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ABSTRACT

Level dependence of tone thresholds at the peaks and in the valleys of sinusoidally 100 % intensity-modulated octave band noise was tested on 16 young normal-hearing subjects. The purpose was to create a reliable method to measure the Psychoacoustical Modulation Transfer Function, PMTF, and to establish a reference. The test frequencies were 0.5 - 4.0 kHz, the length of the shaped tones 4 ms, the modulation frequencies 1.25 - 20 Hz, and the sound pressure levels of the noise 45 - 85 dB. For each subject and each modulation frequency the differences between the thresholds at the peaks and in the valleys were plotted as functions of the sound pressure level. The obtained curves show peaks around 60 dB SPL, although most pronounced for the lower modulation frequencies. Speech reception thresholds in noise show a similar level dependence. Thresholds in the valleys are highly dependent on modulation frequency: Lower modulation frequencies give lower thresholds. The peaked level dependence of the thresholds at the peaks of the noise add some information on a "severe departure" from Weber's law. The qualities of the outer hair cells might explain the results. The method might be useful for diagnostics and for hearing instrument fitting to obtain maximum speech recognition. Results for sensorineurally hearing-impaired will follow.

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INTRODUCTION

Psychoacoustical measuring methods have been developed with several purposes: to acquire general knowledge of hearing, for diagnostic purposes, and to reveal the basic abilities necessary for good speech recognition in quiet and in noise. Such measuring methods might also make it possible to determine the maximum speech recognition capacity of a specific ear, or to optimize the hearing aid fitting according to the resources of a particular ear. This work explores one possibility to optimize the hearing instrument fitting by using a psychoacoustic measure. The results may also have diagnostical value.

Capacity regarding the time, frequency and intensity dimensions has been measured, e.g. temporal resolution (Fitzgibbons and Wightman, 1982; Zwicker and Schorn, 1982), frequency selectivity (Zwicker and Schorn, 1978; Florentine, Buus, Scharf and Zwicker, 1980), frequency and intensity discrimination (Arlinger, 1976). Measuring these capacities adds some information to that of the audiogram, but not enough for good predictions of total speech recognition. It is likely that results of measurements in each of these dimensions separately would give higher correlations to the recognition of speech sounds containing difficulties in that particular dimension, than to the recognition of speech as a whole. To investigate this, studies of speech features and auditory capability in parallel are required (Rosen and Fourcin, 1986). By combining the results of measurements in these dimensions in a way that takes into account the relations to various types of speech sounds, higher correlations to speech recognition as a whole might be acheived. Also possible compensatory strategies might be included in such a procedure. An approach some way towards this, would be to try psychoacoustical measurements involving more than one dimension at a time.

The natural, slow intensity modulations of speech provide essential information for speech recognition. This fact was proved in the 1970-ies for sound transmitted through technical communication systems and in room acoustics; at that time Houtgast and Steeneken presented their method for predicting speech recognition of communication systems and room acoustics for normal-hearing persons (Steeneken and Houtgast, 1980), and IEC organized an international evaluation of their method of measuring Modulation Transfer Function, MTF, and Speech Transmission Index, STI, our department making the Swedish contribution. The results were good (IEC 268-16, 1983). Equipment for measurements according to the simplified method, RASTI, is commercially available.

However, not only technical transmission systems may distort the natural, slow intensity modulations of speech. Also the ear itself may do it more or less. By measuring in a similar way on an ear, that ear's combined abilities in the time/intensity dimensions might be mapped.

For a noise carrier, modulated to 100 % by a sinusoid and received by the ear, the neural response will not reflect the same degree of modulation. Backward and forward masking will fill in the valleys in the noise to some extent, reducing the modulation from 100 % to a lower value. By measuring the threshold for a short tone placed in the middle of the valley the depth of the resulting valleys can be estimated. Comparison either to the threshold of the tone in continous unmodulated noise or to the threshold for the tone when placed at the peak of the noise may give an indication of the capacity of the ear, and gives a basis for calculating a Psychoacoustical Modulation Transfer Function, PMTF.

We developed a method to measure on the ear according to the mentioned principles, and so did Ahlstrom at the same time (Ahlstrom, 1984). Ahlstrom used amplitude-modulated noise like Viemeister (1973), who first thought along these lines. We used intensity-modulated noise like the MTF-STI-method. However, at 100 % modulation the signals are the same, although for example 10 Hz modulation frequency at intensity-modulation corresponds to 5 Hz modulation frequency at amplitude-modulation. Our results showed high correlations to speech recognition scores, 0.85 in quiet and 0.71 in noise, which are high values regarding speech recognition (Hagerman, Olofsson and Lindblad, 1987). However, we did not consider the method stable enough, since adaptation effects occured at measuring thresholds for continous unmodulated noise, which we used for comparison. *The investigation to be presented here puts a modification of our method to the test.* In agreement with Ahlstroms method it makes use of thresholds at the peaks of the noise for comparison. *Not only the method but also the influence of sound pressure level is tested. An obvious level dependence varying with frequency might support the use of this method to choose the levels in the hearing instrument. By presenting the speech signals at the levels where the patient has the best capacity to follow intensity variations, the highest possible speech recognition might be obtained.*

I. METHODS

A. Stimuli

An octave-band-filtered, sinusoidally intensity-modulated noise was used as a masker in the threshold measurements. The noise was modulated to 100 %. Centre frequencies were 500, 1000, 2000, and 4000 Hz, modulation frequencies 1.25, 2.5, 5, 10, and 20 Hz. The tests were performed at 45, 55, 65, 75, and 85 dB SPL of the modulated noise (RMS-measurements of the modulated noise).

The test tone was a 4 ms long sinusoid, shaped by a raised cosine function, and placed at the centre frequency of an octave band, Fig. 1. The test tone was placed either at the peak of the noise, "0°", or in the valley, "180°", Fig. 2, with the repetition frequency 2.5 Hz. However, at the modulation frequency 1.25 Hz the repetition frequency was 1.25 Hz. The shaping of the test tone made its spectrum narrower than the corresponding spectrum of the octave noise in all octaves. The worst case, at 500 Hz, is illustrated in Fig. 3. In the other octaves the noise bandwidths are broader but the test tone bandwidth remains the same.

In order to obtain differences in speech recognition at different sound pressure levels for normal hearing subjects a speech test in noise was chosen. Hagerman's sentences and method for testing the speech reception threshold, SRT, in noise are well established in Sweden (Hagerman, 1982, 1984). Each sentence consists of five words, and all the words in a sentence are test words. The sentences are accompanied by slightly (10 %) amplitude-modulated, speech shaped noise. The speech levels used here were the same as the test levels for the octave band noise.

B. Procedure

Each test ear was tested in nine sessions, the last one consisting of speech recognition measurements. In each of the eight first sessions only one octave frequency was tested, at all combinations of the chosen modulation frequencies and sound pressure levels. A session normally lasted for 1 to 1.5 hours with an interval in the middle. In the first four sessions the octaves 1000 Hz and 2000 Hz were first tested in an order counterbalanced over subjects, and then repeated in the opposite order. During the following four sessions the octave frequencies 500 Hz and 4000 Hz were tested in a corresponding way.

All thresholds were measured by Békésy-technique. This simple test method together with the fairly frequency independent, hammering sound character of the test tone made the task easily understood. The instruction was in brief: "press the button as long as you hear the hammering".

At the beginning of each session two thresholds for the short test tone of that particular session were taken. If they differed more than a couple of dB, the measurement was repeated until considered stable. After that the modulated noise was switched on and it was checked that the subject could manage the task also with the modulated noise. Now the noise was modulated with one modulation frequency, and the thresholds taken at the five sound pressure levels in counter-balanced order. The other modulation frequencies followed, also in counter-balanced order. An example of a test sheet is given in Fig. 4.

The counterbalancing mentioned so far applies to distribution across subjects. An attempt was also made to counterbalance within a subject the order of sound pressure levels at the various modulation frequencies for an octave, as well as the order of modulation frequencies for the various octaves. For each modulation frequency and sound pressure level the threshold with the test tone at the peak and in the valley were taken in immediate succession. Half of the subjects started with a threshold at the peak, half of them with the thresholds in the valley, the balancing included in the counterbalancing of the octave frequencies. After that the order of peak and valley thresholds were alternated to save time: at a new sound pressure level the first threshold was a peak threshold, if the last threshold at the previous sound pressure level was a peak threshold, and vice versa.

At the end of a session another threshold for the test tone without noise was taken, to be compared to the one taken initially. A large difference might be an indication of too long a test session.

In the ninth session speech reception thresholds, SRTs, in noise were taken, i.e. the signal-to-noise-ratios, S/N, that give 50 % correctly perceived words, were assessed. The 50 % level was determined, as described in Hagerman (1984). Half a list, 25 words, was used at every S/N used to obtain a threshold. One initial threshold measurement was used for training. Three thresholds were taken at each of the five sound pressure levels: first one threshold at each level in randomized order, then another one at each level in reversed order, and finally one more at each level in the original order. The order of the word lists and the order of the sound pressure levels were counterbalanced across subjects. The mean of the three threshold measurements at a specific sound pressure level was used at the following data treatment.

Most of the subjects participated in an extra session including repeated measurements at some test points. The purpose was, if possible, to distinguish between test accuracy and variation of hearing from time to time.

C. Equipment

The test subject was seated in a sound-insulated test booth, listening monaurally through TDH-39 headphones with MX-41/AR cushions. The test tone and the noise were generated in a digital front-end-processor, the Technical Audiological Measurement Processor, built at the department, and controlled by a micro-computer, Fig. 5. The level of the noise was determined by the attenuator, and the relation of test tone level to noise level was changed depending on the response from the test subject. The level was changed at a rate of approximately 3 dB/s. A Krohn-Hite filter, 3322R, was used for octave band filtering with a slope of 24 dB/octave.

Fourteen Békésy turning points were used to obtain one threshold value. The first two turning points were not used for calculations. From the remaining six upper turning points the computer calculated a median. The same procedure was applied to the lower turning points. The mean of the two medians was chosen as the threshold. All the turning points were stored for later calculations of the number of turning points needed for satisfactory accuracy.

At the SRT measurements the speech and noise signals were presented from a Revox B77 tape recorder, the levels of the speech and the noise set by attenuators, and the resulting signals added by a mixer, before presentation in the TDH-39 headphones with MX-41/AR cushions.

D. Subjects

Sixteen young normal-hearing subjects, 8 males and 8 females, participated in the experiment. Their hearing thresholds in the frequency range 250 Hz to 8000 Hz did not exceed 20 dB, and were mostly considerably better. Their age ranged from 17 to 29, with the same median, 22.5, for the male group and the female group. One of the boys had both ears tested separately, which means there were 17 test ears. Five of the boys had done their military service, three had not. The subjects were asked about their listening habits and noise exposure and also about hearing impairments among their closest relatives. They seemed to have been normally or less than normally exposed to strong sounds, with no obvious hereditary disposition for hearing impairment. The subjects were paid for their participation.

E. Data treatment

During a test session the differences, in dB, between peak and valley thresholds were plotted against sound pressure level on a chart. Points regarding the same modulation frequency were connected. This procedure gave the experimenter a running overview of the dependence on level and modulation frequency. After the retest the two charts for the same octave and the same subject could easily be compared visually.

The peak and valley thresholds, as well as threshold differences were subjected to analyses of variance (BMD08V). Possible differences between male and female group and between military service and no military service group were considered by means of t-test (Hays, 1973). Small, but not significant, differences were found between these groups. The relation between SRT in noise and threshold differences and peak and valley thresholds was analysed by means of regression analysis (BMD02R). Also threshold differences at lower sound pressure levels than the level for the SRT-measurement were introduced in some of the analyses. The difference between variances for replications at the same occasion and on different days were tested by means of F-test (Edwards, 1973). Psychoacoustical Modulation Transfer Functions and Speech Transmission Indices were calculated.

II. RESULTS

Individual thresholds at the peak and in the valley are given in Appendix, as means of the two replications at each data point. Differences between thresholds at the peak and in the valley are also given in that table, as well as the individual results of the speech test. The corresponding threshold and threshold difference means for the group are given in Table I and in Fig. 6 (differences) and Fig. 7 (thresholds). The standard deviations are given in Table II.

A. Differences between thresholds at the peak and in the valley

As mentioned at the beginning, the idea of measuring tone thresholds of an ear at the peak and in the valley of modulated noise emanates from the theory of Modulation Transfer Function, where the essential point is to study the decrease in the degree of modulation, i.e. the span between peak and valley for various frequency bands and modulation frequencies. Therefore in our case, considering speech recognition, the difference between peak and valley thresholds should be the most interesting. The group means of the difference, plotted against levels in Fig. 6, show a nice, clear pattern: the influence of all parameters is strongly significant at a level of at least $p<0.01$, Table III.

The most distinctive parameter is the modulation frequency, which accounts for 55 % of the variance. Low modulation frequencies give large differences between thresholds at the peak and in the valley. Higher modulation frequencies give smaller differences. The ear can more easily follow the slow intensity changes than the rapid ones.

There is obviously an influence of sound pressure level too, which accounts for 14 % of the variance. All curves have their maxima around 55 to 65 dB SPL. The maxima are often situated at higher sound pressure levels for low modulation frequencies than for higher ones, which is most easily seen by extrapolating the lines through the highest points or by comparing a 1.25-Hz-curve to a 10- or 20-Hz-curve.

The octave frequency influences the threshold differences in different ways at low and high modulation frequencies. At low modulation frequencies the largest threshold differences are found at 2 kHz and 1 kHz. For the highest modulation frequency, 20 Hz, the threshold differences seem to increase with increasing octave frequency.

The standard deviation for the group at each test point varied between 1.3 dB and 6.7 dB (Table II), with larger variability between subjects at the higher octave frequencies.

By an analysis over all subjects and parameters a subject's standard deviation at replication at different occasions was found to be 2.2 dB, which was less than for the thresholds at the peak and in the valley separately. They were 2.3 and 2.6 dB respectively. The peak and valley thresholds vary together.

The standard deviations at a few combinations of octave and modulation frequencies for two and six replications in succession, and without taking off the headphones, are listed in Table IV. The standard deviations for successive replications are smaller than those for different occasions, although not significantly. The standard deviations at the 4 kHz octave are larger than at the lower octave frequencies. However, only the difference in standard deviation between 4 and 2 kHz at 5 Hz modulation frequency for six replications in succession, i.e. the largest difference, is slightly significant, $p<0.2$.

The correlations between threshold differences for neighbour modulation frequencies in the same noise octave are significant at $p<0.01$, and so is the case for all but one combination of threshold differences for the same modulation frequency in adjacent noise octaves.

B. Thresholds at the peak

Tone thresholds at the peak of the modulated noise are drawn with solid lines in Fig. 7. They are expressed in dB relative to the noise, with an arbitrary reference level, not in SPL. These curves, showing the thresholds at the peaks at various modulation frequencies, show a level dependence and have their maxima at 55 to 65 dB like the threshold difference curves.

There is some influence of the modulation frequency at higher octave frequencies and lower sound pressure levels.

All thresholds at the peak are significantly correlated to each other, at least at a significance level of $p<0.05$ (the lowest correlation being between thresholds in the most remote octaves, the 0.5 kHz and the 4 kHz octaves). The correlations are strongest between thresholds with different modulation frequency but within the same octave, then $p<0.001$.

C. Thresholds in the valley

The tone thresholds in the valley of the modulated noise are drawn with dotted lines in Fig. 7. For all the octaves the thresholds in the valley increase when the modulation frequency increases, and the level dependence changes in a characteristic way: The lowest modulation frequency gives bowl-shaped curves. For the highest modulation frequency the bowls have turned upside down. The curves corresponding to the modulation frequencies in between change gradually from one shape to another. The modulation accounts for 67 % of the variance.

Between 75 and 85 dB SPL a few subjects have steeper downward slopes for thresholds in the valley than for thresholds at the peak. This results in threshold differences getting larger again at the highest sound pressure levels.

The correlations between thresholds in the valley are significant mainly for neighbour modulation frequencies in the same noise octave.

D. Speech test

The individual speech reception thresholds in noise show the same type of level dependence as the tone threshold differences, also with peaks at 55 to 65 dB.

The mean SRTs in noise for the 17 ears as well as the mean threshold differences over all octave bands for these ears are shown in Fig. 8 for comparison.

For some subjects with threshold difference curves turning upwards again between 75 and 85 dB, the same effect can be seen on the SRT-curve.

In a regression analysis treating all the sound pressure levels together, the highest correlation between a threshold difference and the absolute SRT in noise was 0.46, significance $p<0.001$. This happened in the 1 kHz octave at the modulation frequencies 1.25 - 5 Hz. The corresponding correlation for the threshold at the peak was 0.42. By using only the data from 85 SPL, where the threshold differences are smaller and of the same magnitude as can be expected from hearing-impaired ears, higher correlations can be achieved. For 2 kHz, 5 Hz, the correlation reaches 0.68. The correlation at 1 kHz, 5 Hz remains.

E. PMTF calculations

Calculations of the Psychoacoustical Modulation Transfer Functions and the corresponding Speech Transmission Indices from the thresholds at the peak and in the valley give the same type of level dependence as the SRTs and the threshold differences. PMTFs at four sound pressure levels are shown in Fig. 9.

III. DISCUSSION

A. Threshold differences and SRTs in noise

The question about a level dependence for thresholds for short tones in modulated noise has got a positive answer. Strikingly enough the maximum threshold difference occurs at 55 to 65 dB in each octave tested: at the sound pressure level of normal speech at the distance of 1 m! This is true also for the SRTs in noise, in agreement with Hagerman's earlier data (Hagerman, 1982). The maximum correlation of 0.42 between a single threshold difference and the SRT in noise is moderate and is not made very much larger by adding a reasonable number of threshold differences at other combinations of octave and modulation frequencies. They are obviously not independent enough.

A drawback, however, is that the tests were performed neither in silence, which would not differentiate between sound pressure levels for normal-hearing subjects, nor with speech noise with natural intensity fluctuations which should differentiate, but with a speech noise amplitude-modulated only to 10 %. Deeper modulations might have made the correlation higher. Another reason to expect only moderate correlations for normal-hearing subjects is that we do not know what capacity, i.e. what difference between thresholds at the peak and in the valley, is required for normal performance and what is overcapacity or refinement of speech recognition. At the calculation of the physical Modulation Transfer Functions the dynamic range is limited to 30 dB, but the transfer to the psychoacoustical domain might require a change of the practical range, too. Psychoacoustical MTF-STI-calculations were made from the threshold differences with a 30 dB limitation, as in the physical MTF-STI-calculations, but the calculations do not add any information to what is given by the threshold differences. When quite a few hearing-impaired subjects have been tested, we might know where to limit the threshold difference in the calculations. This idea is strengthened by the fact that, at 85 dB SPL calculated separately, the correlation between the threshold differences at 2 kHz, 5 Hz, and the SRTs in noise was higher than when all the sound pressure levels were involved in the regression analysis, 0.68 compared to 0.42. At 85 dB SPL the threshold differences were smallest, and perhaps of the magnitude to expect from hearing-impaired subjects. If the threshold differences give enough information there is no special interest in calculating the MTF-STI. On the contrary, in a clinic it might be most convenient just to inspect the level dependence of the threshold differences.

A similar performance for hearing-impaired subjects should mean a great potential for fitting hearing instruments. Placing the speech sounds at the sound pressure level with the largest span between thresholds at the peak and in the valley should, according to the MTF-STI-theory, give optimal speech recognition. Naturally, it would be very valuable to be able to predict absolute speech recognition from the threshold differences. However, there are certainly more abilities than those measured in this test involved in speech recognition. Thus, it would be welcome enough to find and be able to use the optimal sound pressure levels of an ear to reach optimal speech recognition scores for that particular ear wherever those scores are placed on an absolute scale.

B. Tone thresholds at the peak and in the valley

The thresholds at the peak show a level dependence corresponding to the phenomenon described by Carlyon and Moore (1984, 1986) as a "severe departure" from Weber's law. They ascribe the deterioration in sensitivity between 25 and 55 dB to a saturation in firing response in most of the VIIIth-nerve fibres: This regards 6.5 kHz, where phase-locking is absent. However, in the latter paper, describing an experiment in which a masker is gated on and off in each signal interval, the effect is obvious for a short tone, 20 ms, also at 4 kHz although not at 500 Hz. There is also an increase in sensitivity above 65 dB. This corresponds very well to the peaks we have got at 55 to 65 dB SPL. But there are several differences between the experiments: in the noise, in gating versus full intensity modulation; in duration of the test tone, our test tone is shorter, 4 ms; and in the results, we have got some level dependence at all frequencies tested, even at 500 Hz.

Katsuki, Suga and Kanno (1962) presented results indicating two populations of neurons, a large one with maximum number of thresholds around 30 -40 dB SPL and a small one with its maximum number around 75 dB SPL. Around 60 dB SPL there are very few neuron thresholds, resulting in a decrease in sensitivity, as pointed out and shown on students by Campbell (1964). Our results agree very well with this. Liberman (1978), confirmed the existence of a population of neurons with high thresholds and low spontaneous firing rates.

Pickles (1988) summarizes the probable causes of response from inner and outer hair cells like this (p.161): "The stereocilia of inner hair cells do not contact the tectorial membrane directly, and so are probably moved by viscous drag of the surrounding fluid. At low frequencies, therefore, inner hair cells respond to the **velocity** of the basilar membrane. The stereocilia of outer hair cells, on the other hand, make contact with the tectorial membrane, and outer hair cells respond to the **displacement** of the membrane. Inner hair cells therefore seem suited to detecting the a.c. component in the response of the basilar membrane, which they signal to the central nervous system. Outer hair cells respond to the d.c. as well as the a.c. component. It is possible that the outer hair cell afferents signal the d.c. component in the response of the basilar membrane."

The thesis by Brundin (1991) describes the mobile behaviour of the motion of the reticula lamina, the surface below the stereocilia. She describes frequency-specific length changes of the outer hair cells following the envelope of the stimulus and with intensity dependent amplitude. In addition the recticular lamina showed a displacement, like a kick, in a narrow frequency interval. This displacement response followed the duration of the tone and was more sharply tuned than the vibration response. It showed saturation, causing a broader tuning, and fatigue. Damage of the outer hair cells meant a smaller displacement response, which leads to the conclusion that the displacement response is generated by the outer hair cells. She proposes that the displacement response is transmitted to the inner hair cell either via the tectorial membrane or by a radial motion of the reticular lamina. Thereby a sharply tuned shearing motion perceived by only a few inner hair cells should cause a sharply tuned neural response.

All this might be the underlying process for the amplitude function of the basilar membrane shown by Johnstone, Patuzzi and Yates (1986). It shows a saturating part with saturation at 40-80 dB SPL, explained by an active process, followed by a linear part at higher levels, explained by a passive process. *The total function agrees well with the nonlinearity found in our results*.

Out of the frequencies we tested, 500 Hz is the only one producing a dominating a.c. component in the intracellular voltage of the inner hair cell according to Palmer and Russel (1986). In our results the mean thresholds at the peak at 500 Hz are constant (within the standard deviation) up to 65 dB SPL. At the higher octave frequencies the thresholds increase up to about 65 dB SPL. At 2 and 4 kHz the thresholds are influenced also by the modulation frequency. It is possible that both level dependence and influence of modulation frequency may be ascribed to the behaviour of the outer hair cells: The more dominating the d.c. component in the response of the basilar membrane (here caused by the modulated noise) the more the outer hair cells influence the response, and the more their number and possible delays in their feedbacksystem, caused by the character of the sound stimulus or by pathology, influence the thresholds.

The intimate relation between frequency selectivity and temporal phenomena indicated by Brundin's work has also been found by e.g. Hall and Grose (1989) for modulation masking release at 15 Hz modulation frequency (the lowest modulation frequency they tested).

The thresholds in the valley show a level dependence at higher modulation frequencies like that of the thresholds at the peaks of the noise. It seems reasonable to believe that this is a result of limited recovery after the peaks. Actually for the highest modulation frequency, 20 Hz, the threshold in the valley is sometimes higher than the corresponding threshold at the peak. This finding is consistent with the finding of Scott and Humes (1990). They report a phase-shift at higher modulation frequencies. However, they measured with broadband noise, and the phase-shift occured at a higher modulation frequency (64 Hz amplitude-modulation).

Humes (1990) reports results from tests with amplitude modulated, speech-shaped masking noise and various tone and modulation frequencies. Tone thresholds at the peak and in the valley at one sound pressure level are shown as functions of modulation frequency. The slopes of the functions are the same as for the corresponding parameters in our data. However the span between peak and valley thresholds is not as large in our data as in Humes'. The most obvious difference between our approaches is the bandwidth of the noise, which might be responsible for the difference in span.

Also comparisons to Ahlstrom's (1984) peak and valley thresholds reveal a larger span for the speech noise than ours. However, Ahlstrom's results for high pass and broad band noise show smaller threshold differences. Our results seem to fall somewhere between his high pass and speech noise data which is not unreasonable. To which extent the discrepancies depend on noise spectra and test method remains to be explained. The noise in our Békésy-method is continous in contrast to the noise used in 2IFC-methods.

Threshold differences similar to ours have been reported by Hall, Davies, Haggard and Pillsbury (1988) considering one test condition measuring comodulation masking release by means of thresholds at the peak and in the valley. The result comparable to ours regards the difference between thresholds for a 400 ms, 1 kHz tone in unmodulated noise at 1 kHz, bandwidth 1 kHz, and the same noise modulated with a 15 Hz square wave.

In brief there has been several investigations dealing with problems more or less closely related to ours. However, none of them includes more than a very small part directly comparable to our test conditions, and the level dependence has not been investigated before. There are always differences in signals too, e.g. in bandwidth and duration of the noise, and in duration of the test tone. The results are partly concordant to, partly deviating from ours, the main differences being the size of the threshold differences, the rapid detoriation of the PMTFs (decrease of threshold differences) with increasing modulation frequency, and the departure from Weber's law also at lower frequencies. Physiological research so far faintly outlines a possible explanation by the function of the outer hair cells.

IV. CONCLUSIONS

- For young normal-hearing subjects there is a level dependence of thresholds for 4 ms tones in intensity-modulated octave band noise modulated with frequencies up to 20 Hz.

- There is a maximum in the difference between thresholds at the peak and in the valley of the noise at 55 to 65 dB SPL. This occurs at the same levels as the best SRT in noise. The shapes of the level dependence of the threshold difference and the SRT are similar, indicating that an approach like the one used for the MTF-STI-method is worth trying.

- The peaked level dependence of the thresholds at the peak of the noise adds some information on "a severe departure" from Weber's law.

- Thresholds in the valley are highly dependent of modulation frequency: Lower modulation frequencies give lower thresholds.

- The results might be explained by the qualities of the outer hair cells.

It remains to be tested if hearing-impaired subjects show similar patterns. If so, it should be investigated if the knowledge can be used for hearing instrument fitting, placing the speech sounds at the sound pressure levels with the best capacity to gain maximum speech recognition. Results from such an investigation will follow in another report.

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TABLES

TABLE I.

Thresholds for short tones at the peak and in the valley of modulated octave band noise, and the difference between these thresholds, at various octave frequencies, modulation frequencies and sound pressure levels. Tone frequency equal to octave centre frequency. Mean values over 17 normal-hearing ears, in dB relative to the noise, with an arbitrary reference level.

Octave, kHz	Mod. freq., Hz	Thresh. pos./ diff.	Sound pressure level, dB 45	55	65	75	85
0.5	1.25	peak	68.0	69.6	69.8	66.2	62.3
		valley	51.9	49.2	47.7	48.2	49.5
		diff.	16.1	20.4	22.1	18.0	12.8
	2.5	peak	68.7	70.1	70.1	66.3	61.7
		valley	55.3	54.5	54.4	55.8	54.9
		diff.	13.3	15.6	15.7	10.5	6.8
	5.0	peak	68.1	69.7	70.0	66.6	62.4
		valley	59.6	58.5	59.6	60.5	57.7
		diff.	8.5	11.2	10.4	6.1	4.7
	10.0	peak	69.1	70.4	71.0	67.1	63.4
		valley	63.7	64.3	65.8	64.7	61.4
		diff.	5.4	6.1	5.2	2.4	2.0
	20.0	peak	67.8	69.1	69.4	65.9	62.8
		valley	65.8	66.6	68.2	66.0	63.1
		diff.	2.0	2.5	1.2	-0.1	-0.3
1.0	1.25	peak	68.9	71.5	71.7	67.0	62.9
		valley	51.0	48.1	46.9	49.1	50.7
		diff.	17.9	23.4	24.8	17.9	12.3
	2.5	peak	70.2	73.4	71.7	66.3	61.1
		valley	55.0	54.0	55.8	57.7	55.7
		diff.	15.3	19.4	16.0	8.7	5.4
	5.0	peak	70.9	73.7	72.2	66.3	61.9
		valley	58.6	58.9	61.0	61.0	58.2
		diff.	12.3	14.8	11.2	5.3	3.7
	10.0	peak	71.1	74.3	72.9	67.4	63.3
		valley	62.6	64.1	66.7	64.4	61.0
		diff.	8.5	10.1	6.2	3.0	2.3
	20.0	peak	70.5	73.4	72.3	67.0	62.6
		valley	64.9	68.1	70.0	66.1	62.2
		diff.	5.6	5.3	2.3	1.0	0.4

TABLE I continued.

Octave, kHz	Mod. freq., Hz	Thresh. pos./ diff.	Sound pressure level, dB 45	55	65	75	85
2.0	1.25	peak	71.0	73.2	74.8	69.9	66.2
		valley	52.1	49.4	48.0	48.7	51.4
		diff.	18.9	23.7	26.9	21.2	14.9
	2.5	peak	72.0	75.5	75.6	69.9	65.3
		valley	55.7	54.3	55.4	57.3	57.4
		diff.	16.3	21.2	20.2	12.7	7.8
	5.0	peak	72.3	76.3	76.4	70.6	66.1
		valley	59.8	59.7	62.0	63.1	60.4
		diff.	12.5	16.6	14.3	7.5	5.7
	10.0	peak	73.7	78.1	77.4	71.8	66.7
		valley	65.3	66.9	69.3	67.3	63.0
		diff.	8.4	11.2	8.0	4.4	3.7
	20.0	peak	75.1	78.9	77.0	71.3	66.8
		valley	69.6	71.4	73.0	69.2	64.9
		diff.	5.4	7.6	3.9	2.1	1.9
4.0	1.25	peak	70.5	72.0	72.6	69.6	67.0
		valley	53.8	50.9	50.2	49.2	52.1
		diff.	16.8	21.1	22.4	20.4	14.9
	2.5	peak	71.6	73.2	73.5	69.8	66.5
		valley	57.4	56.0	55.6	57.1	56.8
		diff.	14.2	17.3	17.9	12.7	9.7
	5.0	peak	73.4	75.6	75.4	71.7	67.9
		valley	61.2	61.0	61.6	61.0	59.9
		diff.	12.3	14.6	13.9	10.7	8.0
	10.0	peak	75.8	77.0	76.9	72.1	68.1
		valley	67.0	66.6	67.0	65.7	63.5
		diff.	8.8	10.5	9.8	6.4	4.6
	20.0	peak	76.7	78.6	77.4	72.4	68.4
		valley	70.3	70.9	69.7	67.1	65.5
		diff.	6.4	7.7	7.7	5.2	2.9

TABLE II.

Thresholds for short tones at the peak and in the valley of modulated octave band noise, and the difference between these thresholds, at various octave frequencies, modulation frequencies and sound pressure levels. Tone frequency equal to octave centre frequency. Standard deviations, in dB, over 17 normal-hearing ears.

Octave, kHz	Mod. freq., Hz	Thresh. pos./ diff.	Sound pressure level, dB 45	55	65	75	85
0.5	1.25	peak	3.10	2.66	2.74	3.20	2.79
		valley	2.92	2.63	2.92	2.84	2.08
		diff.	1.91	2.44	3.79	4.24	3.15
	2.5	peak	2.86	2.83	2.52	2.52	2.54
		valley	3.09	3.22	3.38	2.89	2.45
		diff.	2.00	2.58	4.03	3.00	2.21
	5.0	peak	3.45	3.26	2.79	2.69	2.40
		valley	3.35	3.36	2.97	2.75	2.16
		diff.	2.42	2.99	3.11	2.58	2.02
	10.0	peak	3.09	3.40	2.67	2.85	2.45
		valley	3.44	3.38	3.41	2.10	2.26
		diff.	2.21	2.78	2.88	1.67	1.30
	20.0	peak	3.81	3.42	3.00	2.45	2.47
		valley	3.84	3.99	3.38	2.82	2.01
		diff.	1.46	2.34	1.75	1.29	1.57
1.0	1.25	peak	3.29	3.53	3.84	3.07	2.58
		valley	2.73	2.85	2.62	4.40	4.08
		diff.	3.31	3.70	4.51	4.92	4.03
	2.5	peak	3.72	4.37	4.45	3.69	3.67
		valley	2.95	2.97	3.92	3.99	3.21
		diff.	2.96	4.10	4.58	3.79	2.72
	5.0	peak	4.42	4.34	3.90	3.57	2.94
		valley	2.74	3.52	4.08	3.36	2.92
		diff.	3.59	3.27	4.55	2.24	2.08
	10.0	peak	3.11	3.68	4.22	3.40	2.11
		valley	2.74	3.30	3.75	3.04	2.51
		diff.	2.39	2.92	2.77	1.53	1.72
	20.0	peak	4.05	4.87	4.06	3.49	2.50
		valley	3.80	5.40	4.41	3.66	2.29
		diff.	2.18	3.29	2.35	1.25	1.49

TABLE II continued.

Octave, kHz	Mod. freq., Hz	Thresh. pos./ diff.	Sound pressure level, dB 45	55	65	75	85
2.0	1.25	peak	4.22	4.59	3.25	2.75	2.64
		valley	3.46	3.87	4.64	5.58	5.33
		diff.	3.72	4.49	5.60	6.52	4.36
	2.5	peak	4.71	4.46	3.84	2.96	2.80
		valley	3.79	5.08	6.18	5.62	3.44
		diff.	3.52	4.46	6.74	5.68	3.12
	5.0	peak	5.08	4.44	3.74	2.62	2.51
		valley	4.40	4.52	5.12	4.28	2.85
		diff.	3.91	3.78	5.56	3.88	2.35
	10.0	peak	4.99	4.80	3.16	2.33	2.31
		valley	5.46	5.92	5.24	3.26	3.13
		diff.	2.66	4.10	4.76	2.85	2.57
	20.0	peak	4.78	4.37	3.71	2.39	2.33
		valley	6.05	5.99	4.41	3.27	2.83
		diff.	2.77	4.82	3.77	2.49	2.47
4.0	1.25	peak	4.02	4.76	4.04	3.15	2.60
		valley	4.15	4.36	5.33	5.96	5.34
		diff.	4.48	3.85	5.04	5.72	5.19
	2.5	peak	5.18	4.88	4.32	3.59	2.87
		valley	4.14	4.57	5.47	6.19	4.34
		diff.	4.01	3.68	4.96	6.52	3.36
	5.0	peak	5.70	5.75	4.48	3.83	3.00
		valley	4.07	5.57	5.83	5.09	3.78
		diff.	4.11	4.66	4.28	4.82	2.96
	10.0	peak	5.66	5.58	3.95	3.73	3.24
		valley	5.12	4.85	5.71	4.28	4.29
		diff.	3.30	3.59	5.46	3.85	2.75
	20.0	peak	5.65	4.64	3.92	3.74	2.99
		valley	6.27	6.42	6.46	4.86	3.98
		diff.	3.65	4.13	4.99	4.82	2.76

TABLE III.

Variance analyses for thresholds and threshold differences. Significance level at least $p<0.01$ for all variables and combinations of variables:
S, subject; B, octave band; M, modulation frequency; L, noise level.

Source of variation	Sum of squares	d.f.	Mean square	F-ratio	Variance accounted for, %
Difference, top-valley thresholds:					
S	8180.	16	511.2		4
B	5899.	3	1966.	20.	3
M	105200.	4	26300.	610.	55
L	27420.	4	6856.	92.	14
SxB	4629.	48	96.44		2
SxM	2740.	64	42.81		1
BxM	1180.	12	98.31	9.7	1
SxL	4777.	64	74.64		2
BxL	1957.	12	163.1	5.4	1
MxL	5686.	16	355.4	33.	3
SxBxM	1955.	192	10.18		
SxBxL	5833.	192	30.38		
SxMxL	2765.	256	10.80		
BxMxL	827.8	48	17.24	2.5	
SxBxMxL	5310.	768	6.914		
Within cell	8404.	1700	4.944		
Total	192762.8				
Threshold at the top:					
S	13330.	16	833.1		13
B	16800.	3	5601.	37.	16
M	2377.	4	594.3	50.	2
L	38060.	4	9514.	110.	36
SxB	7325.	48	152.6		7
SxM	759.7	64	11.87		
BxM	1367.	12	113.9	19.	1
SxL	5637.	64	88.08		5
BxL	1183.	12	98.61	3.5	1
MxL	526.2	16	32.89	11.	
SxBxM	1157.	192	6.025		
SxBxL	5480.	192	28.54		4
SxMxL	793.5	256	3.100		
BxMxL	534.9	48	11.14	5.1	
SxBxMxL	1674.	768	2.179		
Within cell	8812.	1700	5.183		
Total	105816.3				

TABLE III continued.

Source of variation	Sum of squares	d.f.	Mean square	F-ratio	Variance accounted for, %
Threshold in the valley:					
S	18640.	16	1165.		9
B	2956.	3	985.3	4.7	1
M	137900.	4	34460.	700.	67
L	1476.	4	368.9	12.	1
SxB	10090.	48	210.2		5
SxM	3136.	64	49		1
BxM	783.6	12	65.3	4.9	
SxL	1995.	64	31.18		1
BxL	666.	12	55.5	4.9	
MxL	5897.	16	368.6	38.	3
SxBxM	2561.	192	13.34		
SxBxL	2174.	192	11.32		
SxMxL	2458.	256	9.603		
BxMxL	629.	48	13.11	2.2	
SxBxMxL	4521.	768	5.887		
Within cell	11440.	1700	6.727		
Total	207332.7				

TABLE IV.

Standard deviation at replication, in dB, for the difference between thresholds at the peak and in the valley.					
	Octave, kHz	Mod.fr, Hz	Females N=7	Males N=9	Total N=16
2 repl. on different days	all	all	2.20	2.25	2.22
2 repl. in succession	0.5	5	1.63	1.74	1.70
	2	5	1.73	1.49	1.60
	4	5	3.03	1.47	2.29
	2	2.5	1.25	2.38	1.95
	total		2.03	1.80	1.90
6 repl. in succession	0.5	5	1.72	1.99	1.88
	2	5	1.90	1.65	1.75
	4	5	2.51	2.39	2.44
	2	2.5	1.81	2.04	1.94
	total		2.01	2.03	2.02

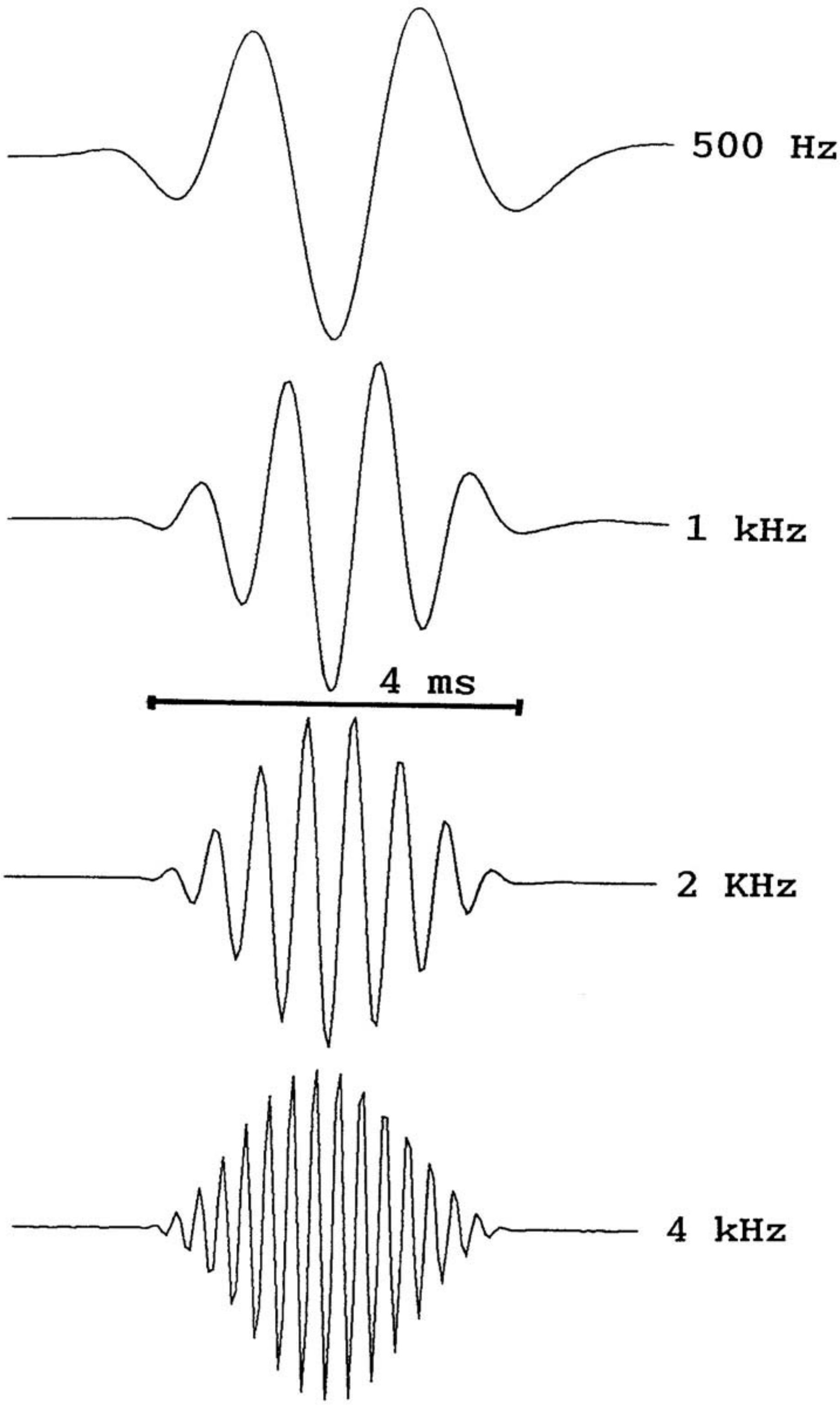

FIG. 1. Test tone.

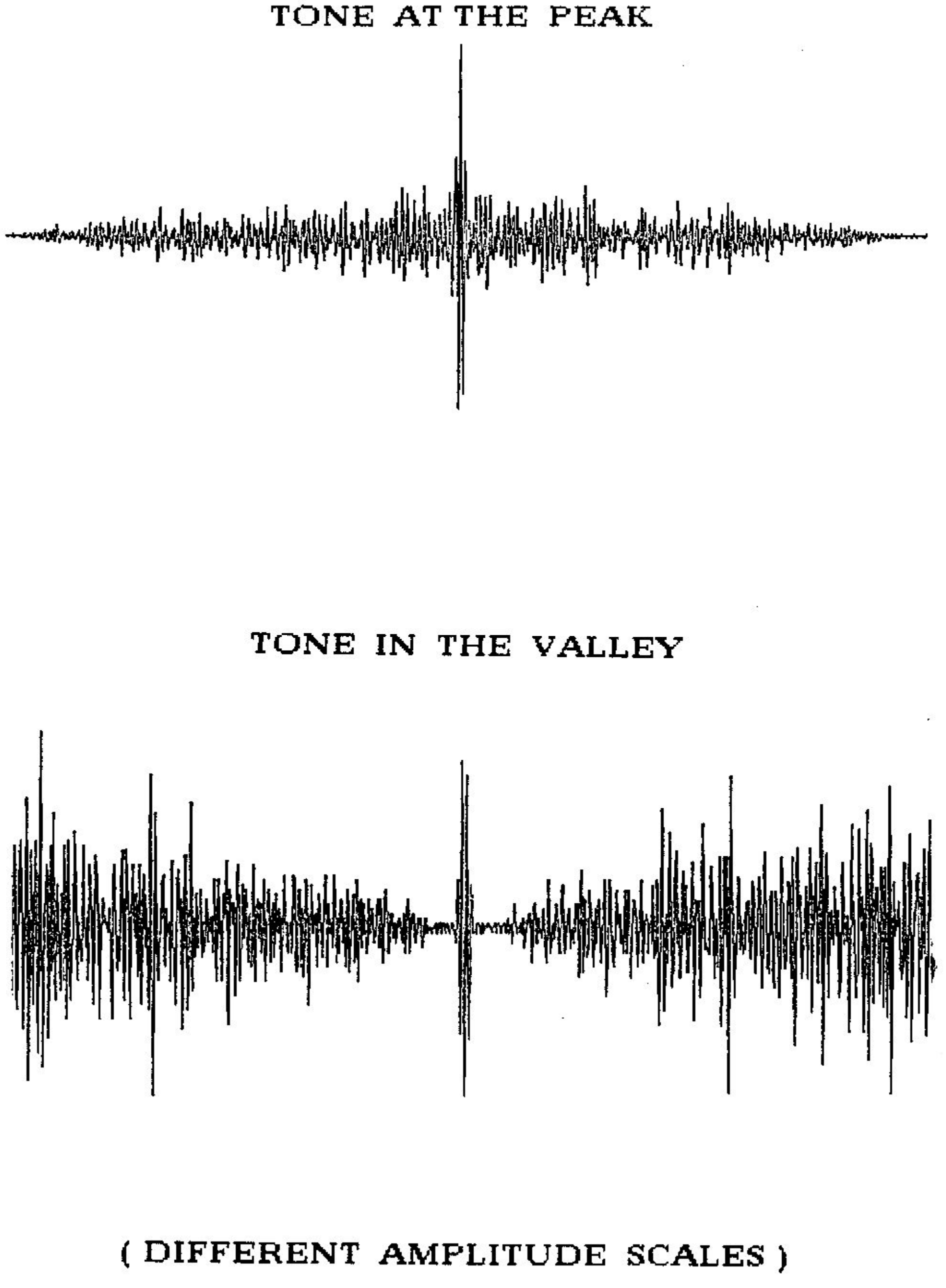

FIG. 2. Examples of test tone at the peak and in the valley of the modulated noise.

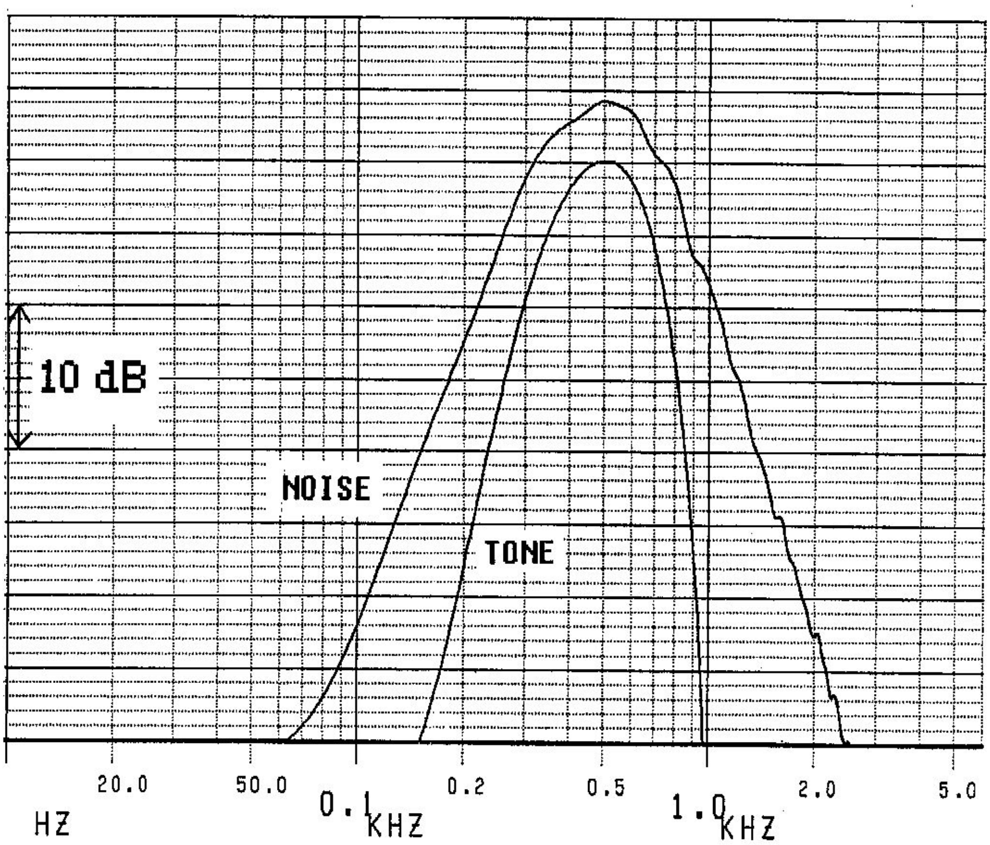

FIG. 3. Spectra of test tone and octave band noise at 500 Hz, worst case.

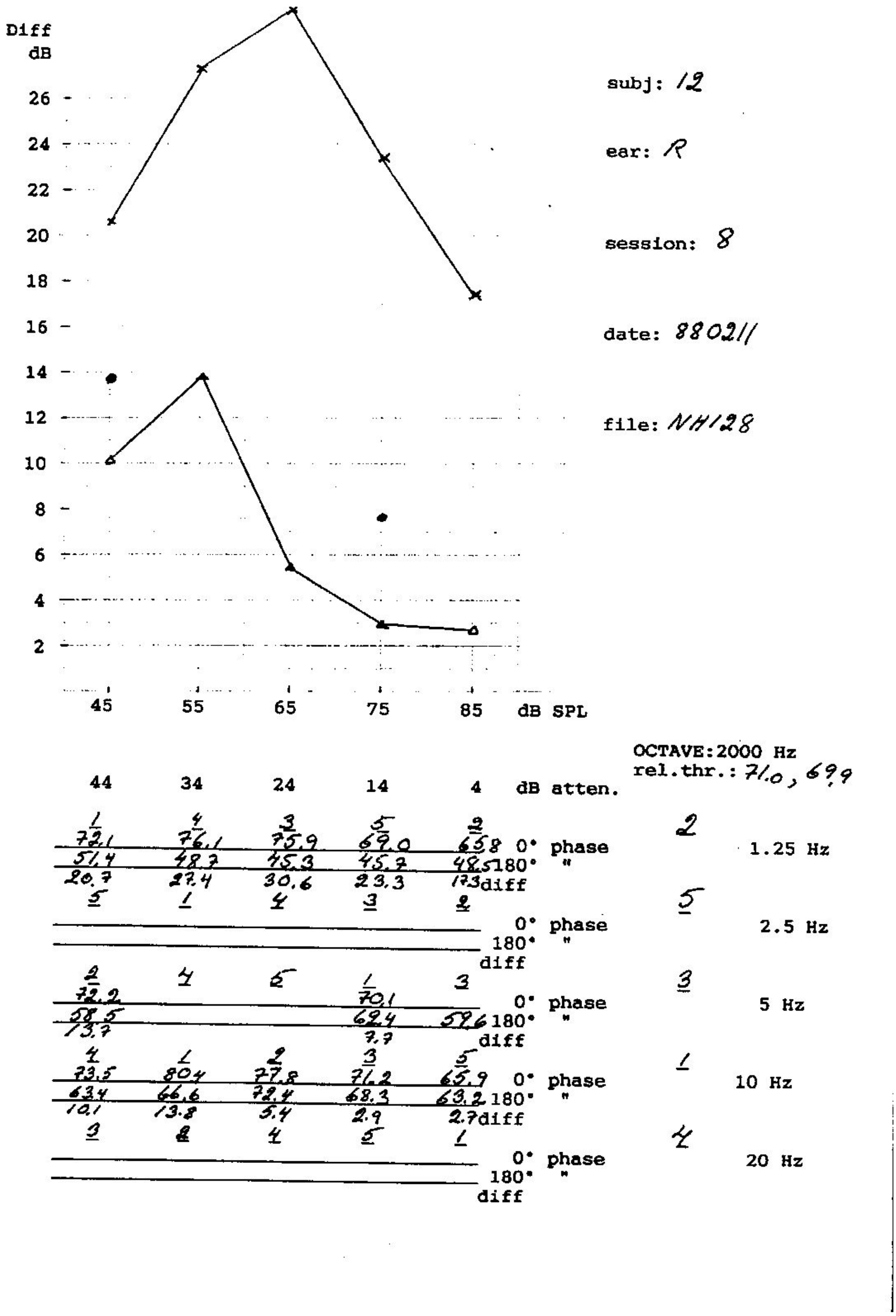

FIG. 4. Example of test sheet, 2000 Hz.

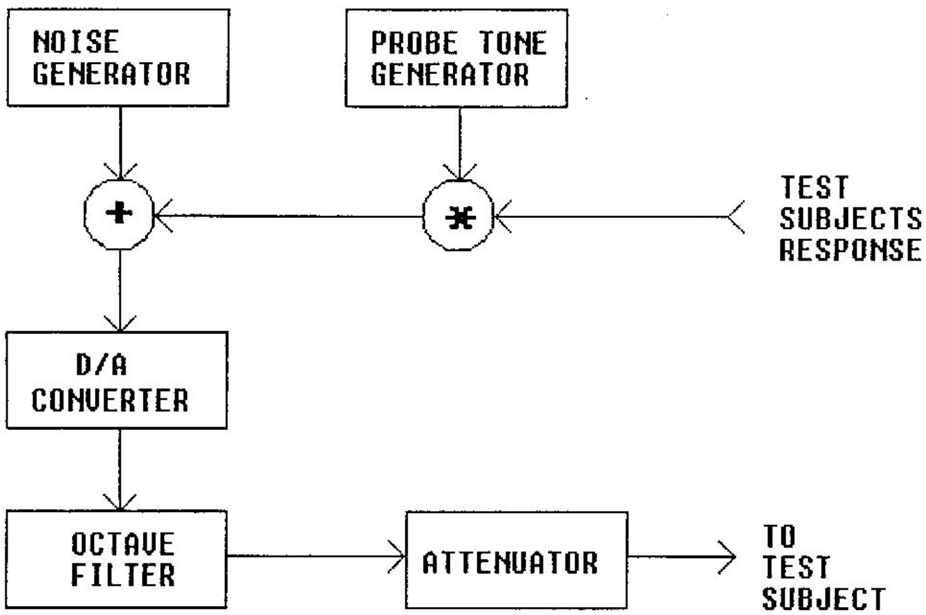

FIG. 5. General principle of test equipment.

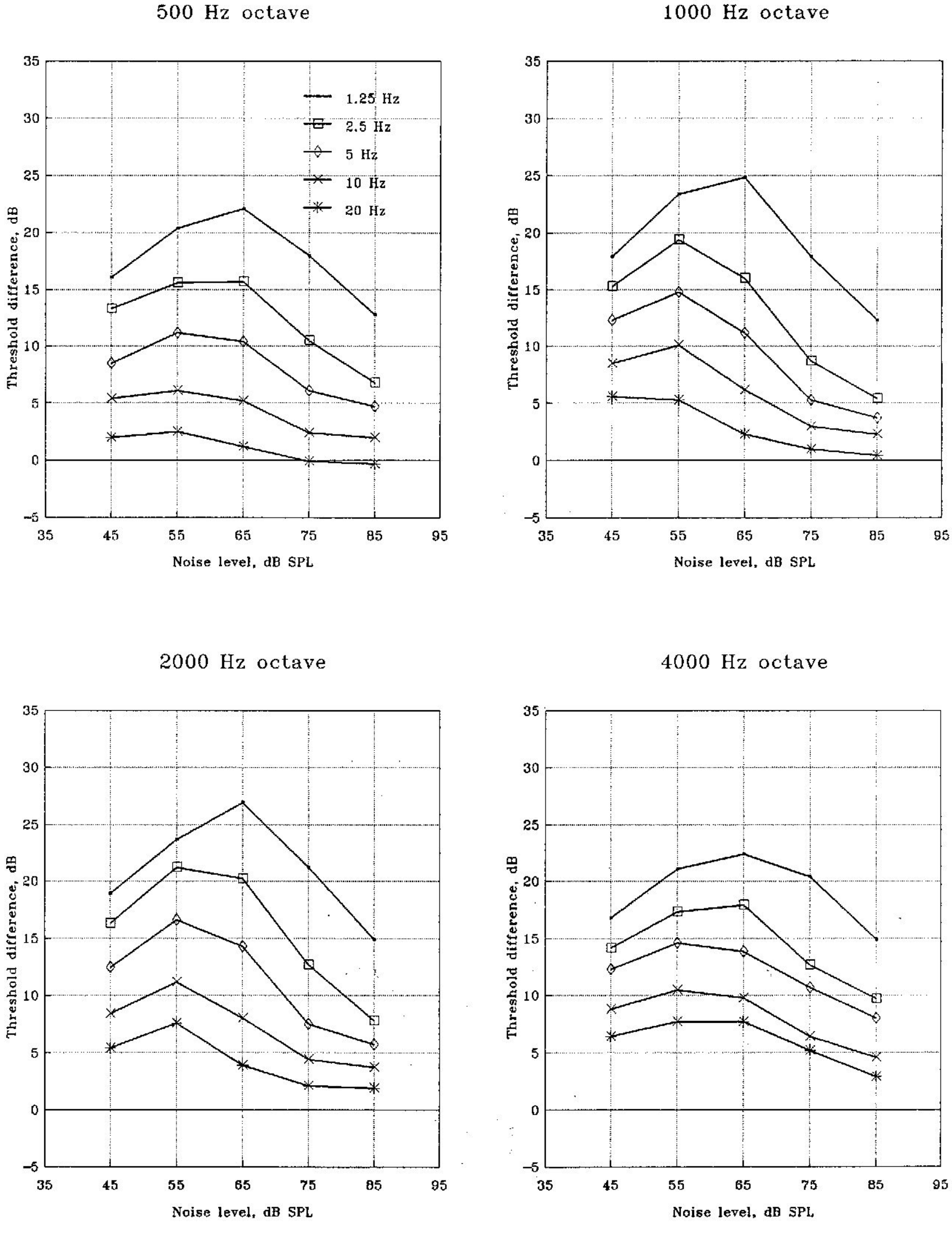

FIG. 6. Difference between thresholds at the peak and in the valley of the intensity-modulated octave band noise. Means over 17 young normal-hearing ears at four octave and five modulation frequencies.

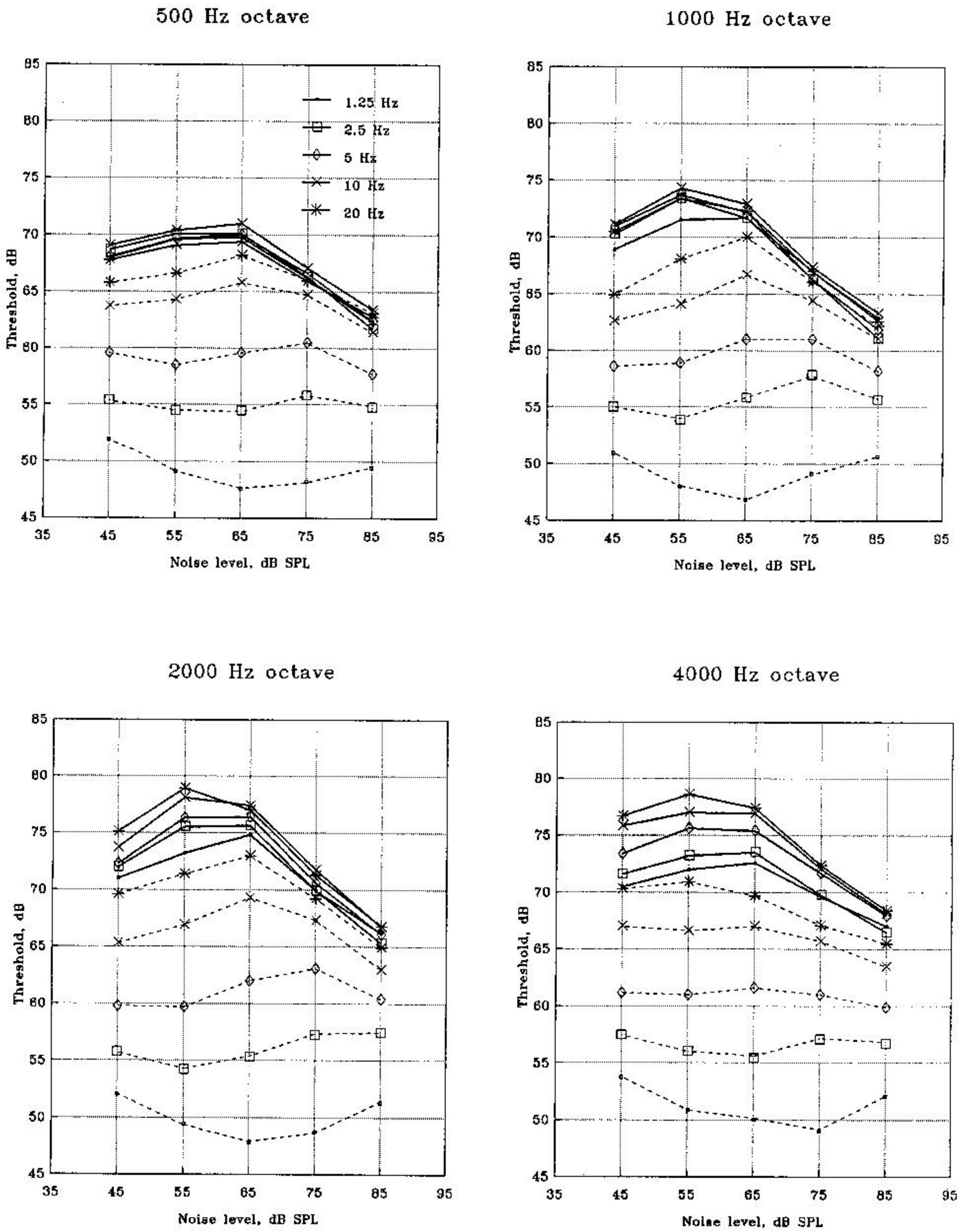

FIG. 7. Thresholds at the peak (solid lines) and in the valley (dotted lines) of the intensity-modulated octave band noise. Means over 17 young normal-hearing ears at four octave and five modulation frequencies. Thresholds expressed relative to the noise, with an arbitrary reference level, not in dB SPL.

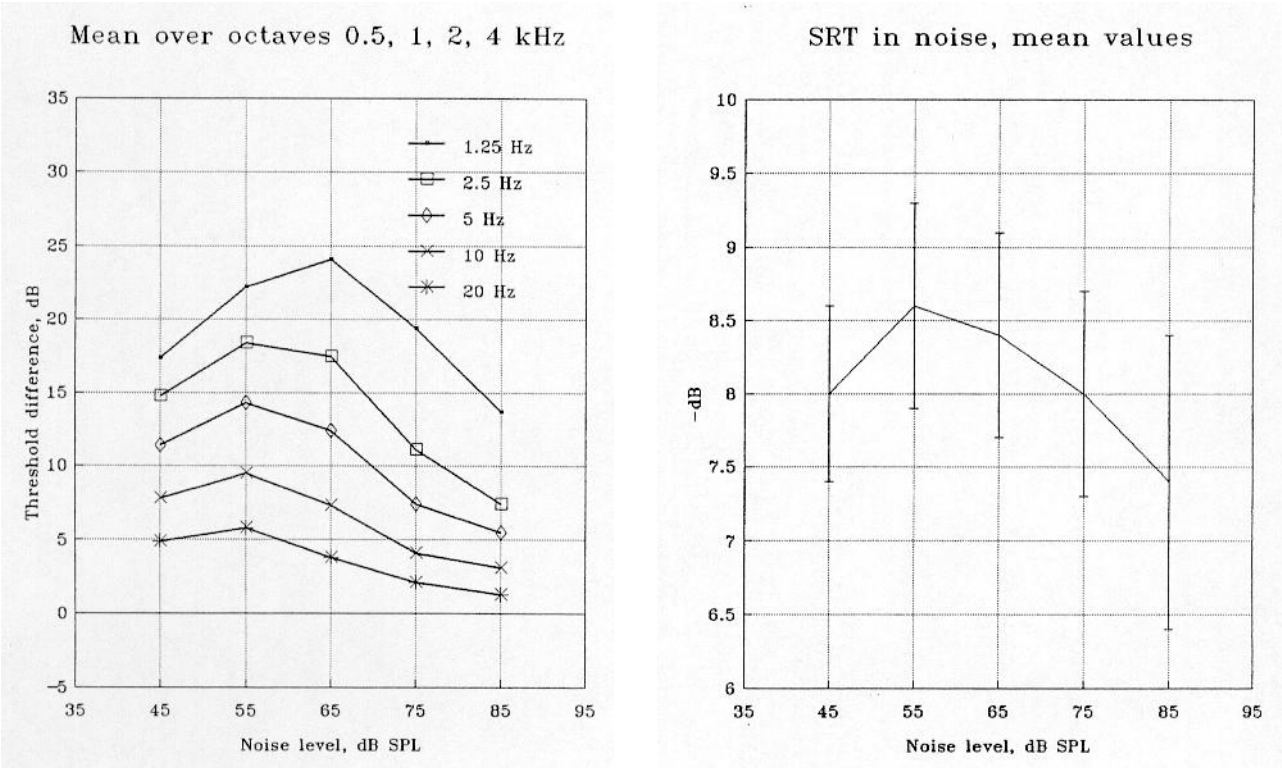

FIG. 8. To be compared: Means, over four octaves, of difference between peak and valley thresholds and SRTs in noise. 17 young normal-hearing ears. Note the reversed dB-scale for the SRT in noise.

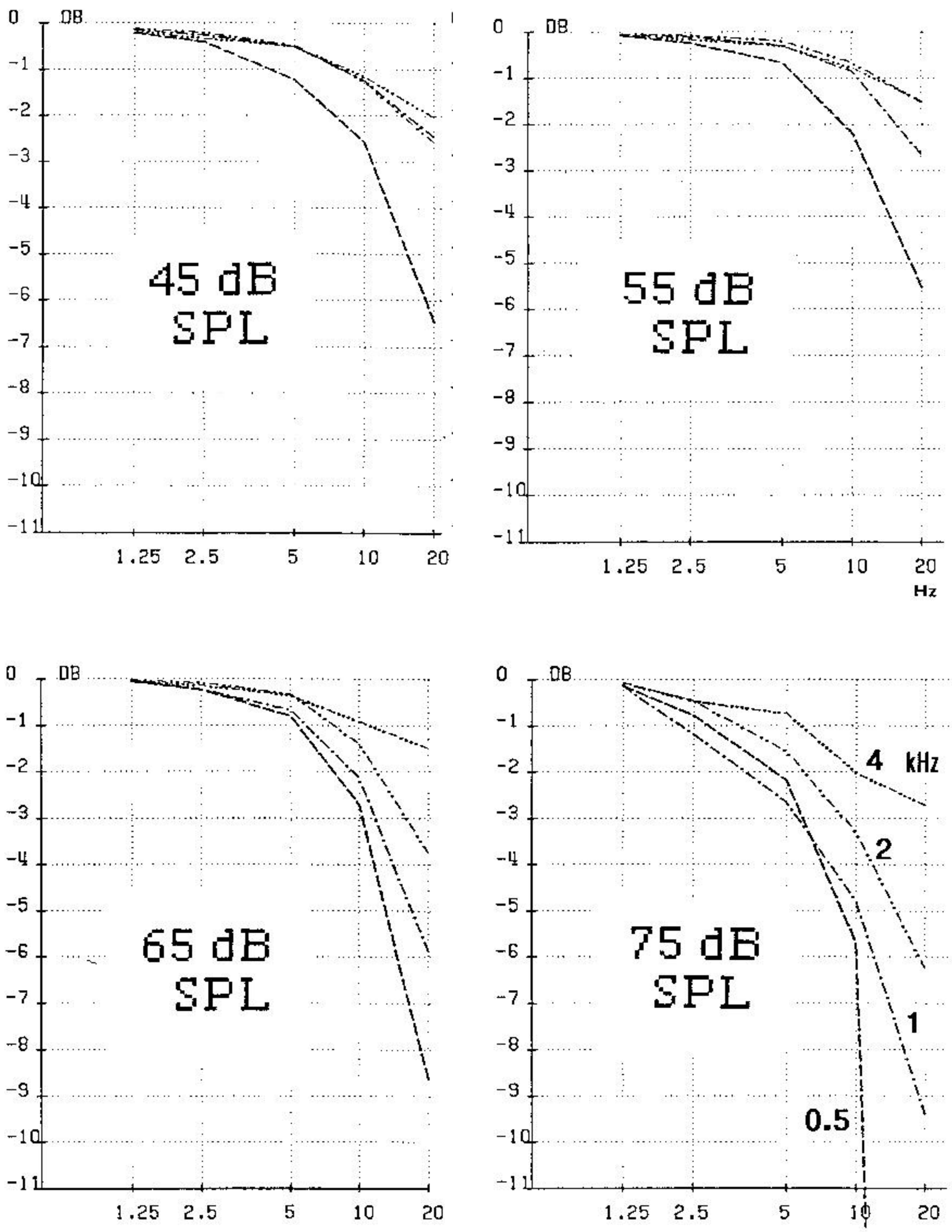

FIG. 9. Psychoacoustical Modulation Transfer Functions at four sound pressure levels. 17 young normal-hearing ears.

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*TA92	1978	Statistical treatment of data from listening tests on sound-reproducing systems. *A Gabrielsson*
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*TA85	1977	Adjective ratings and dimension analyses of perceived sound quality of hearing aids. III. *A Gabrielsson, H Sjögren*
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*TA76	1975	Similarity ratings and dimension analyses of perceived sound quality of hearing aids. *A Gabrielsson, H Sjögren*
*TA75	1974	Adjective ratings and dimension analyses of perceived sound quality of hearing aids. I. *A Gabrielsson, H Sjögren*
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TA69	1972	Frequency discrimination for bands of noise. *A Gabrielsson, B Johansson, A-C Lindblad, A Pettersson, B Rosenqvist*
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