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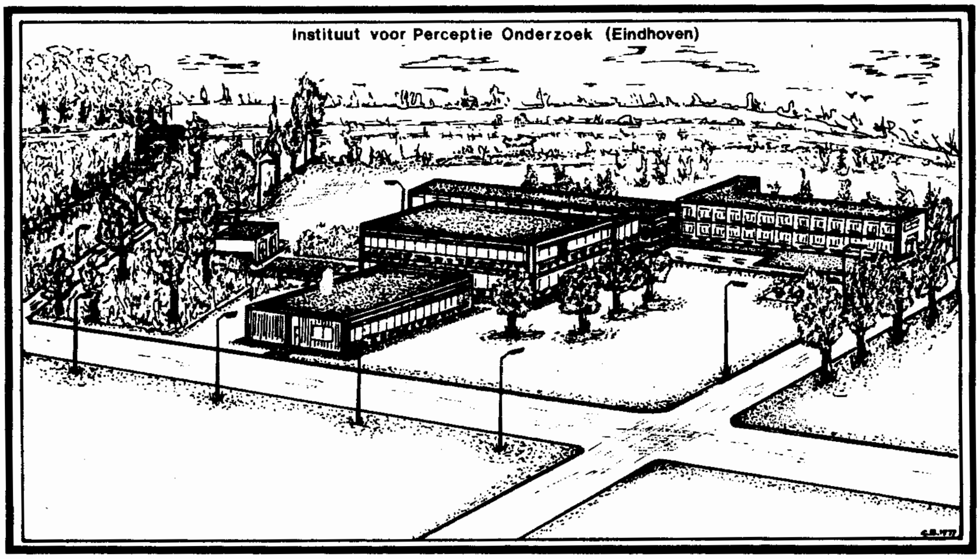

Editor: A.J. Breimer

Typist: Jeanneke van Esch

INSTITUTE FOR PERCEPTION RESEARCH — INSTITUUT VOOR PERCEPTIE ONDERZOEK

P.O. BOX 513 EINDHOVEN HOLLAND

TELEPHONE NATIONAL (040) 756605 / TELEPHONE INTERNATIONAL +3140 756605

Speech intelligibility in noise for listeners with sensorineural hearing damage

B. Leshowitz

Introduction

The great majority of hearing-impaired listeners suffer from physiological deficits present at the sensory cell level in the cochlea. These disorders are often termed "sensorineural" and cannot be medically treated either by surgery or drug therapy. The only assistance available to listeners with sensorineural hearing damage is amplification of the sound afforded by the personal hearing aid. Unfortunately, efforts to ameliorate hearing disorders with amplification have not been entirely successful. Indeed, almost every listener with sensorineural hearing loss reports that, under many everyday conditions of background noise, speech reception is not improved by the hearing aid.

The foregoing does not contradict the audiological observation that the hearing aid often performs a useful function. Under the restricted condition of near total quiet, amplification of the sound, consisting mainly of the desired speech signal, above the threshold of audibility does allow good speech reception. How much of the listener's acoustical day consists of substantial quiet is of course, the fundamental issue.

Examination of the noisy communication situation experienced by the hearing-impaired listener reveals a straightforward explanation of the widespread dissatisfaction with the personal hearing aid. It is well-known that a concomitant of sensorineural hearing loss is an increase in the ratio of speech level to noise level required for just intelligible speech over that measured for the normal-hearing listener. Measured in terms of speech-to-noise ratio, the hearing deficit may be as large as 10 to 15 dB (Plomp, 1978). When it is realized that in many common moderately noisy communication situations, the normal listener must process speech at or near the threshold of intelligibility, one can begin to understand the magnitude of the communication problem faced by the listener with impaired-hearing. The personal hearing aid cannot possibly improve the quality of partially masked speech since it provides indiscriminate amplification of both speech and noise. Thus, while the listener with a hearing deficit may report the presence of a speech signal, unless the speech-to-noise ratio exceeds some critical value, the listener will perceive the speech as muffled and unintelligible. Effectively he will be deaf in all but the most ideal listening conditions.

An auditory disability is generally assumed to be present when the listener cannot engage in tête-à-tête conversation in quiet. Without minimizing this hearing activity, a cursory analysis of the typical listener's acoustical day reveals that the majority of speech communication takes place in ambient noise. Assessment of hearing capacities from pure-tone threshold and speech intelligibility measurements made in quiet can therefore hardly be expected to capture the everyday acoustical experiences of the hearing-impaired listener.

Implicit in our emphasis on measurement of speech reception under realistic conditions of moderate background noise is the assumption that the standard evaluation of hearing in terms of the audiogram provides an inaccurate description of the listener's auditory capacities. On the assumption that threshold elevation in the speech region measured in the quiet is the best predictor of speech reception, it is common audiological practice to evaluate the hearing impairment by averaging the pure-tone thresholds at 500, 1000 and 2000 Hz. While there is little doubt that this index of hearing loss does indeed predict the speech reception threshold in quiet, there is much less justification for its continued application under the less ideal conditions of moderate background noise. That listeners with normal low-frequency hearing and selective high-frequency hearing loss often experience great difficulties in perceiving speech in noise has frequently been reported in the anecdotal observations of practicing audiologists (Courtois, 1975). Specifically, listeners with an abrupt high-frequency loss due to noise trauma as well as the presbyacusic patient characterized by a more gradually sloping audiogram are the two major categories of the hearing-impaired population thought to be especially vulnerable to noise.

The major aim of the present investigation was to determine whether there is a well defined class of listeners incapacitated by their inability to understand speech in noise to an extent far in excess of what would have been predicted from inspection of the audiogram.
Positive findings would, it was felt, provide strong evidence that hearing handicap is far more prevalent in the general population than has heretofore been recognized. Having established the existence of an appreciable population of noise-sensitive listeners, efforts could then be directed to developing a psychoacoustical framework for understanding the speech communication handicap.

In the audiological literature the claim is often made that there is an increase in the upward spread of masking for listeners with sensorineural hearing deficits. Thus, we speculated that increase in the speech-to-noise ratio observed for listeners with selective high-frequency hearing loss ought to be accompanied by a marked increase in masking above that measured for normal-hearing listeners. Moreover, in view of the speech communication handicap reported for these listeners, the enhanced masking effect ought to take place in the low-frequency region of speech where pure-tone thresholds are normal. A positive relationship between the pure-tone masking pattern and speech reception in noise would, we reasoned, not only have obvious practical implications for audiological procedures for assessing the effective hearing handicap, but would also constitute an intriguing research problem for the physiological acoustician interested in basic hearing mechanisms. Although the physiological correlates of behavioural thresholds are not well established, it is not unreasonable to infer minimal sensory-cell loss in regions of normal hearing. Accepting this supposition, then what underlying processes are responsible for the abnormal suprathreshold effects observed in seemingly normal regions of hearing?

Experiments

The primary strategy of the research was to assess intelligibility of speech presented
 against a noise background for listeners with selective high-frequency hearing loss

and near-normal hearing in the speech frequencies. A second goal was to relate speech reception in noise to the pattern of pure tone masking for individual listeners.

Subjects

Listeners with predominantly sensorineural hearing damage served as the experimental group. When the air-bone gap exceeded 20 dB, the conductive loss was assumed to be sufficiently great to eliminate the subject from participation in the experiment. The pattern of hearing revealed by the audiogram in conjunction with the listener's case history provided the basis for classifying the experimental subjects according to etiology of the hearing loss. Listeners categorized as having "noise trauma (T)", for example showed a precipitous loss in the high frequencies and reported that they had been exposed to appreciable levels of environmental noise. Presbyacusic subjects (P) had a more gradually sloping audiogram and had no history of noise exposure. Two female subjects had received extensive medical treatment with a mycine drug, and were classified accordingly (D).

The control group (N) consisted of listeners in the under-40 age group with normal audiograms. A second group (over-40) produced largely similar data often with a slight trend to typical presbyacusic results; those results are not presented in this paper.

Typical audiograms are shown in the results section.

Procedure

Speech intelligibility was measured for each listener using connected discourse as the signal. The task of the subject was to adjust the level of the interfering background (foyer noise) until the speech signal was "just intelligible". The listener was informed that it was not necessary to recognize every word of the text, but only to maintain the intelligibility of the story-line. A Békésy up-and-down psychophysical method was used for this purpose, wherein the subject continuously varied the level of the background noise using an attenuator having a range of 40 dB and steps of 2 dB. The level of the speech constituted the experimental variable and was varied between the listener's speech reception threshold in quiet and 90 dB(A). (For a more complete explanation of the application of the adjustment procedure to measurement of speech intelligibility, the reader should consult the recent paper of Plomp (1976).)

The extent of the upward spread of masking for each listener was assessed in a pure-tone masking experiment. In this paradigm, the masker was a 125 msec, ramps included, gated sinusoid, presented with a linear 25-msec rise-fall time. The masker was presented continuously throughout the listening session with a duty cycle of 0.5. The signal was a 20-msec tone burst which was shaped with a 10-msec rise-fall time. The signal was presented in the temporal centre of the gated masker during three successive masker bursts and deleted every fourth burst. A listening session was devoted to the measurement of a masked audiogram. The frequency and intensity of the masker was held constant. The experimental variable was the frequency separation between signal and masker.

In all experiments, the tonal masker was a 1000 Hz sinusoid, presented at either 75 or 105 dB SPL. Masked thresholds were measured using an adjustment procedure similar to that described earlier in connection with measurement of speech intelligibility. The subject was instructed to adjust the level of the probe using a 2-dB-step attenuator until the probe was at the "threshold" of audibility. Since the intent of the experiment was to examine the spread of masking into the higher frequencies, precautions had to be taken to prevent the listener from basing his threshold measurements on perception of low-frequency combination tones caused by simultaneous presentation of signal and masker. Thus, at frequency ratios of signal (f_s) to masker (f_m) between 1.2 and 1.5 an additional low-frequency masking tone at either $2f_m - f_s$ or f_s-f_m was added. The level of these added tones was at least 20 dB below the primary masker and therefore played a negligible role in determining the course of masking.

Results

In order to facilitate comparison between psychoacoustic and speech-intelligibility measures of performance, masked and unmasked audiograms are plotted along with the speech intelligibility functions. For each group are shown a typical subject (data points) together with total and interquartile ranges across subjects (shaded).

In Fig. 1 are presented the data for listeners having normal hearing (N), as evidenced by normal pure-tone thresholds throughout the entire audible frequency region shown in the upper-left panel. The quality of speech intelligibility at various levels of background noise is given in terms of the speech-to-noise ratio or masked speech-intelligibility threshold and is depicted in the upper-right panel of each figure. In general, it can be seen that intelligibility thresholds of about - 5 dB are obtained at low and moderate noise levels, with a slight increase in threshold apparent at the higher levels of background.

The pattern of pure-tone masking is depicted in the masked audiograms which are plotted in the lower panels of Fig. 1. The masked audiogram relates signal threshold to frequency of the signal presented against a longer-duration 1000 Hz tonal background. As expected, we observe the asymmetry of the masked audiogram which is consistent with the standard observation of an upward spread of masking into the higher frequencies. Comparing the masking patterns obtained at the two masker levels of 75 and 105 dB, we note that the spread of masking becomes more prominent with an increase in the level of the masker. The present masking results, while in good qualitative agreement with the classical findings of Wegel and Lane (1924), are, we feel, noteworthy insofar as they demonstrate that perfectly reasonable masking results can be obtained using a method of adjustment with listeners having only minimal experience in psychoacoustical experimentation. In view of the consistency of the measurements of masking across listeners comprising the control group, it was deemed appropriate to compute an averaged masked audiogram. The latter serves as a standard measure of performance against which masking for the hearing-impaired listeners are compared and is indicated by the dashed line in the appropriate figures.

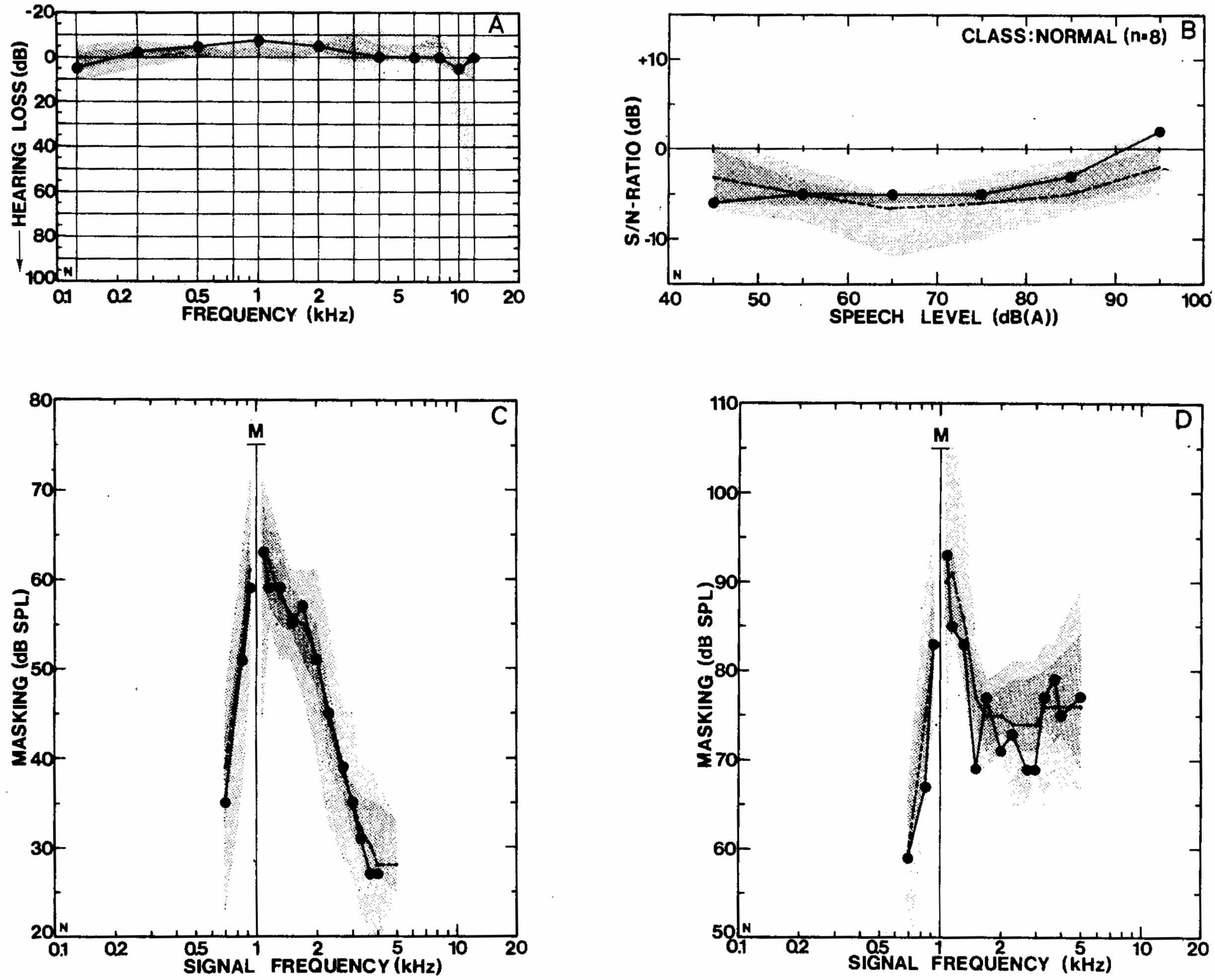

Fig. 1. Combined data for listeners with normal hearing.
Panel A shows audiograms, panel B gives speech intelligibility thresholds in noise (as S/N-ratio) as a function of speech level, and panels C and D show masked audiograms for 1 kHz maskers of 75 and 105 dB, respectively. Throughout, data point represent data of one typical subject, dashed lines averages across subjects (n = 8) and hatched areas indicate interquartile and total ranges.

In Figures 2, 3 and 4 are plotted the performance functions for listeners classified as "noise tramata"(T), "presbyacusic" (P) and"ototoxic"(D), respectively. From inspection of these data several trends emerge, which, we feel, characterize the listening performance of listeners with selective high-frequency hearing loss due to sensorineural hearing damage. Most important, we note that according to the Average Hearing Loss index (as deducible from the audiogram) all of our impaired listeners would be considered to have near-normal hearing. That the audiograms do not accurately portray the hearing capacities of these listeners is immediately obvious from examination of the suprathreshold performance functions for masking and speech intelligibility. First, the masked audiograms (solid curve) reveal considerably more upward spread of masking than that obtained from normal listeners (dashed curve). Moreover, this enhanced spread of masking observed for impaired listeners is manifested in frequency regions where pure-tone thresholds in quiet are perfectly normal. While the reader can confirm this observation from inspection

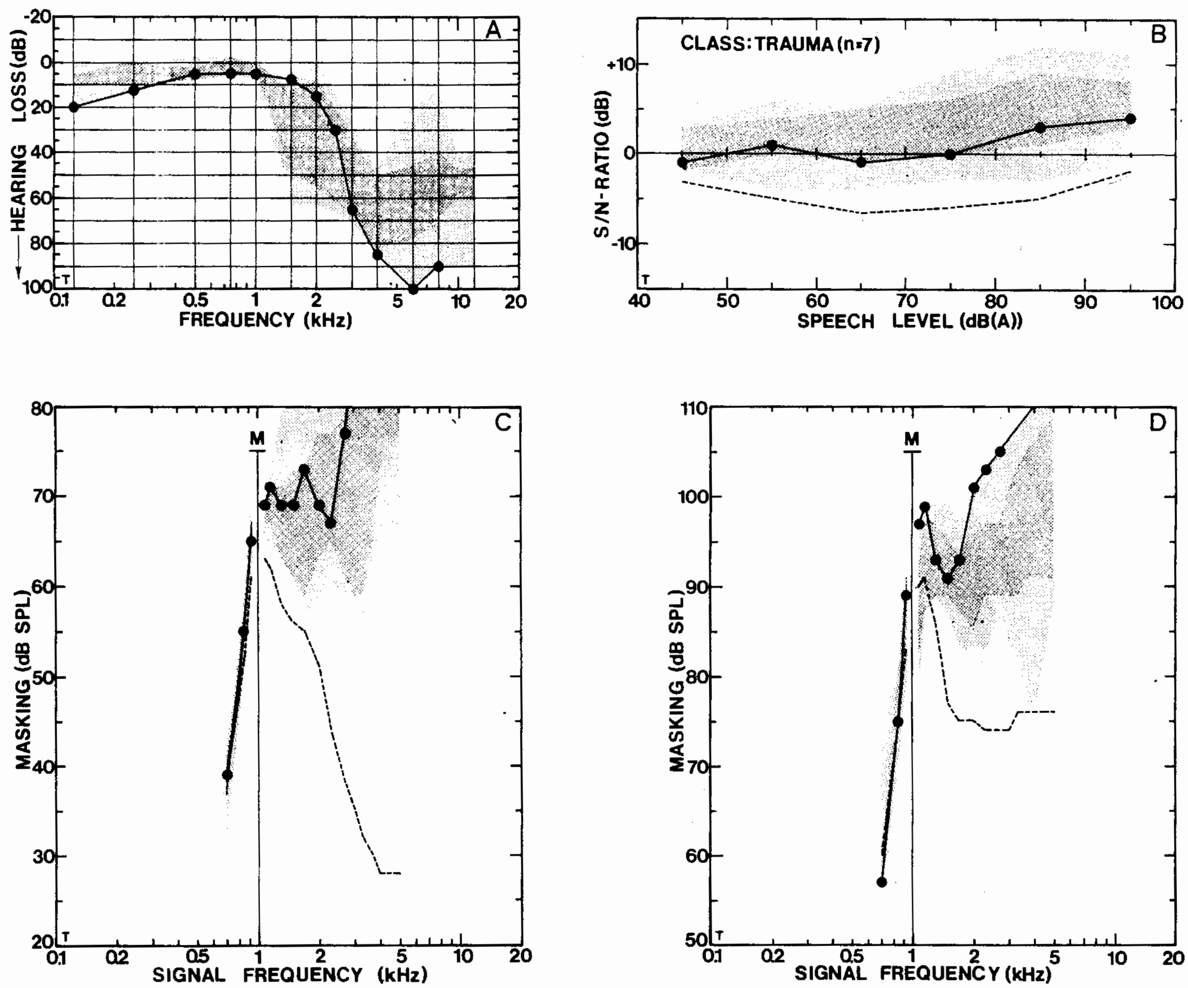

Fig. 2. Combined data for listeners with noise trauma. Lay-out of panels as in Fig. 1.

of any impaired subject's masked audiogram, let us illustrate the point by referring to subject JB's performance. In Fig. 2a we observe that in the low-frequency region, thresholds in quiet are normal, whereas above 2000 Hz a precipitous fall-off in hearing sensitivity occurs due to acoustic trauma. Concentrating our attention on the region above the masker at 1000 Hz and below the area of threshold elevation, it can be seen from the masked audiograms that masking is about 20 dB greater than is recorded for normal listeners. From examination of the masking patterns of other listeners with selective high-frequency loss, we observe elevations in masking as large as 40 dB. Moreover, this enhanced masking effect often occurs in frequency regions remote from the region of hearing loss where pure-tone thresholds are normal.

The speech intelligibility signal-to-noise thresholds are plotted in panels D. There is anything from a 5 to 15 dB increase in the speech-to-noise ratio relative to performance of normal listeners. Moreover, the increase in the S/N is observed throughout the listener's available range of hearing, thus indicating that the aural

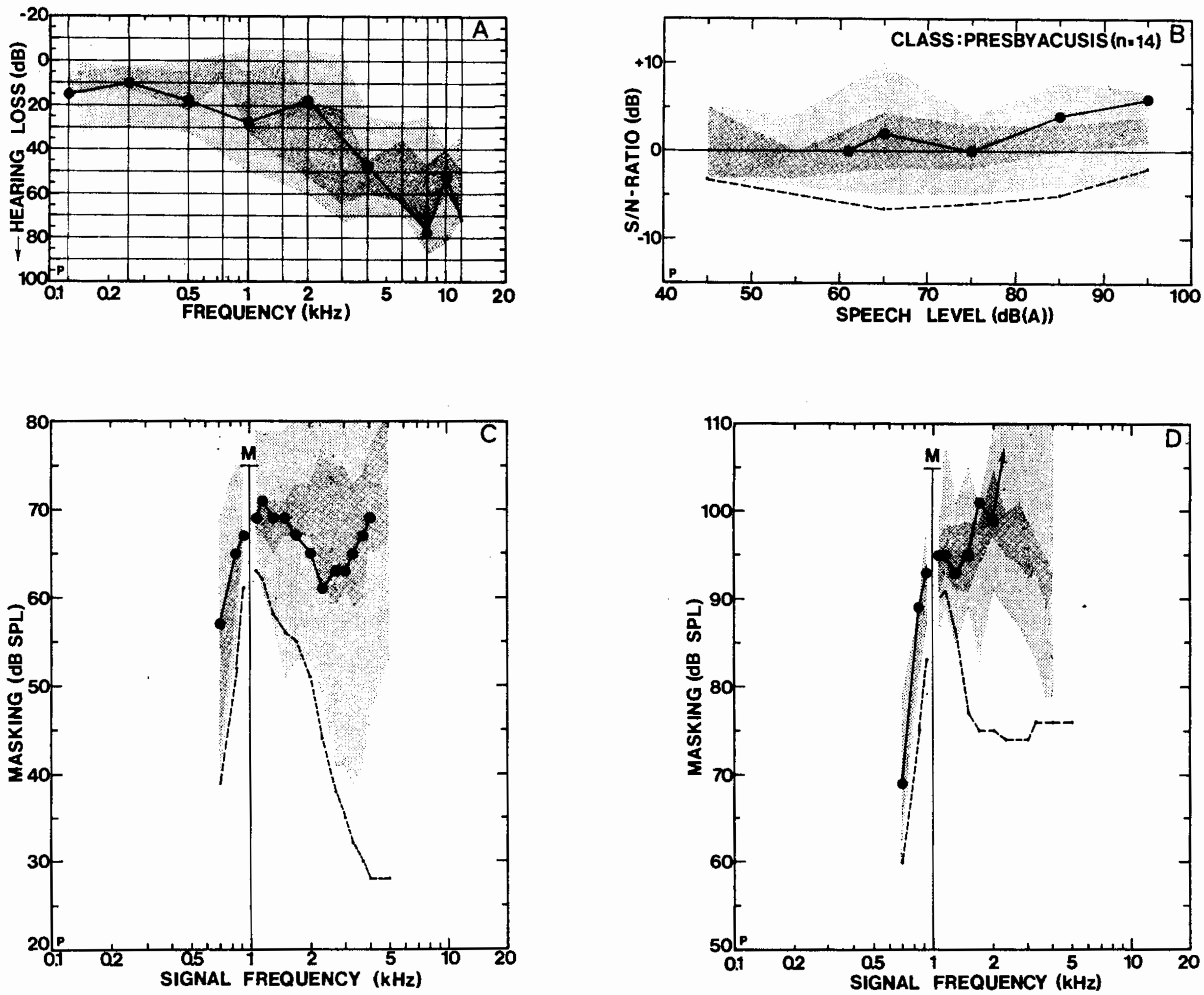

Fig. 3. Combined data for presbyacusic listeners. Lay-out of panels as in Fig. 1.

overload attendant to high-level stimulation cannot account for loss of speech intelligibility experienced by listeners with predominantly high-frequency hearing loss. A rise in speech threshold seems to be related to a significant upward spread of masking.

Discussion of results

In summarising the main experimental findings the following results should be emphasized: (1) for normal hearing adults, the good agreement between the present data and similar findings in the literature is evidence of the suitability of the psychophysical procedure of adjustment to measurement of both speech intelligibility and pure-tone masking for inexperienced listeners; (2) relative to the normal control group, listeners with selective high-frequency hearing loss show as much as 40 dB more masking at high frequencies; (3) the increased upward spread of masking observed with impaired listeners is often found in regions of normal pure-tone thres-

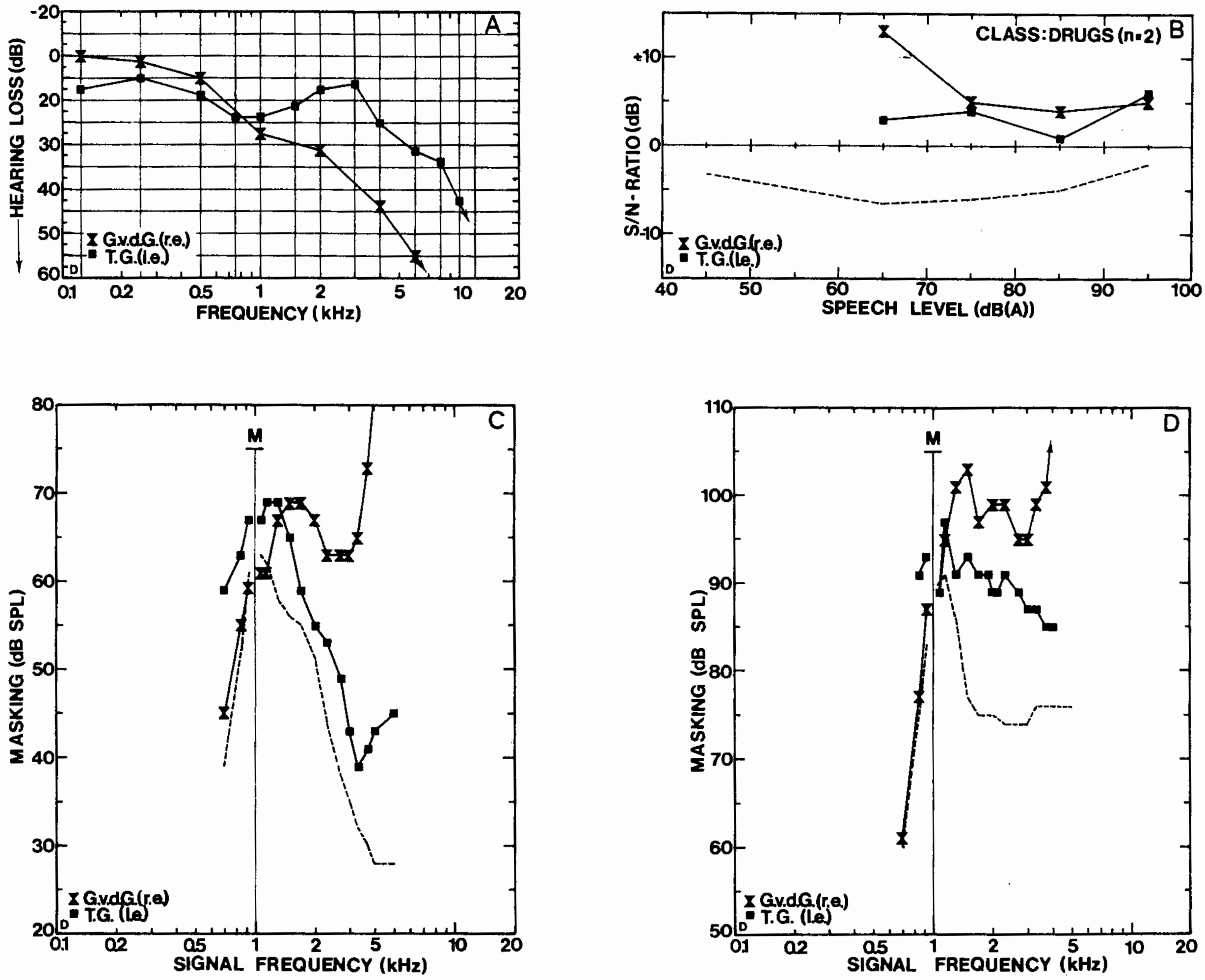

Fig. 4. Combined data for two ototoxic listeners. Further lay-out as in Fig. 1.

hold; (4) masked speech-intelligibility thresholds of impaired listeners are in the order of 5 to 15 dB worse than normal observers; (5) whereas measurement of hearing in terms of the traditional Average Hearing Loss index frequently does not serve to distinguish members of the experimental and control groups, suprathreshold measures of speech intelligibility and pure-tone masking show essentially no overlap between the two groups.

Although both the smallness of the number of subjects partaking in the present experiment and the limited stimulus parameter space investigated limit the generality of the present findings, the potential implications of the results are so far-ranging that they deserve detailed consideration. Following a discussion of how the present results bear on our notions of mechanisms underlying auditory masking, more applied audiological problems of diagnosis and treatment of perceptual handicaps are considered. In the concluding subsection are presented some final observations on how the present laboratory findings may influence the reformulation of medico-legal statutes governing determination of hearing handicap.

The upward spread of masking and sensorineural hearing loss

Investigations directed at measuring pure-tone masking for listeners with sensorineural hearing loss have not produced a consistent picture of auditory masking in the impaired ear. For example, De Boer and Bouwmeester (1974), who investigated masking patterns produced by narrow bands of noise, have demonstrated increased amounts of masking above the passband of the masker in ears with cochlear pathology, presumably attributable to pronounced harmonic distortion. Nelson and Bilger (1974), on the other hand, have obtained equivalent masking for probes placed at the octave above the pure-tone masker. Reports in the older clinical literature, unfortunately, do not help us to understand the discrepancy between the two reports.

In an attempt to resolve the apparently contradictory findings Leshowitz and Lindstrom (1977) investigated the spread of masking in regions of normal and elevated threshold within the same ear. The shape of the psychoacoustical tuning-curve, relating the level of tonal masker just sufficient to mask the fixed frequency probe, served as the measure of frequency resolution. They observed a complete loss of frequency selectivity in regions of threshold elevation, whereas in the normal regions of hearing, tuning curves appeared to be similar to those of normal listeners. In a second experiment, however, they obtained evidence indicating that in normal regions of hearing there were aspects of auditory processing that had been altered by the presence of a lesion in a remote region of the cochlea. It is well known that presentation of two primary tones gives rise to perception of additional tones, called combination tones, not present in the stimulus. In listeners with abrupt high-frequency hearing loss, Leshowitz and Lindstrom observed a marked reduction in the generation of odd-order combination tones although the primary tones were both presented in regions of presumably normal hearing.

Additional evidence of abnormal auditory processing in seemingly normal regions of hearing was also obtained in the present experiment. From inspection of the masked audiogram it has been observed that when both the probe and masker were located in regions of normal hearing, masking was as much as 30 dB greater than observed in listeners with completely normal audiograms. We are hard pressed to account for this observation in the light of the generally accepted view that there is minimal sensory cell degeneration in regions of normal behaviour threshold. On the assumption that a near-normal complement of sensory cells exists in regions of normal threshold, we are forced to conclude that the physiological insult is more subtle than has heretofore been realized. Investigations of the physiological correlates of the pronounced masking effect observed in regions of normal threshold in the traumatized ear present an intriguing and challenging opportunity, one that has relevance not only to a fundamental understanding of the mechanism of auditory masking, but also to understanding the speech handicap experienced by listeners with selective high-frequency hearing loss.

Although we cannot offer speculation about the mechanism underlying the pronounced spread of masking in ears with cochlear pathology, the empirical finding may offer insight into the basis of the speech communication problem characterizing listeners with sensorineural impairment.

In earlier attempts to account for the communication loss reported for listeners with selective high-frequency hearing damage, the threshold dip has been regarded as selective attenuation of high-frequency information. This, together with the limited dynamic range (i.e. recruitment) in the region of threshold elevation has been held responsible for the loss of speech discrimination in noise. This view is consistent with the stated need for selective amplification and automatic gain control in hearing aids.

Quite a different explanation of the speech deficit is suggested by the masking patterns obtained with impaired listeners. As a working hypothesis we suggest that the pronounced spread of masking into the high-frequency regions, including areas of normal threshold, attendant on the threshold dip is a major causative agent for the listener's communication loss in noise. In order to test this notion, a simple demonstration experiment was conducted. A typical high-frequency hearing loss was simulated in a normal listener by presenting a 3000 Hz continuous tone along with the discourse. As before, the task of the listener was to adjust the level of the noise until the speech just became intelligible. Addition of the tone was found to have no effect on speech intelligibility. Thus, we conclude that the loss of high frequency information in the speech waveform is due to threshold elevation and that increased recruitment plays only a secondary role in determining the quality of speech perception. It is clear that detailed measurements of the frequency selectivity and auditory nonlinearities attendant on hearing impairment are needed before we can reach a more fundamental understanding of the hearing disorder.

Assessment of hearing handicap

The hearing handicap, as argued, can be usefully expressed in terms of the difficulty to hear and communicate in an everyday situation of ambient noise. A quantitative index of the individual's performance in such a situation is his speech-intelligibility threshold determined against a background of noise (expressed as signal-to-noise ratio). Insight into the value of this index is gained by analyzing the everyday situation of two competing sound sources, one a primary talker and the other unwanted interference from another speaker or TV, etc. Plomp (1976) has shown that, under ordinary room acoustics and placement of the two sources, the primary sound is about 5 dB above the comfort level for understanding of conversation by the normal-hearing listener. We have seen earlier that listeners with selective high-frequency hearing loss have masked thresholds between 5 and 15 dB higher than the normal control group. Thus the prediction is that almost all our non-normal experimental listeners will have serious, if not insurmountable difficulties in understanding the speaker in noise.

The above hearing handicap can be estimated directly by measuring the listener's masked speech-intelligibility threshold. However, the apparent relationship between speech discrimination in noise and the prominence of the upward spread of masking suggests that it may well be possible to predict the handicap from audiometric measurements of *masked* threshold, thereby bypassing the difficulties inherent in speech-intelligibility measurements.

Using the averaged masked audiogram obtained for the 75 dB-1000 Hz masker for normal observers as the baseline, we can quantify the degree of the upward spread of masking in individual listeners by averaging the elevation of masked threshold at 1500, 2000 and 3000 Hz above the normal masked thresholds. The averaged masked threshold elevation, which we shall call the Handicap Index (HI) in conjunction with a simple decision rule can now be used to predict speech intelligibility.

Fig. 5 is a scattergram depicting masked speech-intelligibility threshold,averaged across speech levels of 65 - 95 dB, plotted against HI for all the listeners partaking in the experiment. If we accept for a moment that a 5 dB elevation of intelligibility threshold gives rise to a significant hearing handicap, we can evaluate various decisions. To illustrate the approach, assume that we adopt a rule whereby all listeners having an HI greater than 10 dB are classified as handicapped. From Fig. 5 we observe that the probability of correctly identifying a handicapped individual is close to unity. Unfortunately, a few individuals are incorrectly classified as having a handicap. Nevertheless, the outcome is deemed quite respectable, especially when it is realized that according to the Average Hearing Level measured in the quiet all listeners would be considered normal. Assessment of hearing handicap with the HI approach, while very promising, must be the substantiated in many additional tests before we can recommend the procedure as a clinical diagnostic tool.

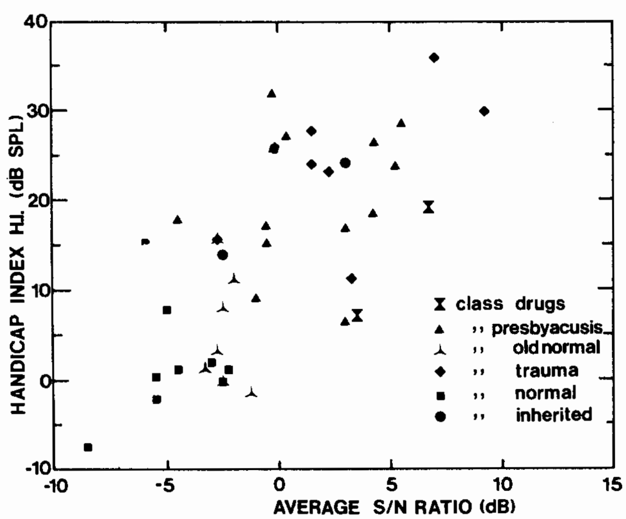

Fig. 5. Scattergram of Handicap Index (i.e., the average "supranormal" upward spread of masking obtained at 1500, 2000 and 3000 Hz) against masked speech intelligibility threshold.

Possibilities for rehabilitation

Practically, all modern hearing aids are designed to produce either selective or broadband amplification of sound. Since wanted speech signal and unwanted background undergo equal amplification, the signal-to-noise ratio is at best unaltered, (in practice it decreases somewhat due to noise in the instruments). This implies that listeners with a flat speech intelligibility loss (all our non-normal listeners) benefit from the traditional hearing aid only in a situation where background is negligible to start with (Plomp, 1976).

If we are to significantly improve the speech-reception capabilities of our typical impaired listener, the signal-to-noise ratio must be increased by about 10 dB. A straightforward approach to solving the hearing dilemma entails detaching the microphone from the hearing aid. By giving the microphone to the speaker, a considerable improvement in the S/N can be realised. From the inverse-square law of physics we know that in the direct sound field acoustic signal strength decreases 6 dB per doubling of distance. At a comfortable speaker-to-listener distance of two metres, the loss of signal strength is about 10 dB. Since ambient noise in a room is about the same level at all locations, bringing the microphone near the speaker improves the S/N by 10 dB. This 10 dB improvement in the S/N provides the margin between intelligible and unintelligible speech and is sufficient to enable most hearing-impaired listeners to understand speech about as well as the unaided normal individual.

Present research efforts of the author and others at the Institute for Perception Research are now being directed at developing a detachable microphone system that not only delivers the required S/N, but is also ergonomically acceptable to the user. The detachable microphone system incorporated in the personal hearing aid has obvious shortcomings; none the less, the concept has received great acceptance as an auditory trainer in schools for the hard-of-hearing. Borrowing from the technology of light transmission of TV audio developed by Sennheiser, a prototype for the detachable microphone system utilising infrared light transmission of the acoustical signal has been developed. The system consists of two components: a transmitter, which includes the microphone; and a receiver comprising an infrared light receiver, an amplifier and an earphone. A detailed report of the initial evaluation of the prototype is beyond the scope of this report. However, it can be stated that we are most encouraged by both the improvements in speech intelligibility rendered by the device and the enthusiastic endorsement that the users have voiced in support of the device.

Conclusion: toward a reevaluation of the medico-legal standards of hearing handicap. It should be abundantly clear that the basic message of the present work is that evaluation of hearing capacities must take place under realistic conditions of moderate background noise. That listeners with audiological evaluations of "normal" hearing based on pure-tone thresholds experience serious difficulties in understanding speech in noise can hardly be unknown to the practicing audiologist. What is painfully obvious is that existing procedures for assessing the hearing handicap still emphasize measurements taken in quiet and therefore do not capture the daily auditory experiences of the impaired listener. Hearing handicaps are often subtle, being manifested most acutely in noise and are undetectable using standard audiological techniques. Likewise, legal standards of damage-risk criteria for environmental noise give carte blanche to insulting agents that do not intrude in the region of the speech frequencies. In other words, high-frequency hearing is legally expendable. The very profound deficits we have uncovered for listeners with exclusively high-frequency hearing loss clearly demonstrate how ludicrous is the prevailing view of hearing handicap.

In conclusion, perhaps the major problem in the impaired-hearing field is to reach a consensus as to what constitutes hearing handicap. Having established an acceptable standard for evaluation of auditory capacities we can then proceed with research directed at developing effective prosthetic devices. And, perhaps more important still, we can begin devising legal standards governing "safe" levels of environmental irritants.

"An ounce of prevention is worth a pound of cure!"

Summary

In this paper experiments are described to establish empirical evidence for the audiological observation that listeners with normal pure-tone thresholds below 2000 Hz and selective high-frequency sensorineural hearing loss often experience great difficulty perceiving speech in a noise background. For patients with either noise trauma or presbyacusis, masked-speech intelligibility thresholds (S/N) were about 10 dB higher than for normal observers. In an effort to provide a psycho-acoustical explanation for the speech communication deficit, pure-tone masking patterns were measured. Relative to the normal control group, listeners with high-frequency hearing loss showed as much as 30 dB more upward spread of masking, often in frequency regions of normal pure-tone threshold. The strong positive relationship between the masked-speech intelligibility threshold and the upward spread of masking suggests that it may be possible to predict the patient's speech perception handicap in noise from audiometric measurements of *masked* threshold. Implications of the present work for development of close-talking-microphone hearing aids are indicated.

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