresholds. A skewed distribution of the data may easily lead to a spurious Pearson product-moment correlation coefficient, which forms the fundament of linear regression.

All these factors contribute to prefering the determination of Speech Hearing Loss in Noise to the pure-tone audiogram in assessment of a hearing handicap due to noise-induced hearing loss.

When considering a Speech-Hearing Loss in Noise of 2.5 dB as a fence for a beginning hearing handicap, 3 categories of employees can be recognized from figure 9:

1 Employees with a hearing handicap.

Employees with a uni- or bilateral SHLN of 2.5 dB or higher. According to Smoorenburg (19) these employees have a speech-reception threshold in noise equal to or worse than non-noise-exposed listeners between 60 and 70 years of age. In a person-to-person conversation this loss can be compensated for by reducing the distance between talker and listener by one quarter. In critical conditions this is felt to be a social handicap. These employees should be strongly advised to wear sound protection. Even, if possible, an attempt should be made to find a less noisy (part of the) job. These employees should receive audiometric follow-up because also within this category there is always a risk of further deterioration of hearing. We suggest a two-years interval.

2 Employees to keep a close "audiometric watch" upon.

a Employees with a uni- or bilateral SHLN between 1.5 and 2.5 dB. When applying the proposed criterion, in this category a hearing handicap is not yet present.

b Employees with a uni- or bilateral SHLN of 1.5 dB or less, but with an averaged 3,4 kHz pure-tone threshold of 25 dB or higher.

For prevention this category will be a challenge, because it will be difficult to motivate the employees for protective measures. Most of them do not have any complaints, and therefore just an advice to wear sound protection will not suffice. A practical demonstration of the effect of hearing loss by e.g. high-frequency filtering of a piece of music or conversation appears to make the problem easier to understand and renders a compliance to methods of sound protection that is more satisfactory. Also for this category we advise a two- years' audiometric follow-up.

3 Employees without pure-tone or speech-audiometric deviations.

Employees with bilateral SHLN smaller than 1.5 dB and an averaged hearing loss at 3 and 4 kHz smaller than 25 dB. This group, without a substantial hearing impairment, also needs instruction about wearing sound protection and should preferably receive a four-years' audiometric follow-up for the time they work in noise.

As can be concluded from the partition into the just described 3 categories, the assessment of the SRT in noise refines the judgement on hearing impairment in a group of noise-exposed individuals. Detection of a beginning hearing impairment for everyday listening situations is reliably, and relatively easily, performed in this way.

We recommend to assess the SRT in noise in addition to the pure-tone audiogram, i.e. as a part of the audiological pre-assessment for employees applying for a noisy job and as a part of periodical follow-up.

Accepting speech-hearing loss in noise as an adequate measure for hearing handicap, we see that even with moderate pure-tone audiometric losses such handicap can be present. This makes the assessment of the SHLN a very sensitive procedure. Comparison of pure-tone thresholds and the SRT in noise by means of analysis of simple and canonical correlation gives an indication of the significance of high-frequency pure-tone thresholds with regard to speech reception in noise. For the individuals who are longer exposed to noise (generally those with the larger high-frequency losses) the correlation coefficients are highest.

The most important conclusion from the analysis of correlation is knowing that high-frequency hearing loss, as found after prolonged noise exposure, may cause hearing problems in noisy everyday listening situations in spite of a normal Fletcher Index. It is of importance to realize that these correlations only hold for sensorineural hearing impairment due to noise exposure. In listeners with e.g. a hereditary sensorineural hearing impairment with a flat or bowl-shaped pure-tone audiogram correlational studies may show a totally different picture.

In case of noise-induced hearing loss it would be tempting to try to use the easily available pure-tone audiogram as a replacement for the assessment of the speech intelligibility in noise or hearing handicap. For groups instead

of individual listeners this is advocated by Smoorenburg (8). Because of the substantial percentage of error in the speech-reception threshold in noise as estimated from the pure-tone audiogram, we are very reluctant to apply this procedure to an individual patient with noise-induced hearing loss. In order to correctly evaluate a hearing handicap for a single noise-induced hearing-impaired individual, assessment of the speech intelligibility in noise, as an addition to pure-tone audiometry, is mandatory.

CONCLUSIONS

-The tested population shows an average age-corrected hearing loss for 2 and 4 kHz that corresponds, according to ISO/DIS 1999.2, with losses acquired in 8-hours daily exposure to 90-95 dBA (see figure 4). However, the variation among individual subjects is very large and about one-third of the employees show no appreciable pure-tone hearing loss caused by their exposure to noise.

- Despite of only moderate pure-tone audiometric losses a hearing handicap can be demonstrated by means of the assessment of the Speech-Reception Threshold in noise.

-For this group the highest correlation coefficient that can be obtained between a simple pure-tone average threshold and the Speech-Hearing Loss in Noise is 0.75 (see Table III) for 3 and 4 kHz. The highest possible canonical correlation coefficient amounts 0.88, corresponding to an explained variance of only 48%, taking into account that the variance represented in the canonical correlation analysis is only a fraction of total variance in the original variables. Therefore the pure-tone audiogram cannot sufficiently predict Speech-Hearing Loss in noise.

-The assessment of the SRT in noise gives an insight into hearing handicap in everyday listening situations.

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computer-software for the canonical correlation analysis. Also we would like to thank him for his critical remarks on the manuscript.

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APPENDIX

ANALYSIS OF CANONICAL CORRELATION

When comparing multiple variables like pure-tone thresholds with the multiple data of the SRT in quiet and at 4 different noise levels, a procedure of mathematical origin can be applied to detect the highest possible correlation coefficient between these two sets of variables. This mathematical procedure is called analysis of canonical correlation. From each set of variables this procedure finds the linear combination that gives the highest correlation. Then from each set of variables all variance related to this linear combination is extracted and the procedure is repeated. In this way a series of linear combinations or components for the two groups of variables is obtained. The linear combination consists of an individually addressed weight factor to each of the variables involved (13 pure-tone thresholds in one set and the SRT in quiet and four noise conditions in the other set of data). For an extensive explanation of the mathematical background of the analysis, see Elazar-Pedhazur (26). Figure 1 shows graphically the results of this manoeuvre for the pure-tone and SRT (quiet and noise) data. The analysis was applied to the pure-tone thresholds and Speech Reception Thresholds of the overall population of subjects and the two earlier mentioned subgroups.

The character I represents the first linear combination or component rendering the highest possible correlation coefficient between the pure-tone thresholds and SRT data. On the vertical axis the required factor-loadings for the respective pure-tone frequencies is plotted. A factor-loading is obtained by correlating the original variable (pure-tone threshold or SRT) with the according to the canonical analysis calculated weight-factors of the other variables in the set. The character II stands for the linear combination rendering the second best and statistically significant canonical correlation coefficient and the factor-loadings that belong to it. The longer the duration of the noise exposition, the more important this second component becomes (correlation coefficients are 0.44, 0.62, 0.76 for the overall group, 10 years and 15 years noise-exposed group, respectively).
Regarding the first component's factor loadings of both pure-tone and speech data an important phenomenon appears: all the pure-tone frequencies are equally weighted, whereas the SRTs at 65 and 80 dB noise level are of less importance than the thresholds in quiet and relatively low noise levels of 35

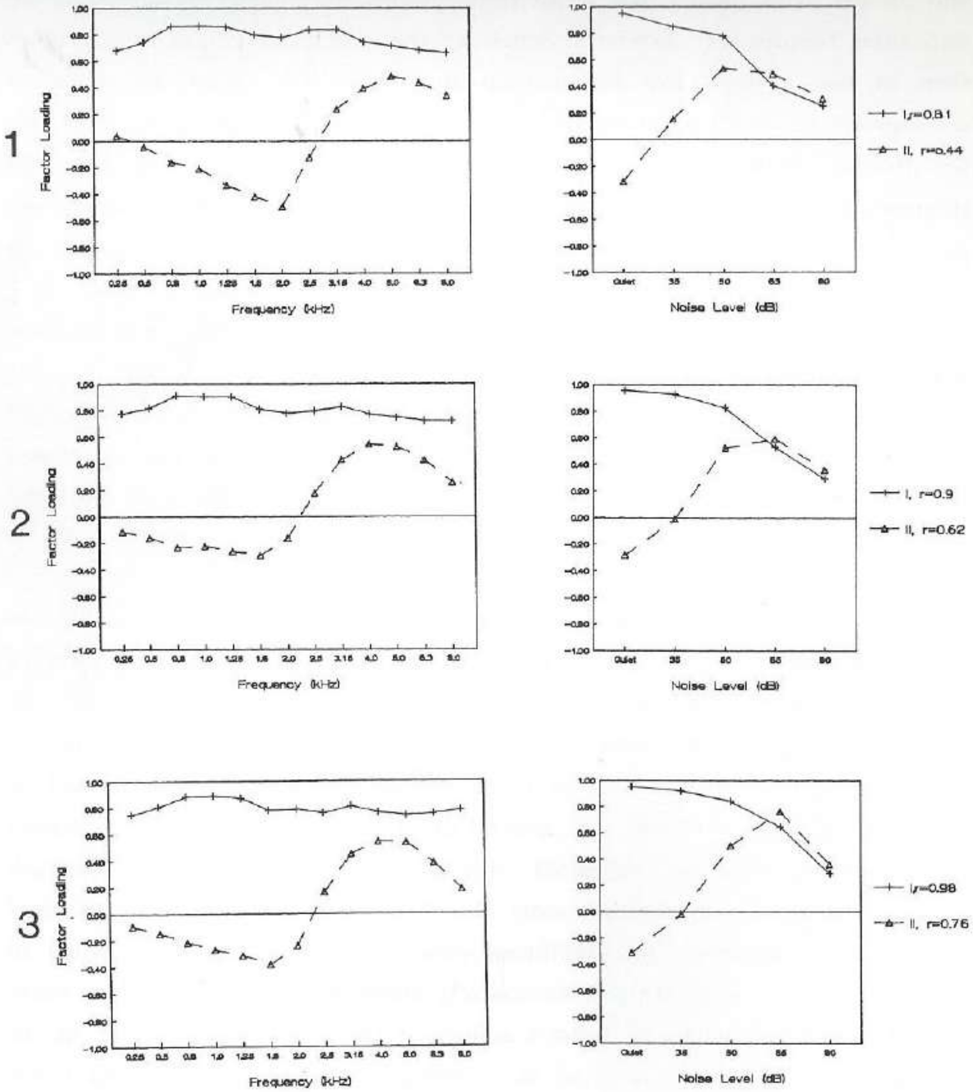

Fig. 1A.
Canonical loadings for individual pure-tone and Speech-Reception Thresholds after canonical correlation analysis between all pure-tone thresholds and SRT in quiet and noise. Left column for pure-tone thresholds, right column for Speech-Reception Thresholds. First and second canonical components are indicated by I and II, respectively, and the canonical correlation coefficient is given
1 overall group
2 10 years or more noise exposure
3 15 years or more noise exposure

and 50 dB. This means that in all three groups the equally weighting of all pure-tone frequencies correlates better to the speech intelligibility in quiet than in noise. Regarding the second component (II), again an important correspondence in all three groups appears: pure-tone frequencies up to 2 kHz are loaded weakly, contrary to the positive factor loadings in the high frequencies. The SRT in quiet and 35 dB noise are loaded negatively, whereas the thresholds at 50, 65 and 80 dB noise level are loaded markedly higher. In other words, selectively positive weighting of pure-tone thresholds above 2 kHz correlates better to the speech intelligibility in noise than in quiet. The longer the noise exposition, the larger this correlation appears to be.

These are the results for the SRTs both in quiet and in noise. In order to investigate the canonical correlation between the pure-tone thresholds and the SRT in noise and quiet separately, the analysis is extended. At the same time a discrimination is made within the SRT in noise, evaluating the 4 different noise levels.

In figure 2 the pure-tone data are canonically correlated with the SRT in noise, eliminating one noise condition at a time successively. The first set of data (A) represents the canonical correlation of the pure-tone thresholds and the speech-reception thresholds in noise of 35, 50, 65 and 80 dB. In the second set of data (B) the SRT at 35 dB is left out, in (C) SRT at 35 and 50 dB is left out and in (D) 35, 50, and 60 dB are left out. The data represented by (E) are the pure-tone thresholds correlated to the SRT in quiet. In each of these canonical correlations only the first component (I) is considered because of the statistically insignificant value of the correlation coefficient of the second component (II). On successively eliminating the SRTs at low noise levels a marked change in factor-loadings of the low frequencies as far as and including 2 kHz occurs in all three groups: the more the low noise levels are excluded, the less important become the pure- tone frequency thresholds up to 2 kHz. This effect becomes more distinct with longer noise exposition, i.e. with increasing high-frequency loss. This is demonstrated by the increasing canonical correlation coefficients for the data sets A, B, C and D when comparing the overall group with the subgroups of 10 years or more and 15 years or more noise exposition. These findings show the correlation of the pure-tone thresholds starting from 2 kHz upwards, with the speech intelligibility in noise.

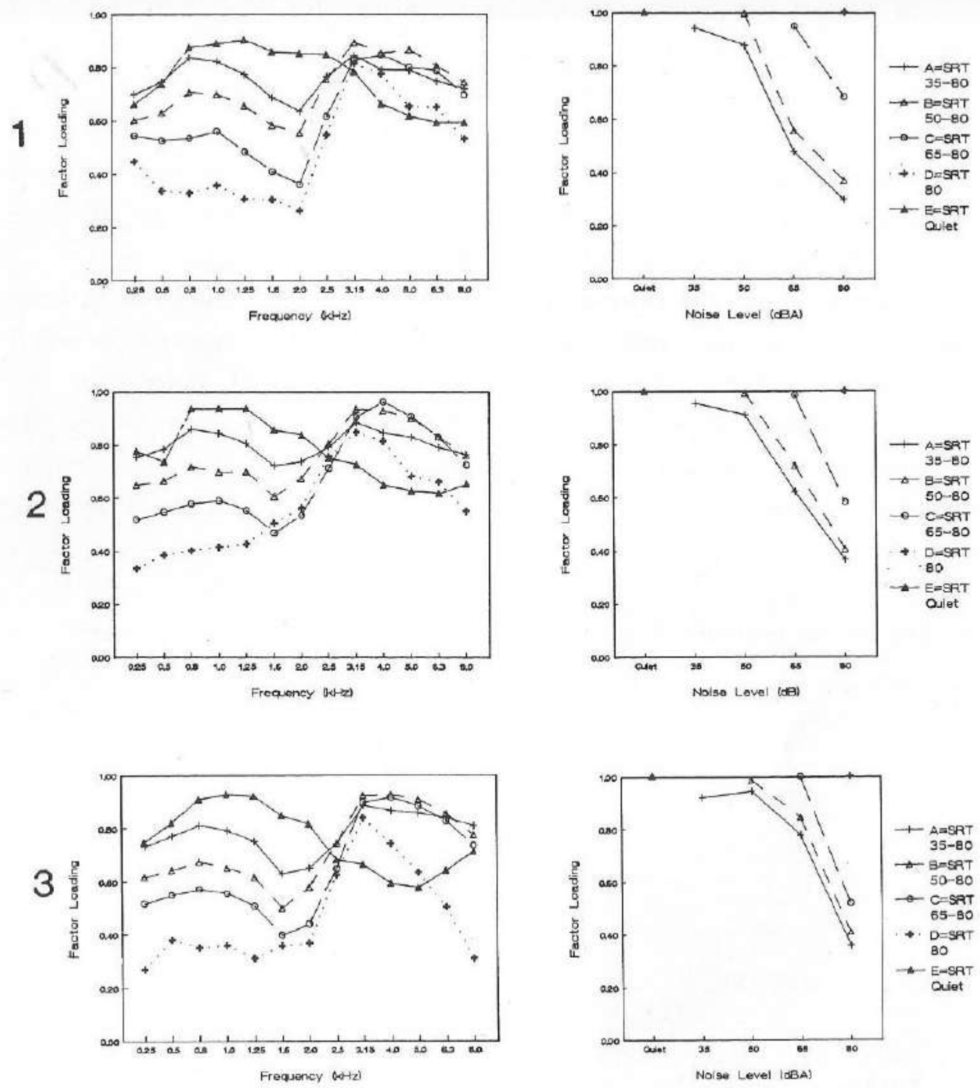

Fig.2A.
Canonical loadings for individual pure-tone and Speech-Reception Thresholds after successively eliminating SRT quiet (A), SRT quiet+35 dB (B), SRT quiet+35+50 dB (C), and SRT quiet+35+50+65 dB (D). E represents the result of canonical correlation of the SRT in quiet with the pure-tone thresholds.

1 overall group
2 10 years or more noise exposed
3 15 years or more noise exposed

In Table I the canonical correlation coefficients for the overall group and the two subgroups are listed together with the percentage of variance used, which is the percentage of variance in the original variables of the SRT in quiet and noise represented by the linear combination of weighted pure-tone thresholds. Eliminating the quiet condition and the lower noise-level conditions successively, this percentage increases gradually in all three groups. The maximum obtainable percentage is 68.

From the canonical correlation coefficient and the percentage of variance that is covered the "redundancy" is calculated. The squared canonical correlation coefficient gives the percentage of explained variance in the linear combination of speech-reception threshold data. In order to find the percentage of explained variance in the original variables we have to multiply the squared canonical correlation coefficient by the percentage of variance

Table IA.

Results of the analysis of canonical correlation for pure tone audiograms and SRT expressed in used variance, redundancy and canonical correlation coefficients.

CANONICAL CORRELATION COEFFICIENTS AND USED "REDUNDANCY".

	Overall group (n=366)	Noise exp. > 10 years (n=148)	Noise exp. > 15 years (n=74)
SRT(Quiet-80 DB)			
used var.	50%	55%	59%
redundancy	33%	45%	51%
canon.corr.	0.81	0.91	0.93
SRT(35-80 DB)			
used var.	49%	56%	62%
redundancy	28%	42%	50%
canon. corr.	0.76	0.86	0.90
SRT(50-80 DB)			
used var.	48%	56%	62%
redundancy	22%	37%	48%
canon. corr.	0.68	0.82	0.88
SRT(65-80)			
used var.	68%	65%	63%
redundancy	12%	25%	37%
canon. corr.	0.42	0.62	0.76

covered. This will give us the percentage of overlap or the "redundancy" between the linear combination of pure-tone thresholds and the set of speech-reception thresholds [for a detailed description, see Elazar-Pedhazur (26)]. The maximum obtained redundancy is 0.51 for the SRT in both quiet and noise in the group with 15 years or more noise exposition, dropping to 0.37 when successively eliminating the quiet and lower noise-level conditions. Apparently, even the canonically weighted pure-tone audiogram is a better predictive factor for the SRT in quiet and for low noise levels (35, 50 dB) than for the SRT in noise of 65 and 80 dB. The longer the noise exposure has been, the more predictive is the canonically weighted pure-tone audiogram with regard to the SRT in noise.

The multiple correlation analysis of the pure-tone thresholds with the speech intelligibility in quiet (figure 2, E) shows a curve which corresponds very much to figure 8: it illustrates the relative importance of the low-frequency pure-tone thresholds up to 2 kHz for the speech intelligibility in quiet. Again this phenomenon is most clear in the group exposed longest to the noise.

THE EFFECT OF STAPEDECTOMY ON THE SPEECH INTELLIGIBILITY IN NOISE

M.J. Middelweerd, L. Feenstra, S. vd Baan and R. Plomp

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ABSTRACT

Speech intelligibility in noise was tested pre- and postoperatively after 27 stapedectomy cases and 10 cases of reexploration after previous stapes surgery. We did not find a postoperative threshold shift (signal-to-noise ratio) for the intelligibility of sentences presented in noise. This finding corresponds well with the absence of postoperative high-frequency sensorineural hearing loss in these patients. Using two types of prostheses we found a significantly better amelioration of the speech intelligibility in quiet for the Schuknecht mini-hole prosthesis than for the House wire loop.

I. INTRODUCTION

Since the first stapedectomy was carried out in 1958, large numbers of cases have been screened for post-operative results and complications, also related to the several different modes of surgery (1,2,3). Apart from occasional (0.5-4%) serious post-operative sensorineural hearing losses, there is evidence of a more general perceptive loss due to (peroperative) cochlear damage in uncomplicated stapedectomy procedures. Smyth and Hassard (1) reported post-operative deterioration of the bone-conduction threshold, especially at 4 kHz in a series of 655 stapedectomy cases. Regarding this threshold shift, there was a significant difference between large-fenestra stapedectomy and small-fenestra stapedectomy in favour of the latter procedure. Mair and Laukli (4) showed, in cases of stapedectomy, evidence of a considerable post-operative loss starting from 8 kHz up to 20 kHz using high-frequency audiometry (air conduction). A control group of myringoplasty cases showed a significantly less high-frequency threshold increase. Bone-conduction thresholds at 0.5 and 2 kHz are not found to increase post-operatively. Fisch (2) in fact reported a postoperative improvement of 10 dB or more in 18% of stapedectomy cases. Chadwell et al. (5) showed a decreased post-stapedectomy speech discrimination in noise for consonant-vowel combinations. Stapedial muscle tendon cleavage was suggested to be the main cause. However, their post-operative pure-tone audiometric records also show a considerable high-frequency loss.

In 1978 Plomp (6) showed the importance of the speech reception threshold (SRT) in noise as a test of speech intelligibility in everyday listening situations. The SRT is defined as the sound-pressure level of speech at which 50% of the speech material (words or sentences) is correctly understood. The SRT in noise is defined as the signal-to-noise ratio of the SRT relative to the presented background noise. In 1979 Plomp and Mimpen (7) reported about the speech-hearing loss in noise as a function of age. Due to presbyacusis, subjects at the age interval of 80-90 years were found to suffer a speech-hearing loss in noise of 5-10 dB. This may seem a minimal loss, but one has to bear in mind that a 1-dB speech hearing loss in noise decreases the sentence intelligibility score with 15-20%. This implies that a subject with a 6-8 dB speech-hearing loss in noise is not able to understand the speaker when a competing speaker is present at about the same distance from the listener. Plomp (6) divided speech-hearing loss in two categories:

1 Class A. attenuation hearing loss. This type of hearing loss concerns a threshold shift in quiet. By increasing the sound level entering the ear one is able to fully compensate for this class A hearing loss.

2 Class D. distortion hearing loss. The speech signal is distorted rather than attenuated. Better intelligibility is only effected by improving the signal-to-noise ratio for the presented speech material. The class D hearing loss is the main determining factor in speech-hearing loss in noise and is significantly correlated with high-frequency pure-tone audiometric loss starting from 2 kHz (8). In case of a successful stapedectomy the air-bone gap will be largely eliminated. the Fletcher Index (averaged air-conduction threshold of 0.5, 1 an 2 kHz) will be decreased and, implicitly, the SRT in quiet. However, due to the suggested post-operative high-frequency cochlear hearing loss in uncomplicated stapedectomy. post-operative speech intelligibility in noise might worsen. This hypothesis establishes the basis of our study.

II. PATIENTS

37 Consecutive stapedectomies were performed on 35 patients by 2 surgeons (L.F., S.vd.B.). Ten of these procedures concerned re-explorations after previous unsuccessful stapedectomy. Sex distribution: 22 females, 13 males. Mean age: 42.4 years (22-67yrs). All patients were operated upon under local infiltration anaesthesia (xylocain 1%, adrenalin 1: 100.000). Sedative and analgetic premedication (Nembutal, Opial) was administered the previous night, 1.5 and 0.5 hour before surgery. Two different types of stapedial prostheses were used: House wire loop (n=23) and Schuknecht Piston Mini-hole (n=14). Directly after placing the prosthesis, hearing improvement was measured by means of Rinne's tuning-fork test (512 Hz). After having obtained a positive Rinne's test at the end of the operation, the procedure was considered to be completed.

III. METHOD

In every patient the pre- and post-operative speech-reception threshold in noise as well as in quiet was determined. Simultaneously conventional pure-tone and speech audiometry (mono-syllabic words in quiet) were performed. The speech material consisted of short meaningful Dutch sentences (6), presented against a background noise with the spectrum equal to the lomg-term average spectrum of the speech material. The sound-pressure level of the noise was chosen at 40 dB above the Fletcher Index of the ear of operation, with a 100 dB maximum. Speech material and noise were presented at the ear of stapedectomy, monaurally via headphones in a sound-insulated room. When necessary, the contra-lateral ear was masked adequately, using white noise. SRT in noise and in quiet were determined one day pre-operatively and after an average interval of 3.5 months post-operatively.The signal-to-noise ratio for correct reproduction of 50% of sentences was chosen to represent the speech-reception threshold. Pre-operatively 3 lists and post-operatively 2 lists of 13 different sentences in noise were presented to every individual patient. For determining the SRT in quiet, one list of 13 sentences was used both pre- and post-operatively. After correct reproduction of the sentence, speech level was lowered by 2 dB, whereas after an incorrect reproduction it was raised by 2 dB. This procedure eventually produces the SRT 50% as an average of the sound-level of all presented sentences in noise. This procedure was repeated for the quiet condition. For this experiment 10 lists of 13 sentences each were available. For every first to tenth operated ear there was a different order in which the speech lists were presented in order to prevent a list-dependent bias. Speech material and noise were digitally stored on a computer disc and generated by a DEC 11/10 computer. The headphone used was a Beyer DT 48.Pre- and post-operative measurements were compared for the primary stapedectomy cases, the re-explorations as well as for the two different types of prostheses by way of an Analysis of Variance (ANOVA).

IV. RESULTS

Figures 1 and 2 show the pre- and post-operative pure-tone audiometric data in primary stapedectomy and re-exploration, respectively. Median and quartile values are plotted. There is no significant post-operative bone-conduction threshold shift in either the primary stapedectomy cases or the re-explorations. Air-bone gap closure is more successful in the 0.5-2 kHz range than for higher frequencies. Table I shows the post-operative changes in all measured audiometric parameters for both primary and revision stapedectomy. For both groups the mean Fletcher Index, the air-bone gap

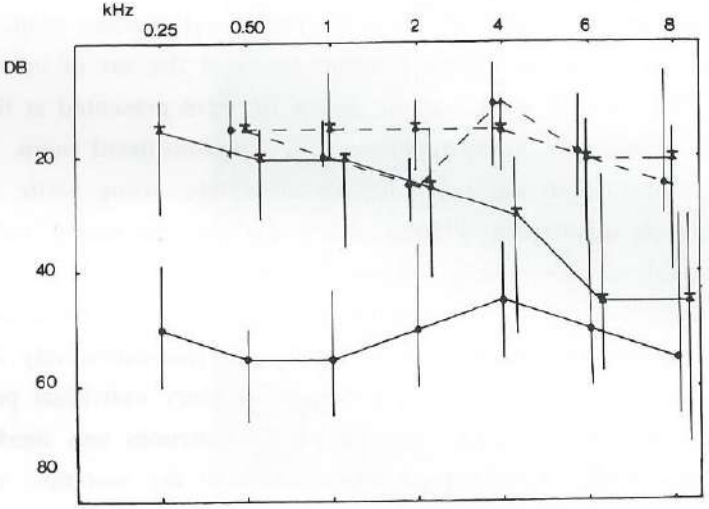

Figure 1.
Pure-tone audiometric data for 27 primary stapedectomy cases.
Median. 25 and 75 percentile scores. Solid curves represent air-conduction, dashed curves bone-conduction:
● symbols are pre-operative, ⧗ are post-operative.

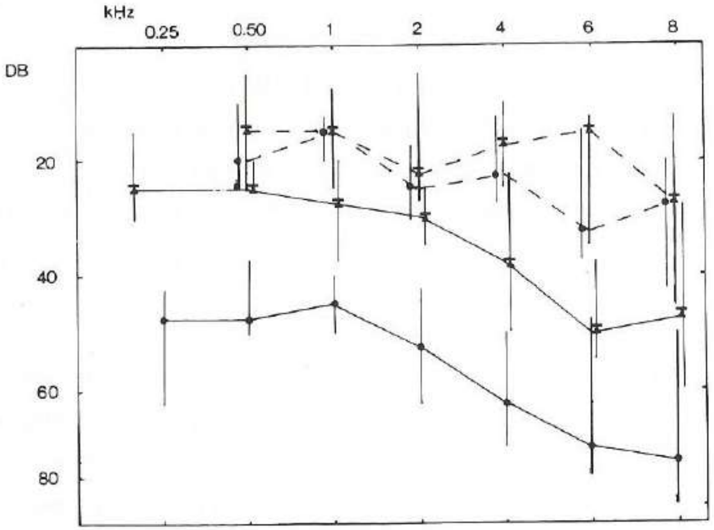

Figure 2.
Pure-tone audiometric data for 10 cases of re-exploration.
Median. 25 and 75 percentile scores. Solid curves represent air-conduction, dashed curves bone-conduction;
● symbols are pre-operative. ⧗ are post-operative.

(0.5-2 kHz). the mid-frequency (0.5-2 kKz = Pm) bone-conduction or perceptive threshold and the SRT in quiet improved significantly. Both the high-frequency (2-8 kHz = Ph) perceptive threshold and the SRT in noise did not change significantly. Regarding the effect of operation. on none of the measured parameters a statistically significant difference ($p>0.05$) was found between primary stapedectomy and re-exploration. Figures 3 and 4 show the Fletcher Index and SRT in quiet. respectively. plotted pre- and post-operatively. These figures show. as expected. a great resemblance. which is quantified in table I. Figure 5 shows pre- and post-operative mean high-frequency perceptive thresholds. defined as the average of the bone-conduction thresholds at 2. 4. 6 and 8 kHZ (Ph). whereas figure 6 shows pre- and post-operative SRT in noise. In both there is no significant threshold shift.

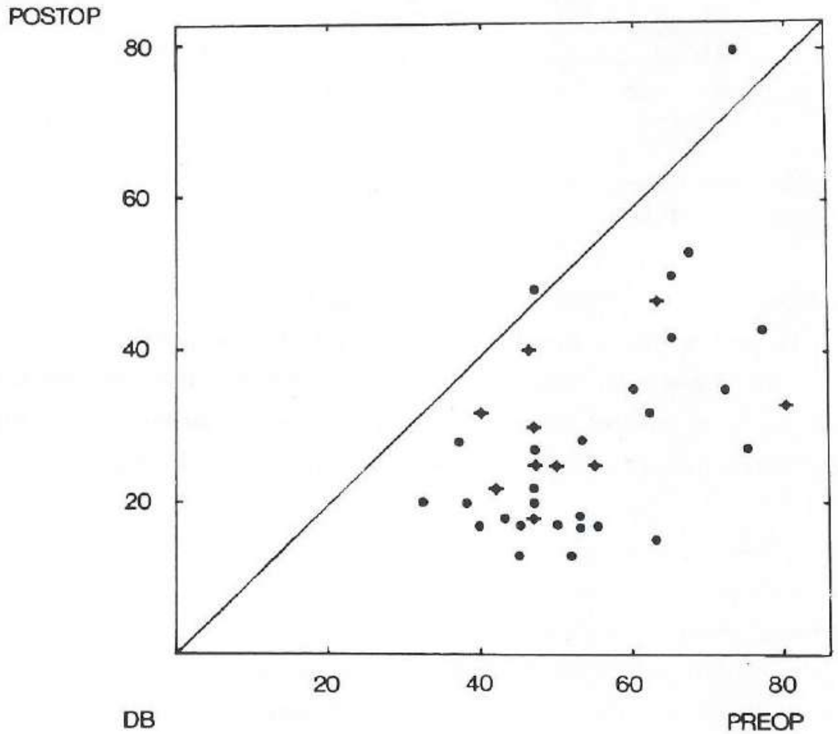

Figure 3.
Post-operative Fletcher index compared to pre-operative.
● = primary stapedectomy; ✦ = re-exploration

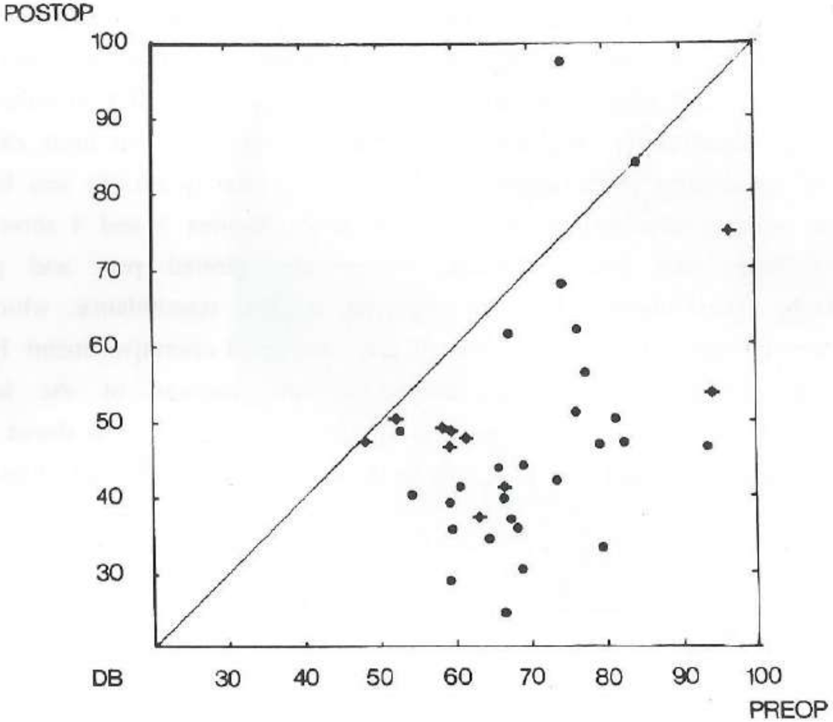

Figure 4.
Post-operative SRT in quiet compared to pre-operative.
● = primary stapedectomy; ✦ = re-exploration

The figures 1-6 are all quantified and statistically analyzed in Table I.
In Table II post-operative threshold changes for the two different stapedial prostheses are shown. An analysis of Variance revealed that the difference between prostheses in the changes of Fletcher Index, air-bone gap, high-frequency perceptive thresholds and SRT in noise are all statistically not significant.
There is however a significant post-operative difference for the SRT in quiet: the Schuknecht prosthesis gives significantly better results ($p=0.0013$).
As mentioned above, there is a significant post-operative improvement of the mid-frequency (Pm) perceptive threshold in both primary stapedectomy and re-exploration. Regarding this threshold shift a significant dependence on the type of prosthesis was found in favour of the Schuknecht prosthesis ($p=0.02$). For the Schuknecht prosthesis this improvement was only found in cases of primary stapedectomy. We do not have an explanation for this phenomenon.

Table I.

Pre-operative audiometric thresholds (dBA) and threshold changes of stapedectomy and re-exploration.

Pm = average perceptive threshold 0.5-2 kHz (mid)
Ph = average perceptive threshold 2-8 kHz (high)
p = p-value from analysis of variance.

	Fletcher index		Air bone gap (0.5 - 2 kHz)		Pm		Ph		SRT quiet		SRT noise	
	pre	post-pre	pre	post-pre	pre	post-pre	pre	post-pre	pre	post-pre	pre	post-pre
Primary stapedectomy	54	-26	34	-21	20	-5	23	+1.5	69.1	-22.4	-4.9	+0.6
N = 27												
Standard deviation		12.8		15.8		6.6		7.6		14.4		2.9
	p < 0.0001		p < 0.0001		p = 0.0007		p = 0.63		p < 0.0001		p = 0.89	
Reexploration	51	-21	28	-15	21	-4	27	-3	68.5	-17.7	-3.4	-0.8
N = 10												
Standard deviation		12.2		15.6		7.9		9.3		10.7		1.9

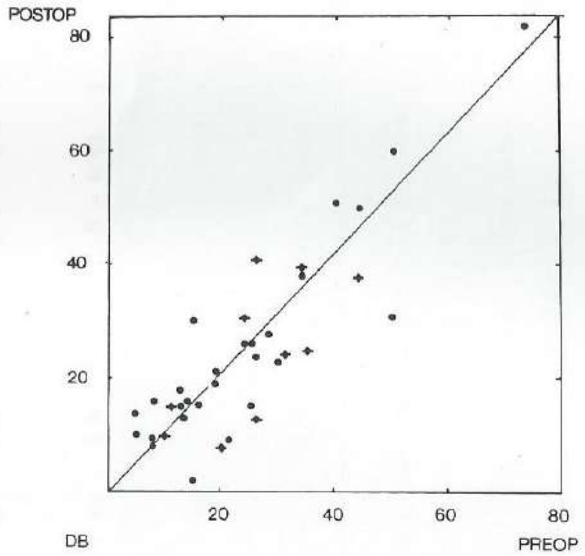

Figure 5.
Post-operative high-frequency perceptive threshold (Ph = 2-8 kHz) compared to pre-operative.
● = primary stapedectomy; ✦ = re-exploration

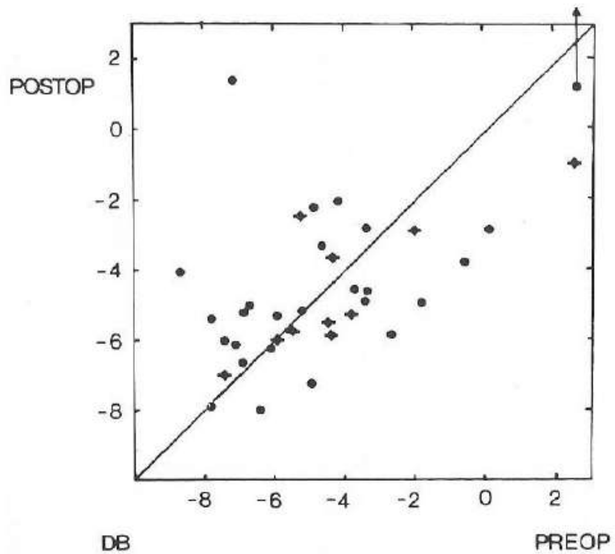

Figure 6.
Post-operative SRT in noise compared to pre-operative (dB signal-to-noise ratio).

Table II.
Pure tone and speech audiometric post-operative threshold changes (dB) for the two different types of prosthesis.
Pm = 0.5-2 kHz, Ph = 2-8 kHz (perceptive threshold)
SD = Standard deviation

Prosthesis	Fletcher index	air-bone gap	Pm	Ph	SRT Quiet	SRT Noise
House wire loop (23*)	-21.0	-16.3	-4.6	+1.5	-14.9	+0.5
SD	(13.9)	(15.7)	(6.4)	(7.1)	(13.9)	(3.0)
Schuknecht (14#)	-30.0	-25.0	-4.0	-1.4	-31.1@	+0.04
SD	(8.5)	(10.3)	(7.2)	(9.4)	(7.9)	2.1)

* = including 6 re-explorations
\# = including 4 re-explorations
@ : Significantly (p=0.0013) greater threshold shift, as compared to House wire loop.

All patients were asked for their opinion about the post-operative hearing gain. Twenty-eight patients were satisfied with the hearing gain in quiet as well as in noisy surroundings. Seven patients were dis-satisfied: four of them complained about bad speech intelligibility in noise and three complained about bad speech intelligibility in noise as well as in quiet. Table III shows the post-operative audiometric recordings of these dis-satisfied patients. Patients number 6 and 7 were re-operated upon because of a persisting air-bone gap. Patient number 6 was included in the group of (successful) re-explorations, whereas patient number 7 was operated after closure of the study.

Table III.
Post-operative audiometric threshold changes (dB) in patients complaining of bad speech intelligibility.
Pm = 0.5-2 kHz, Ph = 2-8 kHz (perceptive threshold)
* = re-exploration

Subjective post-operative discrimination loss in noise

Patient	Fletcher index	air-bone gap	Pm	Ph	SRT Quiet	SRT Noise
no.1*	-30	-32	+2	+5	-22.4	-1.1
no.2	-27	-24	-3	+10	-31.1	+0.6
no.3	-34	-37	+3	-10	-38.6	+6.4
no.4	-9	+1	-10	0	-3.8	+1.7

Subjective post-operative discrimination loss in quiet and noise

Patient	Fletcher index	air-bone gap	Pm	Ph	SRT Quiet	SRT Noise
no.5*	-16	-15	-1	-10	-39.6	-0.3
no.6	+7	+24	-17	-5	+12.8	+9.7
no.7	+1	+8	-7	+9	-6.4	+0.3

V. DISCUSSION

In this group of 35 patients, no significant deterioration of the speech-reception threshold in noise could be measured. This finding corresponds well to the absence of post-operative high-frequency hearing loss. This result is in contradiction to the findings of Chadwell et al. (5), who reported a decrease in post-stapedectomy speech discrimination for consonant-vowel combinations in noise. Apart from the stapedial muscle function loss as described by them the post-operative high-frequency loss in Chadwell's study could very well be responsible for this difference.

In 1970 Huizing (9) reported a selected series of 39 stapedectomies to suffer from a speech-discrimination loss (bi-syllabic words in quiet) due to post-operative sloping of the pure-tone audiogram. The sloping was caused by closing the air-bone gap in the low frequencies, whereas high-frequency air-conduction thresholds improved significantly less. A "cut-off frequency" (starting point of slope) of 1 kHz and, even more frequently of 0.5 kHz, proved to be of substantial negative influence on speech discrimination. On the contrary, a cut-off frequency of 2 kHZ or higher proved to have no influence on speech discrimination at all. Our material (figures 1, 2) shows evidence of a cut-off frequency (air-conduction) at 4 kHz. This might well explain the absence of any deterioration for speech discrimination in our study.

Although post-operative follow-up does not extend more than one year, these post-operative perceptive thresholds have proven not to shift more than the normal age-related progressive high-frequency loss (10).

The group of re-operated patients does not seem to be more at risk for high-frequency losses than the group of primary-stapedectomy patients.

Using two types of stapedial prostheses, we did neither find a difference in post-operative SRT in noise, nor in perceptive high-frequency threshold. The Schuknecht Piston Mini-hole prosthesis however, gives the best post-operative SRT in quiet.

From these results we may conclude that, in case of uncomplicated stapedectomy or re-exploration, post-operative speech intelligibility in quiet will increase and speech intelligibility in noise remains unchanged.

ACKNOWLEDGEMENT

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DIFFICULTIES WITH SPEECH UNDERSTANDING IN NOISE IN SPITE OF A NORMAL PURE-TONE AUDIOGRAM

M.J. Middelweerd, J.M. Festen, R. Plomp.

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ABSTRACT

A group of 15 patients with complaints of having difficulties in understanding speecch especially in noisy surroundings in spite of a (nearly) normal pure-tone audiogram, was subjected to a battery of speech-audiometric tests. The results showed that these subjects had a statistically significantly higher Speech Reception Threshold (SRT) for sentences in noise than a reference group of 10 normal-hearing subjects. This difference was most clear for a fluctuating masking noise. In conditions with much reverberation the patients also proved to be handicapped more than the control group. Binaural hearing gain was equal for both groups. The pathogenesis for the speech-hearing loss is not known, but assessment of the SRT in noise proves to be a valuable asset in objectifying these patients'complaints.

I. INTRODUCTION

Complaints about speech difficulties in speech understanding in conditions with interfering sounds are frequently encountered in an otolaryngologist's office. Quite often an explanation can be found in the otological history and the otoscopic examination combined with routine pure-tone audiometry and assessment of the intelligibility for monosyllabic words in quiet. There are, however, cases in which the routine pure-tone audiogram and speech intelligibility in quiet show (approximately) normal values. This group of patients has received very little attention in the audiological literature. Recently, Abel et al. (1) described a group of "noise sensitive" listeners (mean age 35) with normal pure-tone audiograms. Their speech intelligibility score in a continuous white background noise was worse than for a group of young normal-hearing listeners but equal to the intelligibility in a group of listeners with normal pure-tone thresholds and an average age of 48 years. Upward spread of masking was claimed to be responsible for this phenomenon in the "noise sensitive" listeners.

At our department the Speech-Reception Threshold (SRT) in noise has been the subject of extensive research. For speech hearing loss Plomp (2) developed a descriptive model with two components: A(ttenuation) and D(istortion). The attenuation component can be fully compensated for by sufficient amplification of the speech, whereas distortion is a more qualitative aspect of speech reception which can only be compensated for by a larger signal-to-noise ratio. Using short meaningful Dutch sentences presented in quiet and in steady-state background noise with a spectrum equal to the long-term average spectrum of the sentences, a variety of listeners has been tested: aging people, a noise-exposed population and patients before and after stapedectomy (3,4,5). In general, these listeners show substantially shifted pure-tone thresholds.

The objective of this study is to introduce a test, known to be reliable, into clinical practice where routine audiometry and the patient's history concerning intelligibility of speech show an unexplained discrepancy. Hypothetically this discrepancy can be based upon several possible characteristics of these patients: Diminished alertness, impaired central auditory processing (fusion or discrimination) of binaurally presented speech in background noise, or a reduced frequency resolution which may cause upward spread of masking, abnormal sensitivity for bad acoustics, or abnormal noise sensitivity.

For optimal representation of every-day listening situations in our experiments, a fluctuating masking noise was introduced in addition to the usually employed steady-state noise Festen and Plomp (6) reported a considerable gain in SRT from masker fluctuations for normal-hearing listeners and virtually no gain in a group of hearing-impaired listeners.
A binaural condition was added to check a possible dysfunction in the central fusion. Eventually, we introduced loudspeaker conditions with reverberation to assess effects of the acoustical environment.

II. METHOD

II.1 SUBJECTS

This study concerns 15 patients (8 females and 7 males, mean age 36) with complaints about a diminished speech intelligibility, especially in background noise. Because of their profession (sales representative, teacher, entrepreneur, public officer often involved in meetings, or physician) they are quite aware of and dependent on their ability to understand speech in background noise. Their otological history was taken and appeared to be negative for recurrent otitis media, the use of ototoxic medication, excessive noise exposure, tinnitus and hereditary hearing impairment. At the time of testing the complaints existed for 6 months in one patient and between 2 and 5 years in the rest of the patients.

On otoscopic examination no abnormalities of the eardrum and middle ear were encountered, whereas results on the tuning-fork tests according to Weber and Rinne were also normal. Routine pure-tone audiometry revealed virtually no hearing loss (fig.1) and the intelligibility score for monosyllabic words in quiet was within normal limits.

II.2 SPEECH MATERIAL

A series of test-conditions was applied to establish the SRT in quiet and in noise. The test consists of 10 lists of 13 short meaningful Dutch sentences, containig eight or nine syllables each and read by a female speaker. We used speech material representative of every day conversation, designed by Plomp and Mimpen (7). The speech material was digitally stored on computer disc. The SRT was defined as the signal-to-noise ratio for which 50 % of the

sentences was correctly repeated by the subject. This threshold was determined by means of a simple up and down procedure: in case of a correct reproduction of a full sentence the speech level was lowered by 2 dB, whereas incorrect response caused the speech level to be raised by 2 dB.
Two different background noises were used:
(a) "steady-state" masking noise with a spectrum equal to the long-term average of the speech material;
(b) "fluctuating" masking noise with the same spectrum as the steady-state noise and a modulation waveform equal to the envelope of running speech. The noise below and above 1 kHz was modulated independently by the speech envelope from the corresponding frequency band and mixed afterwards in order to create an interfering noise that closely resembles the characteristics of speech. The masker level was 65 dBA for both the steady-state and the fluctuating noise. The presentation of the speech and noise and the adaptive testing procedure were controlled by a computer.

II.3 CONDITIONS

Each patient was tested in the following 10 conditions, for each condition one list of 13 sentences was used:
With headphone (Beyer DT48):
1,2 Speech in quiet, monaurally, left and right.
3,4 Speech in steady-state noise, monaurally, left and right.
5-7 Speech in fluctuating noise, monaurally, left and right and binaurally.
With loudspeaker, reverberant room (reverberation time = 2 seconds):
8-10 Speech in steady-state noise, monaurally, with left or right ear occluded and masked and binaurally.

The sequence of these conditions was counterbalanced for every ten patients according to a digram-balanced Latin square, in order to avoid learning effects and sentence-dependent bias. The headphone and loudspeaker tests were performed in the same reverberant room with dimensions of 6.5 x 7 x 7 m. In the reverberant conditions the listener was seated , facing a loudspeaker at a 6-meters distance, from which both the speech and noise signal were produced. In reverberant monaural conditions one ear was occluded with a one-cup headphone and masked by a 65 dB broadband noise. We did not use fluctuating masking noise in the reverberant conditions, because, for 2 seconds of reverberation time it is to be expected that the fluctuations in the noise are already severely reduced.

As a control group 10 normal-hearing volunteers (6 females and 4 males, mean age 31) were tested in the same counterbalanced set-up as the patients. The patients and control group were of comparable social background.
The lower mean age of the control group (5 years) was considered not to be of audiological importance. According to the ISO 1999.2 standard the (averaged) hearing losses for 2 and 4 kHz in a non-noise exposed population are only 1.5 dB and 5.5 dB for 30 and 40 year old males respectively.

III. RESULTS

In figure 1 upper and lower quartile bounderies of the air-conduction pure-tone thresholds are plotted for both the patients and the control group. Compared to the control group, pure-tone thresholds in the patient group are 5 to 10 dB higher although still within clinically acceptable normal limits.

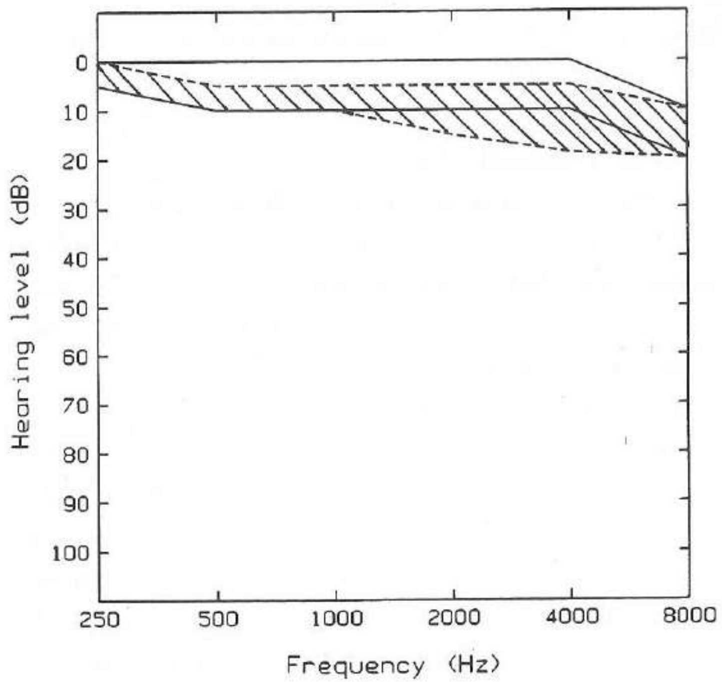

Fig. 1
Range of pure-tone thresholds between the 25 and 75 percentiles for both patients and control group. The hatched area represents the patients' thresholds.

The SRT data were analyzed by way of Analysis of Variance for repeated measures (9) and Student t-tests for independent samples.

III.1 HEADPHONE CONDITIONS.

The monaural SRT in quiet, averaged over listeners and ears is 27.8 dBA (sd=4.1dB) versus 24.2 dBA (sd=3.5dB) for the control group. The 3.6-dB difference is statistically significant ($p<0.05$). The correspondingly averaged SRT in 65-dBA steady-state noise for the patients is 60.3 dBA, which corresponds to a signal-to-noise ratio of -4.7 dB. For the control group this threshold is -5.7 dB, expressed as signal-to-noise ratio, which is slightly but significantly lower ($p<0.05$). The monaural SRT in fluctuating masking noise, averaged over listeners and ears, is -9.6 dB for the patients versus -12.6 dB for the control group. This 3-dB difference is statistically significant, and

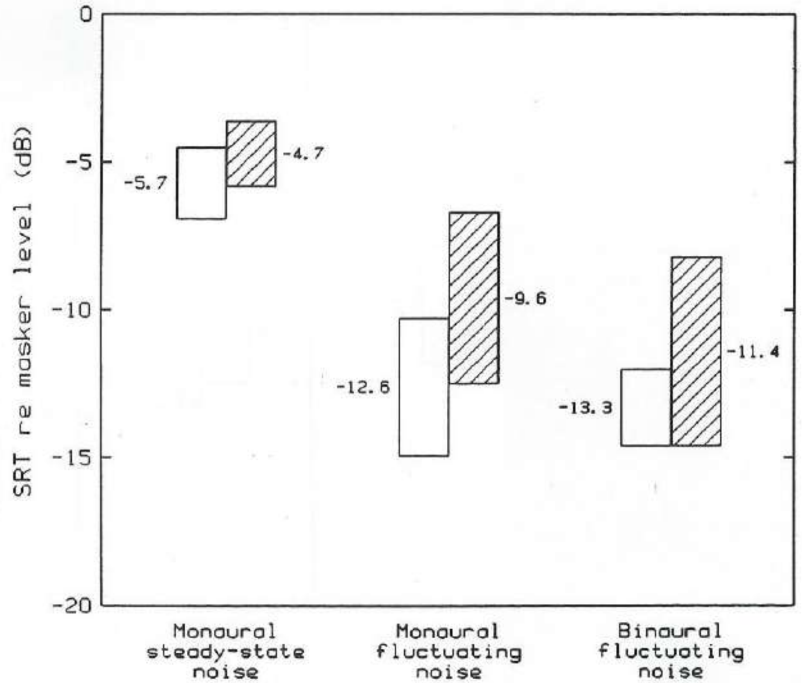

Fig.2
Speech Reception Thresholds in noise for the headphone conditions. For each condition the bars represent the range of signal-to-noise ratios containing 68 % of the thresholds (twice the standard deviation). The average SRTs are marked. Hatched bars are for the patients (n=15) and open bars for the control group (n=10). For the monaural conditions calculation was performed for individual ears.

also significantly greater than the 1-dB difference between patients and control group in case of steady-state noise.

The binaural condition with fluctuating masking noise shows a gain in SRT of 1.8 dB for the patients and 0.7 dB for the control group.
This gain is statistically significant, but the difference in binaural gain between the patients and control group is not. The results for the headphone conditions are plotted in figure 2.

III.2 LOUDSPEAKER CONDITIONS.

Under reverberation considerably higher thresholds are found. The monaural SRT in stationary noise is +1.7 dB in signal-to-noise ratio for the patients and +0.7 dB for the control group. For the binaural condition the

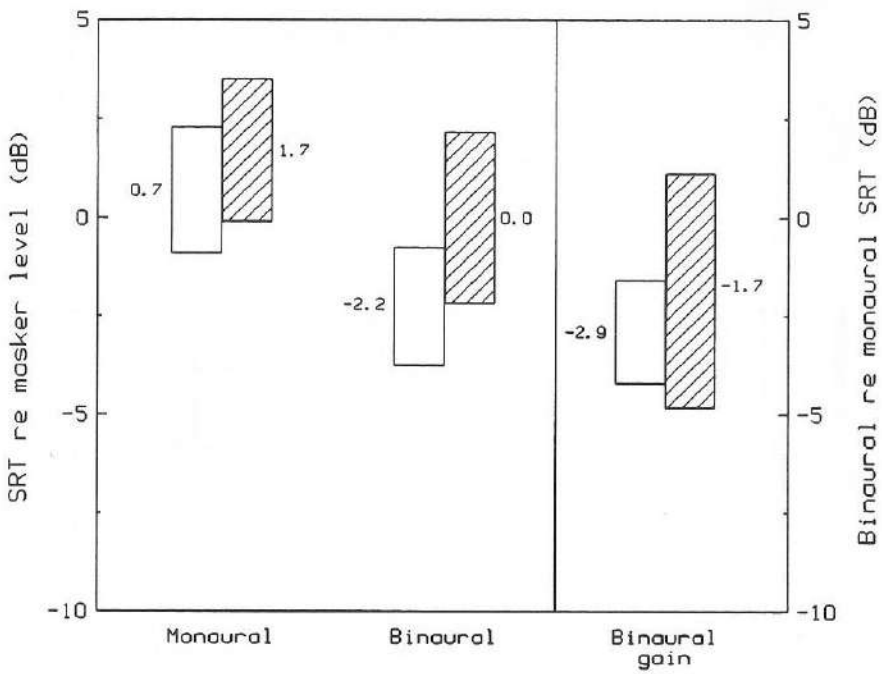

Fig.3
Speech Reception Thresholds in noise for the loudspeaker conditions (reverberation). For each condition the bars represent the range of signal-to-noise ratios containing 68% of the thresholds (twice the standard deviation). Hatched bars are for the patients (n=15) and open bars for the control group (n=10).
For the monaural conditions calculation was performed for individual ears. The two bars on the right represent the binaural threshold-gain.

patients' SRT is 0 dB versus -2.2 dB for the control group, a statistically significant gain of 1.7 and 2.9 dB respectively. The difference in binaural gain between patients and control group again is not significant. The results for the reverberant loudspeaker condition are plotted in figure 3.

IV. DISCUSSION

IV.1 HEADPHONE CONDITIONS.

In all headphone conditions the patients show a higher SRT than the control group. The 3.6-dB difference in quiet is indeed statistically significant, but audiologically such a small threshold difference in quiet is neglectable. On the contrary, the 1 dB difference in steady-state noise may seem small but we have to realize that critical listening conditions in noise are much more common than in quiet and 1 dB in signal-to-noise ratio is equivalent to 18-20 % score in the intelligibility of sentences (3,7). The difference between patients and control group is most clear when using fluctuating noise (3 dB monaurally and 1.9 dB binaurally). This difference in SRT is significantly larger than in case of steady-state noise. This finding is in close agreement to the results of Festen and Plomp (6). They compared a group of sensori-neural hearing impaired with normal-hearing listeners and found a monaural SRT-difference of 2.7 dB in steady-state noise versus an 8-dB monaural SRT difference in modulated noise. These elevated thresholds might be explained from the apparent inability of our patient group, as for the sensorineurally hearing-impaired listeners, to utilize the small periods of time in the fluctuating masker in which there is speech in the absence of interfering noise: in other words the origin may be an insufficient temporal resolution. Obviously, when a reduced temporal resolution plays a role,the fluctuating noise masker makes the test procedure more sensitive than when using a steady-state noise.

In not yet published data of Festen and Plomp 1 dB signal-to-ratio in fluctuating noise corresponds with 12 % score difference in the intelligibility of sentences for normal-hearing and 15% for hearing-impaired. Considering our patient group as normal-hearing a 3-dB signal-to-noise ratio difference implies a 3x12 = 36% diminished speech intelligibility score compared to the control group. It is clear that this difference may cause complaints.

The binaural gain in fluctuating noise (control group = 0.7 dB, patients =

1.8 dB) is close to the 1.1-dB gain reported by Mckeith and Coles (10) for normal-hearing individuals in a free field 0% noise azimuth condition. The apparently higher gain for the patients is statistically not significantly different from the gain for the control group (p=0.21).

IV.2 LOUDSPEAKER CONDITION.

For the conditions with a combination of steady-state noise and reverberation, the monaural SRT is higher than the masker level. This finding indicates the difficulty of this condition for both patients and control group. In the monaural condition again a statistically significant 1-dB difference in SRT between patients and control group is present. This finding corresponds well to data by Duquesnoy and Plomp (11); they showed the SRT in reverberation can be predicted from the SRT in noise. Considering the binaural gain, both patients and control group benefit significantly from binaural presentation compared to monaural presentation. The difference in gain between patients and control group again is not significant. When comparing the loudspeaker binaural benefit to the headphone condition, the binaural gain for both groups is statistically higher in the loudspeaker reverberant condition. Although these two conditions show more differences, this result is possibly mediated by the absence of favorable factors like interaural time delay in the headphone condition.

V. CONCLUSIONS

In a group of patients with normal or nearly normal pure-tone thresholds and speech reception thresholds in quiet, but complaining about a speech hearing loss in noisy surroundings, the speech-reception threshold in noise revealed significant deviations from a normal-hearing reference group.

When using a fluctuating masking noise the SRT proved to be significantly more elevated with respect to the SRT for the control group than when using steady-state noise. This phenomenon may be attributed to an impaired temporal resolution in the hearing function of the patient group.

Also reverberation hampers the group of patients more than the control group of normal-hearing listeners. The gain from binaural hearing is equal in both groups.

The assessment of the SRT in (fluctuating) noise can be a valuable procedure in non-routine audiologic councelling in an audiology department; instead of dismissing patients as described in our study with "no abnormalities in routine audiometry", it will then be possible to objectively identify the handicap. Unfortunately, at the moment there are no real therapeutical possibilities.

It has been our experience, however, that pointing out the beneficial effects of supportive measures to speech intelligibility, like speechreading, carefully picking a position for attending a meeting and so on, can be of great help especially in this category of patients.

ACKNOWLEDGEMENT

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THE EFFECT OF SPEECHREADING ON THE SPEECH-RECEPTION THRESHOLD OF SENTENCES IN NOISE

M.J. Middelweerd and R.Plomp

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ABSTRACT

The monaural speech-reception threshold of sentences in noise, here defined as the 50% correct-syllables threshold, was measured for a female speaker with and without speechreading via a video monitor. The additional visual information resulted in a 4.6-dB lower threshold for a group of 12 subjects and in a 4.0-dB lower threshold for a group of 18 elderly subjects compared to the auditory presentation alone.

I. INTRODUCTION

Recently, Plomp and co-workers (for a review, see Plomp, 1986) have studied extensively the speech-reception threshold (SRT) of sentences for normal-hearing and hearing-impaired listeners. Some main parameters in these experiments were: age of the listeners, noise level, and use of hearing aids. In those investigations, the speech signal was invariably presented to the subject by ear only. Auditory SRTs are worthwile in the laboratory for comparing parameters under study, but they are not representative of everyday listening situations. Both normal and particularly hearing-impaired individuals use visual cues to complement those supplied by audition. The contribution of speechreading is necessary to determine the degree to which the hearing impaired are handicapped socially.

The effect of visual cues on speech intelligibility has been studied by several investigators (for a review, see Birk Nielsen and Kampp, 1974). With a few exceptions, these studies used word lists as speech material and focused on the intelligibility scores of the individual speech sounds. The present experiment investigated the effect of speechreading on the SRT for sentences of young, normal-hearing subjects, and elderly subjects having various degrees of prebycusis

II. METHOD

The stimuli were lists of 13 different, meaningful, Dutch sentences typical of everyday conversation, each consisting of eight or nine syllables (Plomp and Mimpen, 1979). A female speech therapist pronounced the sentences in front of a video camera with shadow-free illumination so that lip, jaw, and tongue movements were clearly visible. The video recording showed only the head of the speaker. No attempt was made to correct for any differences among the lists in terms of auditory and visual recognition.

Because voice babble is the most common interfering sound in everyday situations, noise having a spectrum equal to the long-term average of the spectrum of the sentences was used as a masker (Plomp, 1986). This spectrum was determined by analyzing the speech signal of the sentences with a set of one-third-octave bandpass filters; the output signal was digitized and fed into a minicomputer that calculated the root-mean-square value of amplitude samples at 0.5-ms intervals. This noise spectrum makes the SRT values found more independent of the typical spectral properties of the voice involved. The SRT values are expressed as the long-term overall SPL relative to the noise level.

Two groups of subjects were tested: (1) 12 young (age 19-28 yrs), normal-hearing subjects with monaural pure-tone averages (PTAs) for the frequencies 0.5, 1, and 2 kHZ below 5 dB HL and normal Landolt-C visual acuity (NAS-NRC,1980) with or without visual correction; and (2) 18 elderly (age 68-84 yrs) subjects with presbycusis, not wearing a hearing aid, with monaural PTAs below 40 dB HL (except one with a PTA of 46 dB) and Landolt-C visual acuity > 0.5 (corresponding to 10/20 Snellen fraction) with or without visual correction.

The subjects were tested individually in a sound-treated room and sat about 2m from a 50-cm color video monitor. The speech material and the noise were mixed electronically and presented monaurally by earphone (Beyer DT-48) with the sentences at a variable SPL (see below) and the noise at a constant level of about 60 dB SPL.

The stimuli were presented to the subjects in auditory (A), auditory-visual (AV), and visual (V) conditions. For the A and AV conditions, the SRT was defined as the speech-to-noise ratio for which 50% of the syllables of a list of 13 sentences were correctly repeated. For the V condition, the percentage of correctly perceived syllables was calculated. Within-viseme substitutions were not counted as correct.

Proper ranges of speech-to-noise ratios for measuring the SRT in the A and AV conditions were determined during the preliminary test session. Usually four or five lists were sufficient to obtain tentative estimates of the SRTs for both conditions. These presentations also familiarized the subject with the task.

Next, the subject was presented successively with six lists of 13 sentences, three each for the A and AV conditions at sound levels of +2, 0, and -2 dB relative to the tentative estimate of the SRT determined before. The groups of 12 young and 18 elderly subjects were each subdivided in groups of six. The order of the six presentations was counterbalanced for these subgroups to reduce the effects of training, fatigue, and any differences among the lists in auditory and visual recognition. From the three scores for the A and AV conditions, respectively, final estimates of

the two SRTs were determined by linear interpolation. The score of correct syllables for the V condition was measured with three additional sentence lists. As the lists contained different sentences, no subject was presented with the same sentence more than once.

III. RESULTS

Table I represents the average SRT values expressed in speech-to-noise ratios, with their standard deviations, for which the 12 young subjects and the 18 elderly subjects correctly repeated 50% of the syllables of the sentences. All subjects had lower thresholds for the AV condition than for the A condition.

Table I

Speech-to-noise ratios for which 50% of the syllables of sentences were repeated correctly with and without speechreading.

	Young subjects		Elderly subjets	
Condition	S/N ratio (dB)	s.d (dB)	S/N ratio (dB)	s.d (dB)
A (only auditory)	-9.0	1.0	-4.8	1.9
AV (auditory + visual)	-13.6	2.4	-8.8	1.9
Difference	4.6	2.2	4.0	1.4

In order to get an impression of how important speechreading was with respect to inter-individual differences in SRT, the total variance (=sum of squares of the deviations of the threshold values from their mean value divided by their number) was analyzed. Table II gives the results.

For the V condition, speechreading only, the average correct-syllables score was 23.1% for the young subjects and 6.4% for the elderly subjects. This remarkably large difference may be due to the young persons being more prepared to guess than elderly subjects. Because normal auditory and visual

Table II
Analysis of the total variance.

	Young subjects Variance (dB2)	Young subjects % of total	Elderly subjects Variance (dB2)	Elderly subjects % of total
Total variance	8.49	100.0	7.36	100.0
Source speechreading	5.37	63.2	3.87	52.5
Source listeners	2.05	24.1	3.01	40.9
Interaction+error test	1.08	12.7	0.48	6.6

Table III
Correlation coefficients between intelligibility measures and the auditory and visual acuities for the elderly subjects.

	PTA	Landolt-C acuity
Speechreading score V	0.15	0.10
Effect of speechreading AV-A	0.03	0.19

acuities were not strict conditions for the elderly subjects, we checked wether, for this group, the speechreading score and the effect of speecechreading on the SRT (AV-A) were related to the PTA and the Landolt-C visual acuity. The correlation coefficients are presented in Table III. The correlation coefficient between the speechreading score V and the effect of speechreading on the 50% threshold was 0.29.

IV. DISCUSSION

Table I shows that the benefit of speechreading in terms of the 50%

correct-syllables threshold was, on the average, 4.6 dB for the young subjects and 4.0 dB for the elderly subjects. The standard deviations for the various data give some insight into the differences between these two groups. For the young subjects, the small value of only 1.0 dB demonstrates that they spread very little in their auditory SRT (and that the method is accurate). With speechreading added, the standard deviation increased to 2.4 dB, which means that some individuals were much better in taking advantage of visual information than others. For the other group, however, both conditions resulted in the same standard deviation of 1.9 dB; this illustrates that: (1) the interindividual spread in SRT is larger, as should be expected because of the various degrees of presbycusis, but (2) the interindividual differences of the elderly subjects in their speechreading ability were smaller than for the normals. The difference in standard deviation for the benefit of speechreading for the individual subjects (2.2 dB for the normal-hearing and 1.4 dB for the elderly listeners) confirms this conclusion.

The differences in variance due to the sources "speechreading" and "subjects" in Table II illustrate the same effects in another way: (1) The variance due to subjects was larger, but (2) the interaction between "speechreading" and "subjects" was smaller for the elderly individuals than for the other group. Finally, the very small correlation coefficients in Table III reveal that the interindividual differences in speechreading ability of the elderly (with or without auditory information) cannot be explained by differences in their auditory and visual acuities.

The only data on the effect of speechreading upon the intelligibility of sentences found in the literature are from O'Neill (1954) and Hasselrot (1974), both for normal-hearing listeners. Although no SRT values were given in those studies, rough estimates can be derived from their diagrams, equal to about 4-5 dB for O'Neill and 5-6 dB for Hasselrot. Our data are in good agreement with their values considering the large difference in experimental conditions.

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FUTURE CONSIDERATIONS

From the eleven years of experience with assessment of speech-hearing loss in noise, it has been made clear that speech intelligibility in noise is an important, realistic and reliable parameter in obtaining insight into an individual's hearing performance in everyday listening situations. It has also been demonstrated that the SRT for sentences in noise cannot be predicted from the SRT in quiet or from the pure-tone audiogram.

In this thesis three frequently and one rarely encountered clinical manifestations of speech-hearing loss have been analyzed: hearing loss due to noise exposure, otosclerosis, aging and due to unknown origin (Chapter IV). It has become clear that the SRT in noise, especially for both the group of noise exposed listeners and the group of "noise sensitive" listeners as described in chapter IV, represents an entity which is irreplacable by performing pure-tone audiometry.

From a diagnostic point of view the assessment of the SRT in noise claims a place in the test-arsenal of the clinical audiology. For the Dutch situation this possibilityhas come readily at hand since our standardized speech and noise material has been recorded on compact disc recently.

From a therapeutic point of view a tremendous challenge lies ahead. In revalidation of a noise-induceed or presbyacusic hearing impaired individual, Application of a conventional hearing aid will be of only rather limited benefit in noisy conditions. Experience in daily audiologic practice obviously confirms this theory.

Apart from expressing attention for the beneficial effect of speech reading (Chapter V) and other supportive measures, like the use of directional microphones in hearing-aid fitting, much more has to be done: in revalidation of sensorineurally hearing-impaired listeners an improvement of the signal-to-noise ratio for speech perception is mandatory.

At our department research is in progress for the development of a hearing aid that offers the possibility of selectively amplifying frequency regions that contribute to speech intelligibility and at the same time attenuating frequency bands that do not contribute to intelligibility. i.e. masked by interfering noise. In developing such new hearing aid numerous difficulties are encountered. Because of a listener's continuously changing acoustical environment the device should adapt its gain automatically within the various frequency bands. Slow fluctuations in background noise level should be compressed. whereas on the contrary the generally faster fluctuations in natural speech are essential for optimal intelligibility and should therefore not be affected.

A proto-type digital hearing aid that divides the speech and noise signal into 4 separate frequency bands (0.25-0.5 kHz. 0.5-1 kHz. 1-2 kHz and 2-4 kHz) has been designed. For every separate frequency band the speech and noise can be analyzed and "treated". i.e. compressed and amplified. The first experiments with this hearing aid have recently been performed by van Dijkhuizen. Festen and Plomp (1.2) and initially offer satisfactory expectation for clinical application of the device in the near future.

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SUMMARY AND CONCLUSIONS

Assessment of hearing impairment is usually based upon a pure-tone audiogram. in which the hearing threshold for several frequencies is determined. Pure-tone audiometry is of tremendous diagnostic value e.g. because of the possibility of detecting the monaural threshold by adequate masking or discriminating a perceptive loss from a conductive hearing loss. In clinical practice sometimes a speech audiogram is measured in addition to the pure-tone audiogram. Standardized mono-syllabic word lists are used for assessment of speech intelligibility as a function of sound level. The speech audiogram gives us. more than the pure-tone audiogram. an insight into qualitative aspects of the hearing function: in some cases distortion of sounds can be detected by demonstrating a diminishing intelligibility in spite of an increasing loudness level of the presented speech material.

For the assessment of a hearing handicap. however. these simple tests are insufficient. A very important aspect of every-day listening situations is not represented in either pure-tone audiometry or speech audiometry for mono-syllabic words: the influence of background noise. In almost any auditory communicative situation interfering noise is present and the speech level of normal-hearing individuals is adjusted to it. Complaints about hearing impairment mostly first become apparent in noisy conditions like meetings. parties and so forth.

In 1978 Plomp developed a descriptive model for speech hearing loss. In this model speech hearing loss is divided into two components:

1. Attenuation. representing a speech hearing loss which can be fully compensated for by sufficient amplification of the speech. This component is. roughly. equal to the speech-hearing loss in quiet.

2. Distortion. representing a qualitative aspect of hearing loss. Only improvement of the signal-to noise ratio of the presented speech can

compensate for this type of hearing loss. This component is equal to the speech-hearing loss in noise.

The validity of this model has been tested upon groups with several distinct types of hearing impairment due to noise exposure, aging or otologic pathology. The specially for this purpose created speech material consists of ten lists of thirteen different sentences each and an interfering noise with a spectrum equal to the long-term average spectrum of the speech material.

In this thesis several clinical applications of testing the speech intelligibility in noise are described.

Chapter I serves as a general introduction and provides an overview of the historical development of several audiometric procedures and their implications for clinical use. Plomp's model for the Speech-Reception Threshold and some of its applications are described.

Chapter II deals with an audiometric study concerning 183 sheet-metal workers, who have had long-term noise-exposure because of their profession. Pure-tone thresholds and the Speech-Reception Threshold (SRT) in quiet and in noise are compared. The goal of this study was to investigate the hearing handicap due to noise-induced hearing loss by means of the assessment of the SRT in noise, which is a reliable standard for everyday listening situations. The SRT was compared with the pure-tone thresholds by means of analysis of simple and canonical correlation.

The pure-tone average of the 3-kHz and 4-kHz thresholds appears to be the best compromise between simplicity of the simple analysis of correlation and the slightly better predictive canonical analysis in predicting the SRT in noise, and shows a correlation coefficient of 0.75. This means that only 56% of variance in the SRT in noise can be explained from the pure-tone audiogram. For an individual we consider this measure of predictability to be unsufficient to assess the hearing handicap and to replace the determination of the SRT in noise, which obviously represents a distinct quality of hearing.

Chapter III reports on a peri-operative audiometric study of patients who underwent stapedectomy. The study concerns 27 primary stapedectomies and 10 cases of revision surgery after previously unsuccessful stapedectomy. In

otologic literature there are reports on post-operative perceptive high-frequency loss in an otherwise successful stapedectomy. We established the hypothesis, that due to a possible per-operatively originated cochlear trauma a (slight) perceptive high-frequency loss might occur which diminishes the speech intelligibility in noise. At the same time the Speech Reception Threshold in quiet would improve.

However, in both primary stapedectomy and revision cases the speech intelligibility in noise proved to be unchanged after a 3 months' post-operative interval. This finding corresponds well to the lack of post-operative high-frequency perceptive loss in these patients. The study is limited to only two surgeons, so the conclusions which may be drawn are restricted too. However, these results show that it is possible to perform a primary or revision stapedectomy without reducing speech intelligibility in noise.

Chapter IV concerns an investigation of 15 patients who, in a 1.5 year period visited the out-patients' clinic with complaints of hearing impairment in noisy conditions. Routine pure-tone audiometry and the assessment of intelligibility score of mono-syllabic words in quiet showed (nearly) no abnormalities. The SRT in noise was determined by means of the earlier described speech and noise material. The conditions consisted of steady-state and fluctuating noise, monaural and binaural testing and reverberation in order to simulate acoustically poor situations. The audiometric findings in the group of patients were compared with those of a reference group of 10 normal-hearing individuals without hearing complaints and with normal routine audiometric thresholds. In the group of patients we found a statistically significantly worse speech intelligibility score in noise, which was most clear in the condition when fluctuating noise was used. Speech intelligibility in reverberation was also statistically significant worse than in the group of normal-hearing individuals. The difference between monaural and binaural SRT (binaural gain) was equal in both the patients and the normal-hearing individuals.

The results of this study confirm the complaints of these patients, which in conventional audiometry would not have been possible.

Chapter V reports on the supportive effect of speech reading to the speech intelligibility in noise.

A comparison was made between a group of 18 aged people and 12 young normal-hearing students. The aged people showed a mild presbycusis and proved to have a reasonable visual acuity. For both groups the beneficial effect of speech reading proved to be the same and equal to a 4-dB gain in signal-to-noise ratio.

This gain may seem small, but in critical listening situations an increase of 1 dB signal-to-noise ratio is equivalent to an increase of 18% of correctly understood sentences. Based upon these facts it certainly proves to be valuable to stress the beneficial effect of speech reading in an individual patient with a hearing impairment, for compensation of diminished speech intelligibility.

CONCLUSIONS

1 Pure-tone audiometry, even when combined with the assessment of the speech-reception threshold for speech in quiet, gives unsufficient insight into the speech intelligibility in noise. A valuable procedure in the assessment of a hearing handicap is represented by the speech-reception threshold for sentences in noise.

2 Performance of stapedectomy or revision stapes surgery is possible without an increase of the speech-reception threshold in noise.

3 There exists a category of patients, complaining of difficulties in speech understanding in noisy conditions, who appear to show an isolated increase of the speech-reception threshold in noise. This category of patients may be called "noise sensitive" and appears normal-hearing in routine audiometry.

4 Speech intelligibility in noisy conditions can be improved considerably by means of speechreading. The improvement for moderately hearing-impaired elderly listeners is the same as for young normal-hearing subjects and is equal to 4 dB signal-to-noise ratio.

5 The assessment of the speech-reception threshold in noise requires a place in clinical audiometry. Since the recent availability of a compact disc that contains the recordings of the standardized Dutch speech material and noise the test can be performed without many extra provisions in an audiological centre.

SAMENVATTING EN CONCLUSIES

DE KLINISCHE WAARDE VAN HET BEPALEN VAN DE SPRAAKVERSTAANVAARDIGHEID IN LAWAAI

Het vaststellen van slechthorendheid gebeurt veelal op basis van een toondrempelaudiogram, waarin voor een aantal frequenties op nauwkeurige wijze de gehoordrempel wordt vastgelegd. Door het gebruik van verschillende aanbiedingsvormen voor de stimulus (lucht- en beengeleiding) en het toepassen van maskering om de drempeldetectie tot een oor te beperken, is de toonaudiometrie diagnostisch van grote betekenis. In de kliniek wordt in aanvulling op het toonaudiogram soms een spraakaudiogram vervaardigd. Hierbij wordt voor gestandaardiseerde lijsten met monosyllabische woorden de verstaanvaardigheid bepaald als functie van het geluidsniveau. Meer dan het toonaudiogram geeft het spraakaudiogram inzicht in het qualitatieve aspect van de gehoorfunctie; vervorming van geluiden kan bijvoorbeeld tot uiting komen in een afname van de verstaanvaardig- heid bij een toename van het geluidsniveau.

Voor het vaststellen van de handicap ten gevolge van slechthorendheid zijn deze metingen echter onvoldoende. Aan een belangrijk aspect van het verstaan in alledaagse situaties wordt immers zowel bij toonaudiometrie als spraakaudiometrie voorbij gegaan, namelijk de invloed van omgevingslawaai. Omgevingslawaai is in nagenoeg elke situatie waarin wij auditief communiceren aanwezig en vormt een stoorbron, waaraan het niveau van de spraak van goedhorenden is aangepast. Een klacht over slechthorendheid uit zich dan ook veelal het eerst in rumoerige situaties, zoals vergaderingen, recepties e.d.

In 1979 heeft Plomp een beschrijvend model ontworpen voor het verstaan van spraak in ruis. In dit model worden twee parameters onderscheiden voor de effecten van slechthorendheid.

De eerste parameter is een verzwakking en beschrijft de verminderde gevoeligheid van de slechthorende. Omdat een verzwakking zowel op de

spraak als op de storing werkt en slechts de verhouding tussen spraak en en storing de verstaanbaarheid bepaalt. is het effect van deze parameter beperkt tot condities met een gering stoorniveau.
De tweede parameter beschrijft de extra signaalsterkte die de slechthorende nodig heeft om te verstaan. onafhankelijk van de sterkte van het stoorsignaal. Deze parameter zou bijvoorbeeld kunnen worden opgevat als een compensatie voor vervorming van de spraak ten gevolge van slechthorendheid.

De validiteit van dit model is getoetst aan enkele groepen slechthorenden met een verschillende aetiologie: lawaaibelasting. ouderdom en oorpathologie. Het hiertoe speciaal ontworpen testmateriaal bestaat uit tien lijsten van dertien alledaagse zinnen en een bijbehorende stoorruis met een spectrum dat gelijk is aan het gemiddeld spectrum van de spraak over een lange tijd. In dit proefschrift wordt een aantal klinische toepassingen beschreven van het bepalen van de spraakverstaanvaardigheid in ruis.

Hoofdstuk I vormt een algemene inleiding en vermeldt de historische ontwikkeling van enkele audiometrische procedures en hun toepassingsgebied. Het model van de spraakverstaanvaardigheids- drempel volgens Plomp en enkele toepassingen hiervan worden beschreven.

Hoofdstuk II betreft een gehooronderzoek bij 183 personen. die in hun beroep als plaatwerker langdurig aan lawaai zijn blootgesteld. De resultaten van de toonaudiometrie en het spraakverstaan in stilte en ruis worden hier met elkaar vergeleken. Het doel van deze studie was. door middel van de bepaling van de spraakverstaanvaardigheidsdrempel in rumoer te onderzoeken welke mate van gehoorhandicap optreedt ten gevolge van langdurige lawaai-expositie. De relatie van de toondrempels tot de spraakverstaanvaardigheid in rumoer is nagegaan en het blijkt dat bij hanteren van een simpele correlatie-analyse de gemiddelde toondrempel bij 3 en 4 kHZ de optimale voorspeller is voor de verstaanvaardigheidsdrempel in ruis met een correlatie coefficient van 0.75. Dit betekent dat 56% van de variantie in de drempels voor het spraakverstaan in ruis verklaard kan worden uit het toonaudiogram. Het toonaudiogram geeft hierbij een te gunstige schatting van de gehoorfunctie in alledaagse akoestische omstandigheden. Deze voorspelkracht wordt voor een individu als onvoldoende beschouwd ter vervanging van de bepaling van de mate van een auditieve handicap door middel van de spraakverstaanvaardigheid in ruis. welke blijkbaar een min of meer op zich zelf staande entiteit is. Enkele bedrijfsaudiometrische aanbevelingen worden gedaan.

Hoofdstuk III behandelt de resultaten van een peri-operatief gehooronderzoek bij patienten die een stapedectomie hebben ondergaan. Het betreft hier 27 primaire stapedectomieen en 10 her-operaties. In de literatuur wordt melding gemaakt van een perceptief hoge-tonenverlies. dat kan optreden in aansluiting aan een overigens succesvolle stapedectomie. De hypothese ontstond. dat ten gevolge van een mogelijk peroperatief cochleair trauma een gering perceptief gehoorverlies zou ontstaan. waardoor de spraakverstaanvaardigheid in ruis zou zijn afgenomen bij een verbeterde spraakdrempel in stilte. Zowel bij de primaire stapedectomieen als bij de her-operaties bleek de verstaanvaardigheidsdrempel in ruis 3 maanden postoperatief niet slechter te zijn geworden. Dit resultaat was in overeenstemming met het ontbreken van een postoperatief perceptief hoge-tonenverlies bij deze patienten. Omdat het onderzoek zich heeft beperkt tot slechts twee operateurs is ook de conclusie beperkt. De resultaten tonen echter aan dat het mogelijk is een stapedectomie of her-operatie te verrichten zonder reductie van het spraakverstaan in ruis.

Hoofdstuk IV betreft een onderzoek bij 15 patienten. die gedurende een periode van 1.5 jaar op de polikliniek verschenen met klachten over een verminderd gehoor. met name in omgevingslawaai. Routine toonaudiometrie en spraakaudiometrie met monosyllabische woorden lieten nauwelijks afwijkingen zien.
De verstaanvaardigheidsdrempel in ruis werd bepaald met het eerder beschreven spraakmateriaal. De meetcondities omvatten zowel stationaire als fluctuerende ruis. monaurale en binaurale tests. alsmede situaties met galm om akoestisch ongunstige omstandigheden te simuleren. De audiometrische resultaten van de patienten werden vergeleken met die van een controlegroep van 10 normaalhorenden zonder klachten. Bij de patientengroep was er een statistisch significant slechtere spraakverstaanvaardigheid in lawaai. die het duidelijkst tot uiting kwam in de test-conditie met fluctuerende ruis.
De spraakverstaanvaardigheid in galm was voor de patientengroep eveneens statistisch significant slechter dan in de controlegroep. Het drempelverschil

tussen de monaurale en binaurale condities, ook wel genoemd de binaurale gehoorwinst, was voor de patienten even groot als voor de controlegroep.

De resultaten van dit onderzoek bevestigen de klachten van de patienten. Met behulp van de conventionele audiometrie zouden deze klachten niet geobjectiveerd kunnen worden.

Hoofdstuk V bespreekt het ondersteunend effect van spraak-afzien (liplezen) op de verstaanvaardigheid in lawaai.

Een vergelijking werd gemaakt tussen een groep van 18 bejaarden en 12 jonge normaalhorende studenten. De bejaarden toonden een milde vorm van presbyacusis en hadden een redelijke visus. Het positieve effect van spraak-afzien op de verstaanvaardigheidsdrempel in ruis bleek voor beide groepen gelijk te zijn en is equivalent aan 4 dB in de signaal-ruis verhouding. Deze winst lijkt gering, echter in kritische luistersituaties komt een toename van 1 dB in signaal-ruisverhouding overeen met een toename van 18% in de kans op het correct verstaan van zinnen. Op grond van dit gegeven is het dus zeker zinvol slechthorenden attent te maken op het positieve effect van liplezen, ter compensatie van de verminderde spraakverstaanvaardigheid.

CONCLUSIES

1 Toonaudiometrie gecombineerd met het spraakaudiogram voor monosyllaben, woorden of zinnen gepresenteerd in stilte geeft onvoldoende inzicht in de spraakverstaanvaardigheid in rumoer. Een goede maat voor het bepalen van de handicap ten gevolge van slechthorendheid vormt de bepaling van de spraakverstaanvaardigheids-drempel voor zinnen in ruis.

2 Een stapedectomie of her-operatie na een voorafgaande niet succesvolle stapedectomie is uitvoerbaar zonder vermindering van de spraakverstaanvaardigheid in rumoer.

3 Er bestaat een categorie patienten met gehoorklachten, bij wie alleen de spraakverstaanvaardigheid in rumoer verminderd blijkt. Deze patienten zouden "omgevingslawaai-gevoelig" genoemd kunnen worden, zonder vooralsnog een bekend pathologisch substraat.

4 Spraakverstaanvaardigheid in moeilijke omstandigheden zoals omgevingslawaai, kan aanzienlijk verbeterd worden door middel van spraak-afzien. De verbetering van de verstaanvaardigheidsdrempel is voor matig-slechthorende bejaarden met een redelijke visus gelijk aan die voor jonge normaalhorenden en is equivalent aan 4 dB in signaal-ruis verhouding.

5 Het bepalen van de spraakverstaanvaardigheid in ruis behoort een plaats te hebben in het test-arsenaal van de klinische audiometrie. Met het ter beschikking komen van een compact disc, waarop het gestandaardiseerde spraakmateriaal en de stoorruis geregistreerd staan, is deze test met weinig extra middelen goed uitvoerbaar in een audiologisch centrum.

CURRICULUM VITAE

The author of this thesis was born on August 31st 1958 in Zwijndrecht.
In 1976 he passed the gymnasium bèta exam at the Johan de Witt Gymnasium in Dordrecht. In the same year he started medical school at the Erasmus Universiteit in Rotterdam, where he obtained the medical license on February 18th, 1983.
In 1983 and 1984 he served in the Dutch Army as a medical officer at the Inspectie Geneeskundige Dienst Koninklijke Landmacht in The Hague. In the same period he worked as a forensic physician for the municipal police corps of the city of Rotterdam.
On January 1st 1985 he started residency Otorhinolaryngology/Head & Neck Surgery at the Free University Hospital in Amsterdam (program director Prof.Dr.G.B. Snow).
Part of the residency (January 1st 1987 - July 1st 1987) took place at the Westeinde Hospital in The Hague (program director Dr.T. Bottema).
From January 1st 1989 he is certified as an Otorhinolaryngologist and from that date he has been a staffmember at the department of Otorhinolaryngology/Head & Neck Surgery of the Free University Hospital in Amsterdam.