DETECTION AND LOUDNESS OF AM SIGNALS FOR NORMAL AND HEARING-IMPAIRED SUBJECTS

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The study comprises two experiments pertaining to the perception of sounds with parameters changing in time, by normal-hearing subjects and by hearing-impaired subjects, who had a sloping high-frequency hearing loss originating from a cochlear impairment. The first experiment deals with the determination of the AM detection thresholds, for 3 normal-hearing and 3 cochlear-impaired subjects. In the second experiment, the loudness of AM signals of different parameters, relative to the loudness of a sinusoidal tone was determined by the same group of subjects. Measurements were made for carrier frequencies (f_c) equal to: 250, 500, 1000, 2000 Hz, and for modulation frequencies (f_m) equal to: 4, 8, 64, 128, 256 Hz. It was stated that for low f_m the determined detection thresholds for the normal-hearing subjects were roughly similar to those for the cochlear-impaired subjects. However, for higher f_m, the thresholds decrease for the normal-hearing subjects, whereas they tend to increase for the hearing-impaired subjects. Thus, one can assume that for higher f_m, temporal resolution of the auditory system is significantly affected by cochlear hearing loss. As regards the loudness of AM signals, the data showed that for f_m greater than the critical band, the loudness of AM signals increased with f_m for the normal-hearing subjects, whereas it remained independent of f_m for the hearing-impaired subjects.

1. Introduction

The ability to resolve amplitude changes of a signal in time is of crucial importance for the auditory processing of complex sounds such as speech or music. One way to determine auditory amplitude resolution for different rates of its changes is to measure the smallest amount for amplitude modulation, just-noticeable by a subject. The plot of the AM detection threshold againts modulation frequency is called the temporal modulation transfer function (TMTF) and is considered as a general description of the auditory temporal resolution. ZWICKER [40], using a 1-kHz carrier at 60 dB SPL compared modulation thresholds for sinusoidal AM and FM. Zwicker has shown that for the AM detection threshold there was a slight (2 dB) decrease in threshold around 4 Hz, followed by a 3 dB/oct increase in threshold up to

modulation frequency equal to approximately 60 Hz. Above 60 Hz, the AM detection threshold decreases again. Other data from Zwicker indicate that the shape of the threshold over the lower modulation frequency region is independent of the level and carrier frequency. The fact that for higher modulation frequencies the subjects resolve the spectral components of AM sinusoids (i.e. use the spectral cues to determine the threshold), limits in a sense the application of sinusoidal carriers for determining TMTFs. To diminish possible spectral cues, wideband noise as a carrier was used in different studies (ZWICKER and FELDTKELLER [43]; RODENBURG [28]; VIEMEISTER [38, 39]; BACON and GLEITMAN [2]; MOORE et al. [25]). For such a carrier, the long-time power spectrum of sinusoidal AM noise is uniform and invariant with changes in modulation frequency. The mentioned papers suggest that for low modulation frequency (above about 5 Hz), the TMTF shows a lowpass characteristic with a relatively high cutoff frequency and a low attenuation rate. The papers are not fully consistent as the parameters of the characteristic are concerned, and to whether or not there is a highpass segment at a low modulation frequency. BACON and VIEMEISTER [1], using sinusoidal AM noise stated, that TMTFs are similar, in the limit of error, for normal and hearing-impaired subjects at low modulation frequencies and worse for impaired subjects at high modulation frequencies.

The modulation threshold procedure using a broadband noise as a carrier has some limitations. The TMTF cannot be obtained for large modulation indexes and for precisely localized spectral regions. Besides, keeping a constant SL through a bandwidth of a broadband carrier often creates problems. Only a sinusoidal carrier or a narrowband carrier allow to control accurately the SL for a given frequency range. But on the other hand, this carrier can introduce some spectral cues for a subject and in this way can affect his performance.

Another approach aimed to determine the TMTFs involves measuring the threshold for a bandpass-filtered click at various temporal locations in sinusoidal AM noise (VIEMEISTER [38]; RODENBURG [28]). In this case the attenuation characteristic exhibited a lowpass from but had a greater attenuation rate than TMTF based upon the modulation threshold. Unfortunately, this procedure cannot be used to get TMTFs obtained at high modulation frequencies. The effect of the cochlear impairment on temporal resolution is not quite clear (MOORE et al. [25]), unlike frequency resolution where hearing loss affects it unequivocally (TYLER [37]; PICKLES [26]). Some papers indicate that, for example, the detection thresholds of gaps in noise stimuli are larger for subjects with sensorineural hearing loss than for subjects with normal hearing (FITZGIBBONS and WIGHTMAN [6]; FLORENTINE and BUUS [10]; GLASBERG et al. [14]). But when sinusoidal signals are used in the gap detection experiment, thresholds for hearing-impaired subjects are as good as, or even in some cases better than, those for normal-hearing subjects (MOORE and GLASBERG [23]; MOORE et al. [24]). It seems that an important parameter in this case, influencing the results, is the amplitude fluctuation which stimuli contain. The poor gap detection for stimuli with such fluctuations might result from the loudness recruitment.

Temporal resolution measures can also be affected by the sound level used. Some experimental data pertaining to temporal resolution indicate thatperformance by normal-hearing subjects worsens at low sensation levels (FLORENTINE and BUUS [9]; FITZGIBBONS [7]; VIEMEISTER [39]).

The second problem related to the hearing impairment is how loudness summates for complex sounds when impairment of the inner ear produces a high threshold and loudness recruitment. The quantitative psychophysiological approach towards the loudness summation problem was presented by ZWISLOCKI [44]. It was stated that the temporal summation of loudness is a result of neural summation at a high level of the auditory system. The basic problem in the loudness study of sounds, particularly when these are complex or transient-like sounds, is that loudness is a subjective quantity, and cannot be measured directly. One common method of loudness measurement is matching. Subjects are usually presented two sounds, one is the standard-tested stimulus, with fixed level, the other sound, as the comparison (often a 1000 Hz tone), is adjusted in level until the two stimuli are equal in laudness. In other methods subjects are asked to rate loudness of a tested stimulus on a numerical scale (direct magnitude estimation). The fundamental relation which governs the growth of loudness against the intensity is Stevens' power law. The power law asserts that loudness against the intensity is raised to the 0.3 power (or as pressure is raised to the 0.6 power). The power law suggests that a 10 dB increase in sound intensity produces a doubling in loudness. Practically, for individual subjects, this law only roughly holds true. The increase needed to double loudness changes from about 8 to 12 dB, depending upon the level of the stimulus.

An issue related to loudness estimation by subjects with hearing loss is loudness recruitment observed in cochlear-impaired subjects, whose physiological mechanism is still a subject of debate. The phenomenon exhibits an abnormality of intensity coding whereby the growth of loudness of a sound with increase in intensity is steeper than that for normal-hearing subjects. The first theory of recruitment assumed that in a set of fibers with widely differing thresholds the most sensitive receptors had been damaged. The eight nerve data rejected this theory. EVANS [5] pointed out that peripheral receptor damage often causes an elevation in the threshold and, in addition, a broadening of the frequency tuning curve. The broadening of tuning curves in individual fibers gives rise to the stimulation of more fibers for a given increase in intensity and hence a greater growth of loudness for the impaired ear. Loudness, like recruitment in general, is not fully consistent with the new information on peripheral encoding.

SCHARF and HELLMAN [32], investigated loudness of complex sounds composed of sinusoidal components as a function of the frequency spacing (ΔF) between the lowest and highest components and sensation levels. The loudness was measured for normal ears and for ears with a conductive and cochlear impairment. It was stated that subjects with normal and conductive hearing-impairment, when tested at the same sensation levels, estimate loudness in the same way. For higher sensation levels, loudness was constant within ΔF not exceeding the critical band. But for ΔF larger than the critical band loudness increased more and more with ΔF. This implies that as regards the loudness summation, a conductive impairment only changes the sen-

sitivity of the hearing mechanism, in the sense of a reduction of the sound energy that reaches the inner ear. However, for subjects with cochlear impairment, the loudness was approximately independent of the frequency spacing of the components.

LÜSCHER and ZWISLOCKI [22] reported that intensity jnd's (just noticeable differences) obtained with modulation technique, appear to be decreased by cochlear hearing loss when the comparison is made at equal SLs. A similar conclusion is reached by examining the results of SISI tests (SWISHER [35]). But, when the comparison is replotted in terms of equal SPLs, the two groups of subjects appear to perform more alike. Likewise, TURNER et al. [36] investigated intensity discrimination determined with two paradigms in normal and hearing-impaired subjects. It was stated that the jnd's obtained with the continuous-pedestal method were smaller than those obtained with the gated-pedestal method for both groups of subjects. When jnd's of the two groups were compared on the basis of equal SLs, the group with hearing loss showed smaller jnd values than the group with normal hearing for both paradigms. When the comparisons were made for equal (moderate and high) SPLs, both groups showed similar jnd values. Similar study, related to intensity jnd's at equal-loudness levels in normal and pathological ears was made by STILLMAN et al. [34]. They showed that statistically, there was no significant difference between equal-loudness jnd's in the normal and impaired ears, whereas the corresponding SLs and SPLs were significantly different.

From the above presented considerations, it is to be issued that the influence of the cochlear impairment on the perception of sounds is not univocally determined and continues to be a subject of intensive research. Particularly interesting is a closer determination of that perception with reference to signals with amplitude varying in time. Sounds of speech and music are typical examples of these signals. This prompted us to start an investigation whose basic objective was to determine the detection thereholds and the loudness of AM signals, measured by normal and cochlear-impaired subjects.

2. Experiment I. Detection thresholds for AM signals

A. Method

1. *Apparatus and stimuli*. The AM stimuli were digitally generated by an IBM-PC computer and played through 16-bit digital-to-analog converter, at a sampling rate of 20 kHz, and were low-pass filtered at 8 kHz (Tucker-Davis Technology-TDT). The overall duration of each stimulus was 1000 ms, including 20 ms rise/fall times. The stimuli were arranged in pairs, and presented at a sensation level equal to 70 dB. The onset and offset phase of the modulation signal were equal to zero.

At each trial two successive stimuli were presented, one unmodulated-sinusoidal tone (called standard) and the other AM modulated (called signal). Standard and

signal in trial were presented in a random order, and were separated by a 400 ms interval.

The measurements of the AM detection thresholds were made for the sinusoidal carriers of 250, 1000 and 4000 Hz, amplitude modulated by another sinusoidal signal of frequencies 4, 8, 64, 128, 256, and 512 Hz. The entire experiment was computer controlled.

2. Procedure and subjects. Stimuli were presented in a two-interval, two-alter-native, forced choice paradigm (2AFC). A two-down one-up adaptive procedure was used to obtain the 70.7% correct point on the psychometric function (Levitt [21]). Trials started with the depth of modulation (modulation index *m*) well above the anticipated threshold (the initial *m* value was selected on the basis of the preliminary measurements). The depth of modulation was varied by changing the amplitude of the modulation signal. Depending on the correctness of the subject's responses, the depth of modulation was changed according to the two-down one-up rule during the run. The coefficient *m* was changed by 2.0 dB until four turnpoints were reached, and then by a factor of 0.5 dB for the rest of the run. For each threshold measurement, 16 turnpoints were obtained. The threshold estimate of the modulation index *m* was calculated as an arithmetic mean of the last 10 turnpoints. The final threshold value of *m*, for the determined measurement parameters, was counted as an average of at least five single threshold estimates (50 turnpoints). In the case when the standard deviation of the final threshold estimate exceeded 20% of the mean, two additional runs were performed and all estimates were averaged.

The subject's task was to indicate, by pushing an appropriate button, which of the stimuli in a pair was amplitude modulated. Stimuli were presented monaurally to the subjects through AGH 144 headphones. Feedback of the correct answer was provided immediately after each response by light on the response box.

Three subjects with normal hearing (S1, S2, S3), and three subjects with hearing loss (S4, S5, S6) of unknown etiology participated in the experiment. Two of them (S5, S6) had unilateral-like hearing loss. At the frequency region from 125 Hz to 6000 Hz, the thresholds for the better ears for these two subjects were better than $20-30$ dB relative to the thresholds for the impaired ears. For these two subjects, AM detection thresholds and loudness estimation were determined separately for each ear. In this way it was possible to compare detection thresholds of AM signals for the better and impaired ear for the same subject. For the bilaterally impaired subject (S4), only the one ear was tested. Standard audiometric evaluations, bone-conduction thresholds, tympanometry, and acoustic reflex tests indicated that the hearing loss was of cochlear origin. Subjects were tested individually in a sound-treated chambers. Subjects with normal hearing were well experienced in the psychoacoustic ex-periments, but hearing-impaired subjects had no experience in this task. The masking noise was presented to the normal ear when testing the thresholds in the impaired ear. Audiograms for the two tested groups of subjects are included (Fig. 1). Hea-ring-impaired subjects were tested at the same SLs as normal-hearing subjects.
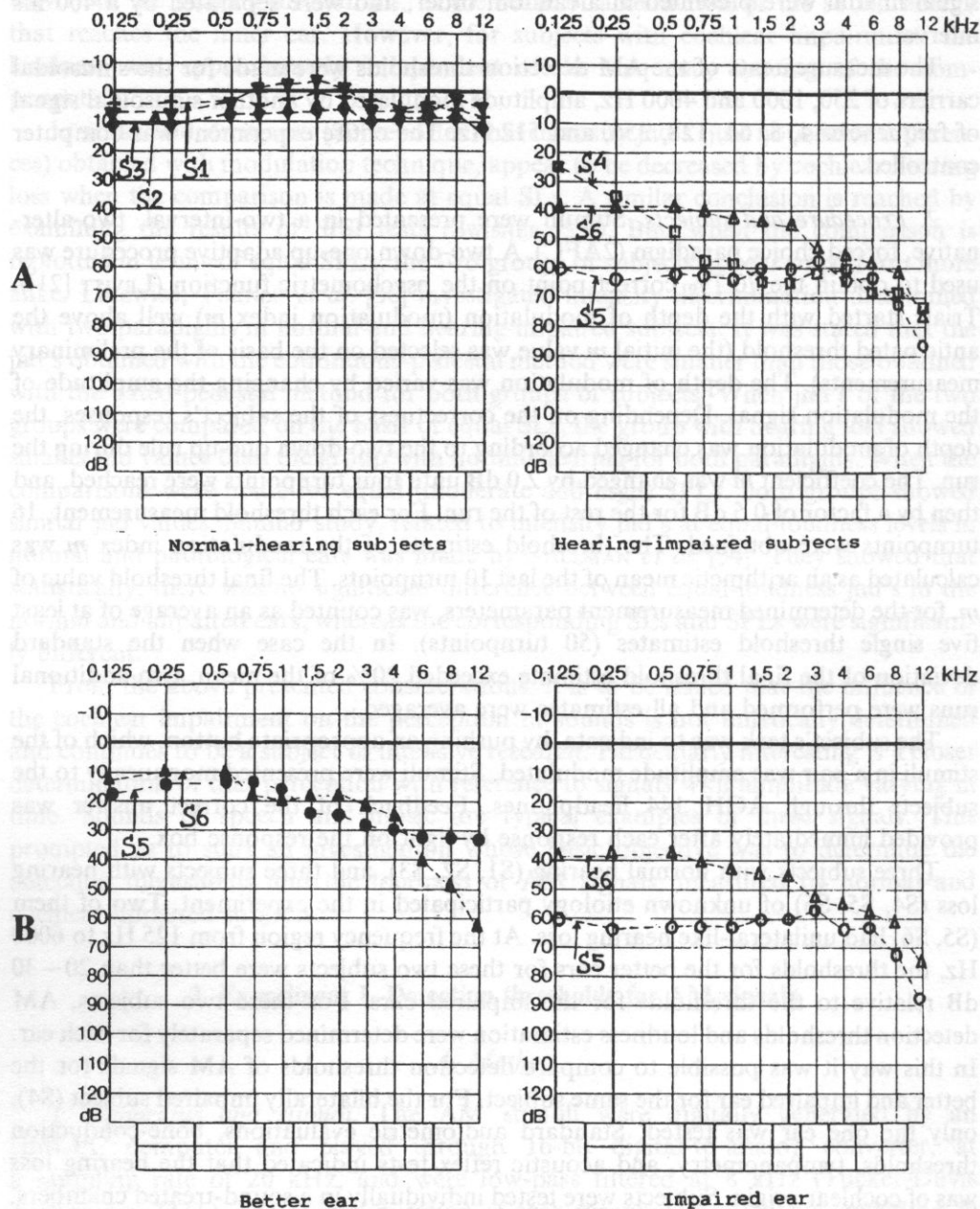
Fig. 1. Audiograms for normal and hearing-impaired subjects (A) and for two unilateraly hearing-impaired subjects (B)

B. Results

Figure 2 shows the comparison of the detection thresholds of the AM signals expressed as $20 \log m$, as a function of modulation frequency (f_m), obtained for three normal-hearing (A) and for three hearing-impaired subjects (B). The thresholds were determined for SL$=70$ dB. The parameter of the curves is the carrier frequency (f_c) equal to 250, 1000 and 4000 Hz. The increase of negative numbers on the ordinate axis indicates the better performance by the subject.

For each subject and each condition the arithmetic mean and standard deviation was calculated. Only mean values are shown in Fig. 2 and 3, and SD ranges are left out for clarity. The SD values for all conditions ranged between $1-3$ dB and only for modulation frequency of 64 and 128 Hz, the SD values sometimes reached 5 dB.

As one can see, the AM thresholds for three normal-hearing subjects are roughly similar. The values of those thresholds for the low f_m are nearly constant, and depending on f_c and the subject, are contained in the limits of -26 to -37 dB. Whereas for higher f_m (exceeding 64 Hz) they get markedly decreased at the rate of $3-5$ dB/oct, depending on the subject. These data are consistent with the investigations of Zwicker [40] and Viemeister [39]. The point the thresholds decrease from depends on the carrier frequency. The higher that frequency, the more shifted is that point towards higher modulation frequencies. Additionally to be noticed a certain dependence of the thresholds on the carrier frequency. The lower that frequency, the higher is the value of the threshold. However, a statistically significant fall of the thresholds about $f_m=4$ Hz, as suggested by Zwicker [40, 41] and Viemeister [39] could not be ascertained.

The time constant $\tau = 1/2\pi f_0$ (where f_0 is the cutoff frequency of the TMTF taken on the level of -3 dB of the TMTF) comprises in the range $2-4$ ms for the carrier from $1000-4000$ Hz. It continues to increase slightly as the carrier frequency increases. The data presented here indicate that there is some change in the shape of the TMTF depending on the carrier frequency.

Figure 2B shows the AM threshold for three hearing-impaired subjects. As can be seen, for $f_m < 64$ Hz the detection thresholds are approximately equal to the thresholds corresponding to the normal-hearing subjects within the limit of error. Characteristic, however, is the fact, that for $f_m < 64$ Hz, the detection thresholds for the hearing-impaired subjects increase (on an average of $5-8$ dB/oct depending on f_c and the subject) along with the increase of f_m. Thus, they show a course, other than for normal-hearing subjects, for whom those thresholds, in that frequency range, were decreasing (on an average $3-5$ dB/oct). Bacon and Viemeister [1] and Formby [11] found out that for high modulation frequency, the TMTF functions for sinusoidal AM noise always show decreasing tendency. The decreasing rate was higher for subjects with sensorineural hearing loss compared to normal-hearing subjects.

An analysis of variance was performed on the data presented in Fig. $2-3$ to test the effect of modulation frequency. It was found out that the effect of modulation
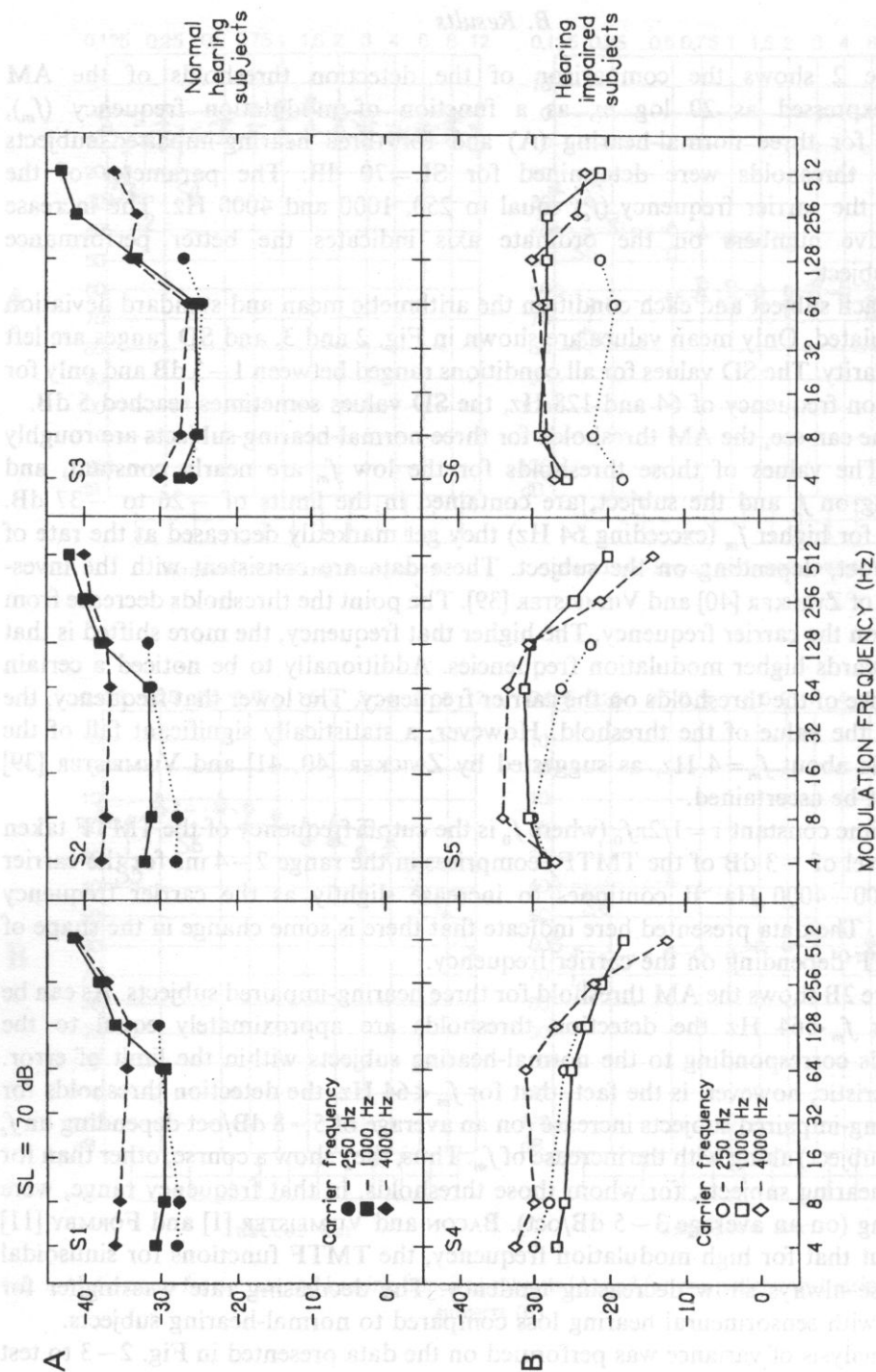
Fig. 2. AM detection thresholds for 3 normal-hearing subjects (A — filled symbols) and 3 hearing-impaired subjects (B — open symbols). Parameter of the curves is the carrier frequency equal: 250, 1000 and 4000 Hz. SL = 70 dB.

frequency was significant ($p < 0.05$) and was decisively different for normal and hearing-impaired subjects.

In Fig. 3 the dependence of the AM detection thresholds on the modulation frequency for two subjects (S5 and S6) of differing hearing loss in the left and right ears is shown. Those thresholds were determined for SL = 70 dB. The parameter of the curves is the carrier frequency, Fig. 3A shows detection thresholds for the better ear, while Fig. 3B for the impaired ear, for the same subject (audiograms of the left and right ears for those subjects are given in Fig. 1). The thresholds shown in Fig. 3 have a shape approximating the thresholds presented in Fig. 2, which confirms the earlier drawn conclusions. As it is seen, for the low f_m the detection thresholds are approximately constant, and depending on f_c and the subject they are contained in the limits of -25 to -33 dB. For the impaired ear that dispersion is slightly larger. More
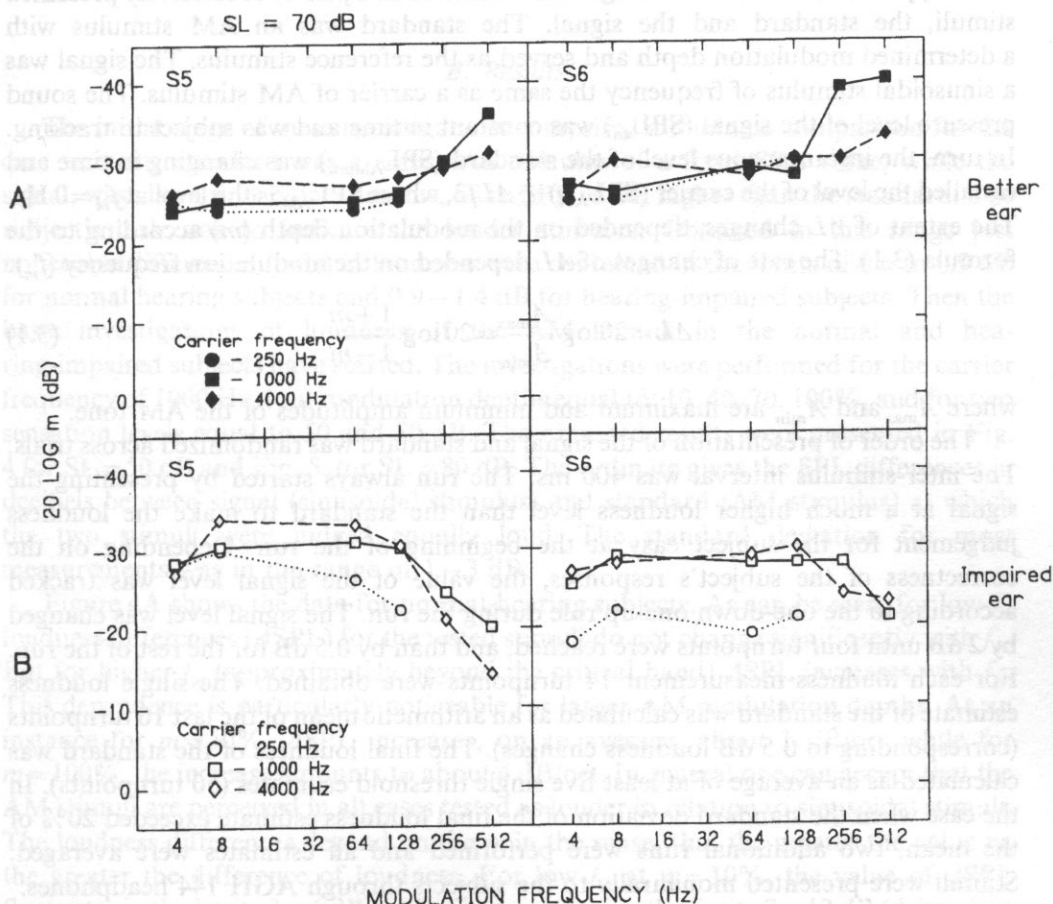

Fig. 3. AM detection thresholds for 2 hearing-impaired subjects , with one better ear (A — filled symbols) and the other one poorer (B — open symbols). Parameter of the curves is the carrier frequency equal: 250, 1000 and 4000 Hz. SL = 70 dB.

essential, however, is the fact, that for higher f_m the detection threshold lowers in the function of f_m for the better ear, whereas for the impaired ear that threshold in the function of f_m rises. Those dependences are analogical as in Fig. 2, which once again confirms the conclusion, that for the higher f_m the cochlear impairment changes the character of the detection threshold for AM sinusoidal carrier.

This fact may constitute an additional diagnostic clue in a clinical application to distinguish the character of the ear impairment.

3. Experiment II. Loudness of AM signal

A. Method

1. *Apparatus and stimuli.* A single trial consisted of a pair of successively presented stimuli, the standard and the signal. The standard was an AM stimulus with a determined modulation depth and served as the reference stimulus. The signal was a sinusoidal stimulus of frequency the same as a carrier of AM stimulus. The sound pressure level of the signal (SPL_{sin}) was constant in time and was subject to tracking. In turn, the instantaneous level of the standard (SPL_{AMinst}) was changing in time and equalled the level of the carrier (SPL_{AM}) $\pm \Delta L/2$, where SPL_{AM} is the level at $f_m = 0$ Hz. The extent of ΔL changes, depended on the modulation depth (m) according to the formula (3.1). The rate of changes of ΔL depended on the modulation frequency (f_m).

$$\Delta L = 20 \log \frac{A_{max}}{A_{min}} = 20 \log \frac{1+m}{1-m} \qquad (3.1)$$

where A_{max} and A_{min} are maximum and minimum amplitudes of the AM tone.

The order of presentation of the signal and standard was randomized across trials. The inter-stimulus interval was 400 ms. The run always started by presenting the signal at a much higher loudness level than the standard to make the loudness judgement for the subject easy at the beginning of the run. Depending on the correctness of the subject's responses, the value of the signal level was tracked according to the one-down one-up rule during the run. The signal level was changed by 2 dB until four turnpoints were reached, and than by 0.5 dB for the rest of the run. For each loudness measurement 14 turnpoints were obtained. The single loudness estimate of the standard was calculated as an arithmetic mean of the last 10 turnpoints (corresponding to 0.5 dB loudness changes). The final loudness of the standard was calculated as an average of at least five single threshold estimates (50 turnpoints). In the case when the standard deviation of the final loudness estimate exceeded 20% of the mean, two additional runs were performed and all estimates were averaged. Stimuli were presented monaurally to the subjects through AGH 144 headphones.

2. *Procedure and subjects.* Among many procedures which have been used over the years to obtain loudness balance one can distinguish traditional techniques comprising: magnitude balance and cross-modality technique (HELLMAN and ZWISLOCKI

[17]; HELLMAN [19]), the method of adjustment (FLETCHER and MUNSON [8]; ROSS [30]), the method of constant stimuli (ROBINSON and DADSON [29]), and recently used, efficient technique based upon adaptive procedures (LEVITT [21]; JESTEADT [20]). In this study, 2IFC adaptive procedure was used. The subject was asked to balance the loudness of the signal with the loudness of the standard, by tracking the signal SPL. In this way, loudness matching was achieved between standard and signal (with the accuracy of jnd in loudness).

The same three subjects as in experiment I participated in this experiment. Two of them (S5, S6) had unilateral-like hearing loss. At the frequency region from 125 Hz to 4000 Hz, the thresholds for the better ears for these two subjects were below, about $20-30$ dB, the thresholds for impaired ears. The loudness was determined separately in the better and impaired ears for these two subjects. The subjects were tested individually in a sound-treated chambers.

B. Results

The initial stage of these investigations comprised a loudness comparison for the case were the standard was a sinusoidal stimulus of a fixed SPL value, while the signal, was also a sinusoidal stimulus, of an SPL value, higher than the standard. The subject's task was to indicate the louder stimulus. Obtained in this range just noticeable differences (jnds) in loudness were contained in the limits of 0.6 to 0.9 dB for normal hearing subjects and $0.9-1.4$ dB for hearing-impaired subjects. Then the basic investigations of loudness of the AM stimuli in the normal and hearing-impaired subjects have started. The investigations were performed for the carrier frequency of 1000 Hz, four modulation depths equal to: 10, 40, 70, 100%, and for two sensation levels equal to 50 and 80 dB. The obtained results were presented in Fig. 4 for SL = 50 dB and Fig. 5, for SL = 80 dB. The ordinate gives the SPL differences in decibels between signal (sinusoidal stimulus) and standard (AM stimulus) at which the two stimuli were judged equally loud. The standard deviation for most measurements was in the range of $1-3$ dB.

Figure 4A shows the data for normal-hearing subjects. As can be seen, for low f_m loudness differences (ΔSPL) for the tested stimuli do not change significantly with f_m. But for higher f_m (approximately beyond the critical band) ΔSPL increases with f_m. This dependence is particularly noticeable for larger AM modulation depths. As an instance for $m = 10\%$, ΔSPL increases, on an average, about 1 dB/oct while for $m = 100\%$, the increase amounts to about 4 dB/oct. In general one can accept that the AM stimuli are perceived in all cases tested as louder in relation to sinusoidal stimuli. The loudness differences depend on the m in the sense, that the greater the value m, the greater the difference of loudness. For low f_m at $m = 10\%$, the value of ΔSPL fluctuates in the limits $3-6$ dB, while for $m = 100\%$ in the limits $7-12$ dB (depending on the subject). Analogical dependences are to be observed also in Fig. 5A, for SL = 80 dB. The ΔSPL values are in this case also a certain linear function of the modulation depth. They are approximately constant for low f_m, whereas for higher f_m

Normal hearing subjects

Hearing impaired subjects

SL = 50 dB

S3

S6

S2

S5

S1

S4

Modulation depth
- 10 %
- 40 %
- 70 %
- 100 %

Modulation depth
- 10 %
- 40 %
- 70 %
- 100 %

MODULATION FREQUENCY (Hz)

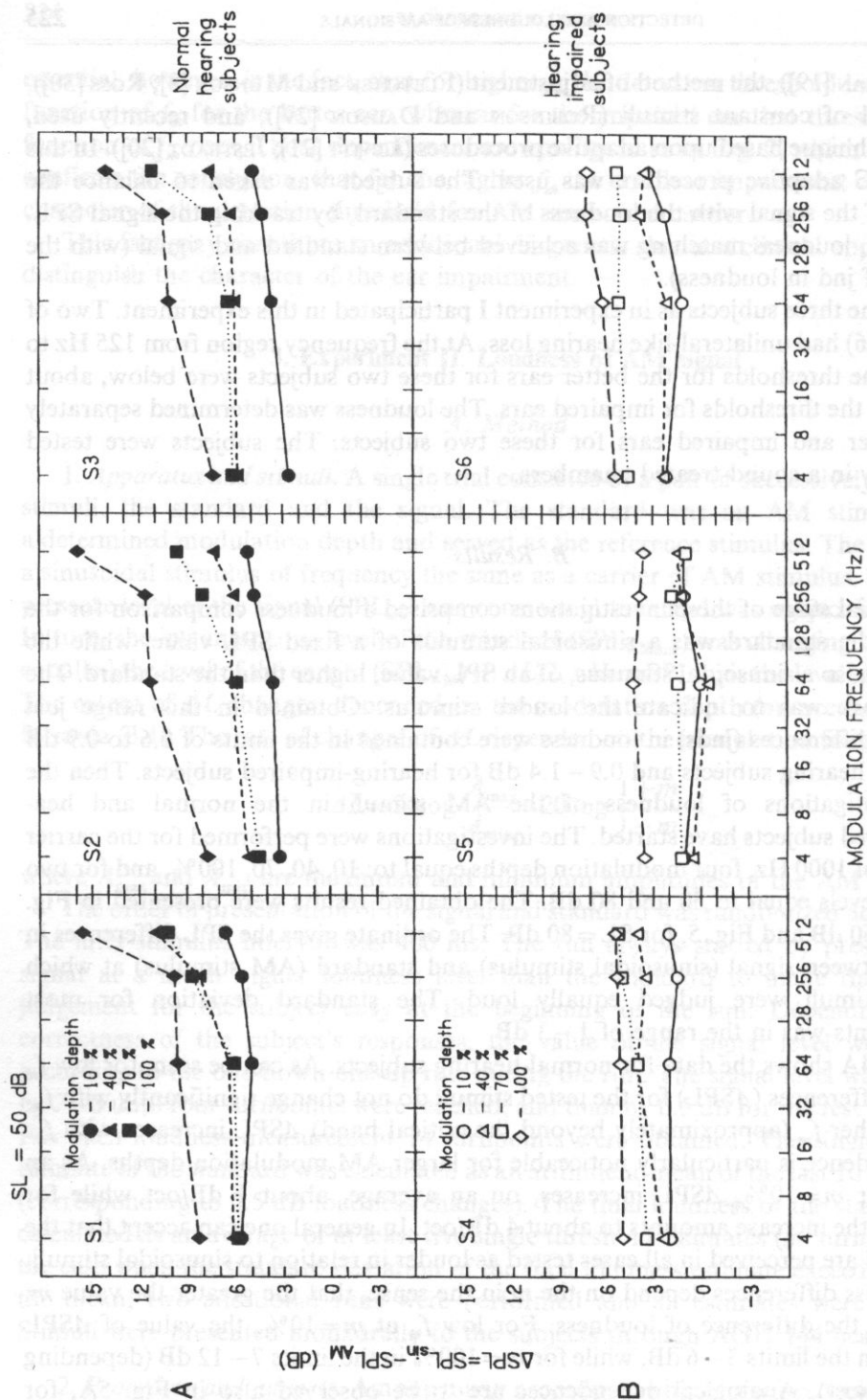$\Delta SPL = SPL_{sin} - SPL_{AM}$ (dB)

A

B

Fig. 4. SPL differences between signal and standard as a function of modulation frequency. The ordinate gives the difference in dB between SPL of the signal (sinusoidal stimulus) and SPL of the standard (AM stimulus) for the matched (balanced) signal to standard loudness. Matching was done by 3 normal-hearing subjects (A — filled symbols) and 3 hearing-impaired subjects (B — open symbols). Parameter of the curves is the modulation depth equal: 10, 40, 70 and 100%. Sensation level (SL) = 50 dB.
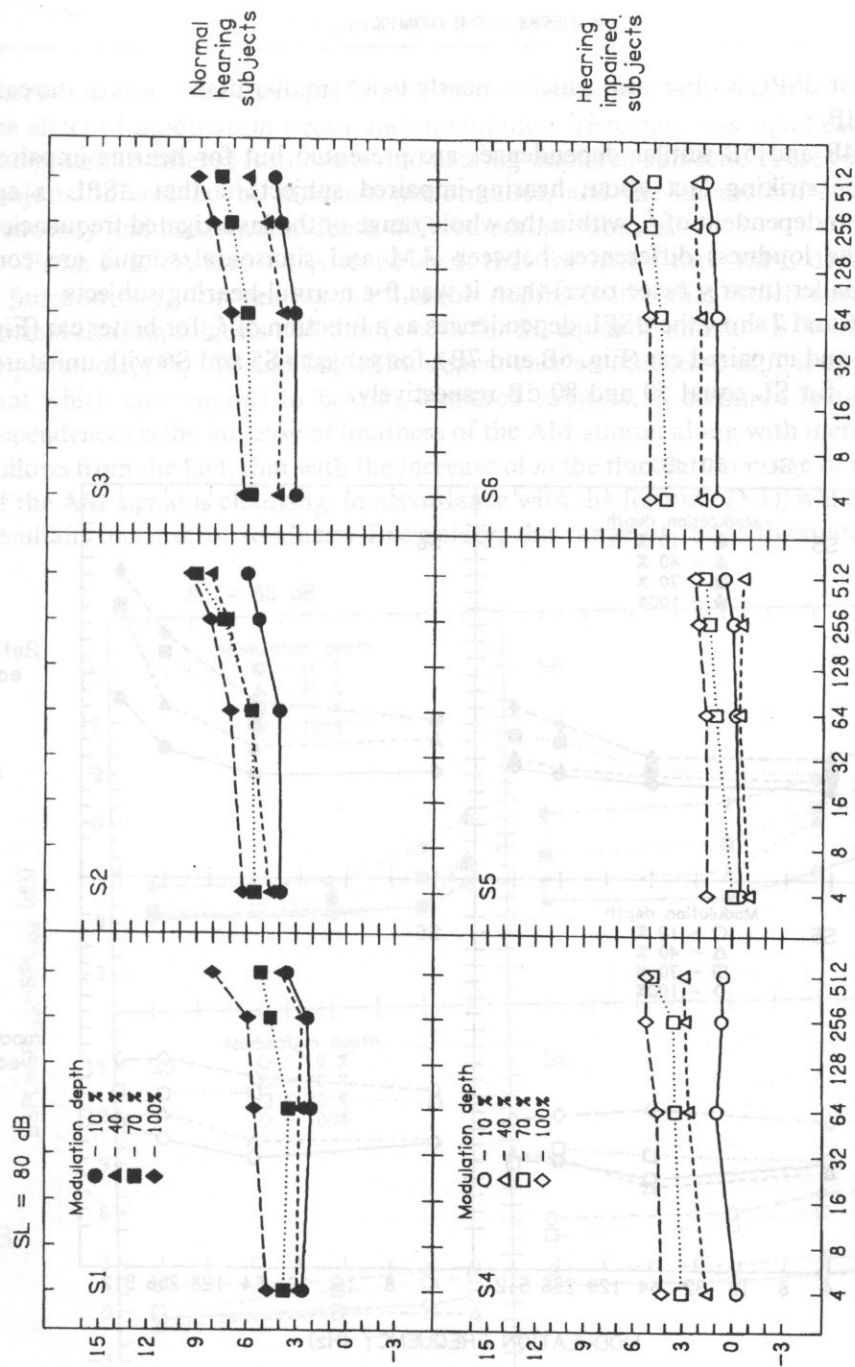
SL = 80 dB

S1   S2   S3

S4   S5   S6

Modulation depth
○ − 10 %
△ − 40 %
□ − 70 %
◇ − 100 %

Modulation depth
● − 10 %
▲ − 40 %
■ − 70 %
◆ − 100 %

MODULATION FREQUENCY (Hz)

4 8 16 32 64 128 256 512

$\Delta SPL = SPL_{sin} - SPL_{AM}$ (dB)

15 12 9 6 3 0 −3

A

B

Fig. 5. As Fig. 4 but for SL=80 dB.

an increase of ΔSPL is observed, which is nearly twice smaller than it was in the case of SL = 50 dB.

In Fig. 4B and 5B similar dependences are presented but for hearing-impaired subjects. The striking fact about hearing-impaired subjects is that ΔSPL is approximately independent of f_m within the whole range of the investigated frequencies. Moreover the loudness differences between AM and sinusoidal stimuli are considerably smaller (nearly twice over) than it was for normal-hearing subjects.

Figures 6 and 7 show the ΔSPL dependences as a function of f_m for better ear (Fig. 6A and 7A) and impaired ear (Fig. 6B and 7B), for subjects S5 and S6 with unilateral hearing loss, for SL equal 50 and 80 dB respectively.
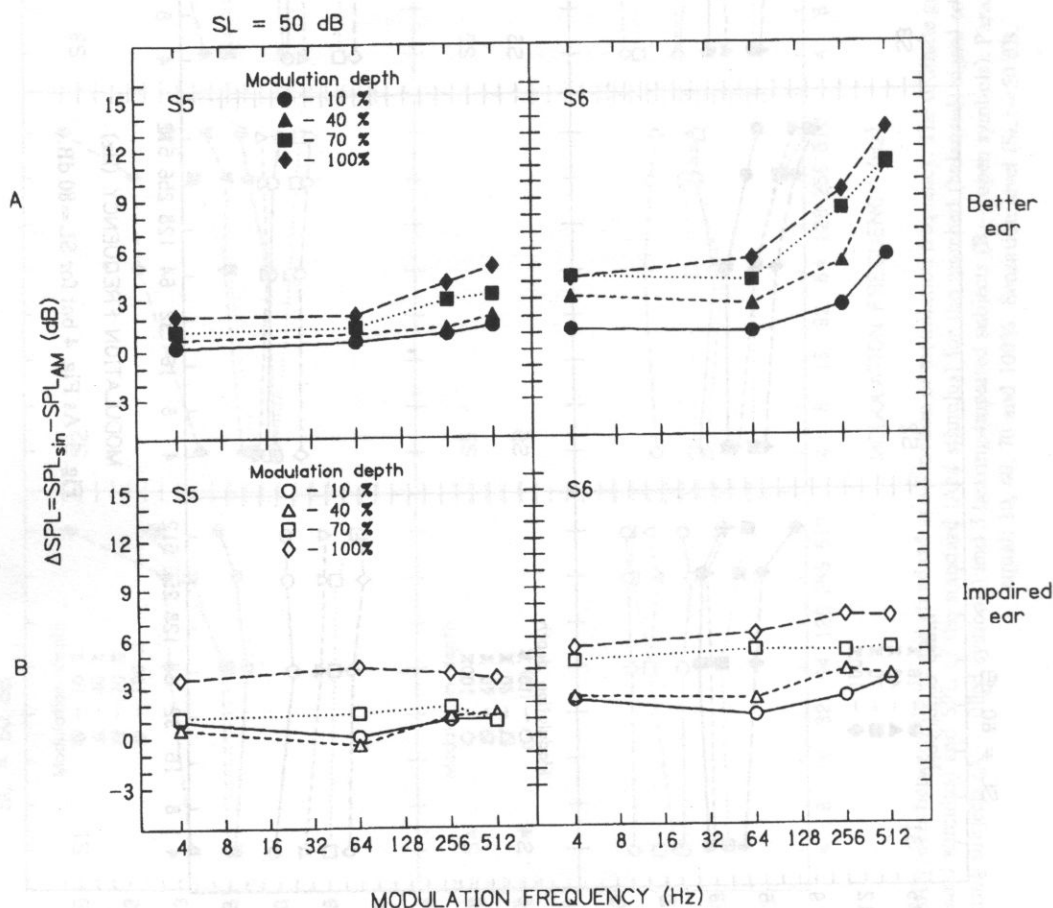
Fig. 6. SPL differences between signal and standard as a function of modulation frequency. The ordinate gives the difference in dB between SPL of the signal (sinusoidal stimulus) and SPL of the standard (AM stimulus) for the matched (balanced) signal to standard loudness. Matching was done by 2 hearing-impaired subjects, with one better ear (A — filled symbols) and the other one poorer (B — open symbols). Parameter of the curves is the modulation depth equal: 10, 40, 70 and 100%. Sensation level (SL) = 50 dB.

An analysis of variance performed on the data presented in Fig. 4 — 7 showed that the effect of modulation depth and modulation frequency was significant ($p < 0.05$) and generally differed for normal and hearing-impaired subjects. These two groups of subjects differed in the loudness performance, and the interaction of modulation frequency and modulation depth differed across subjects.

From Fig. 6A and 7A is to be seen, that for better ear, ΔSPL dependences as a function of f_m for various modulation depths is like that which corresponds to normal-hearing subjects and that is both for SL equal 50 and 80 dB. Whereas for the impaired ear, (Fig. 6B and 7B) ΔSPL dependence as a function of f_m is approximately that which corresponds to hearing-impaired subjects. A common feature of those dependences is the increase of loudness of the AM stimuli along with increase of m. It follows from the fact, that with the increase of m the fluctuation range of the intensity of the AM signal is changing, in accordance with the formula (3.1), which causes the resultant increase of loudness. Exemplary, the range of those fluctuations for the
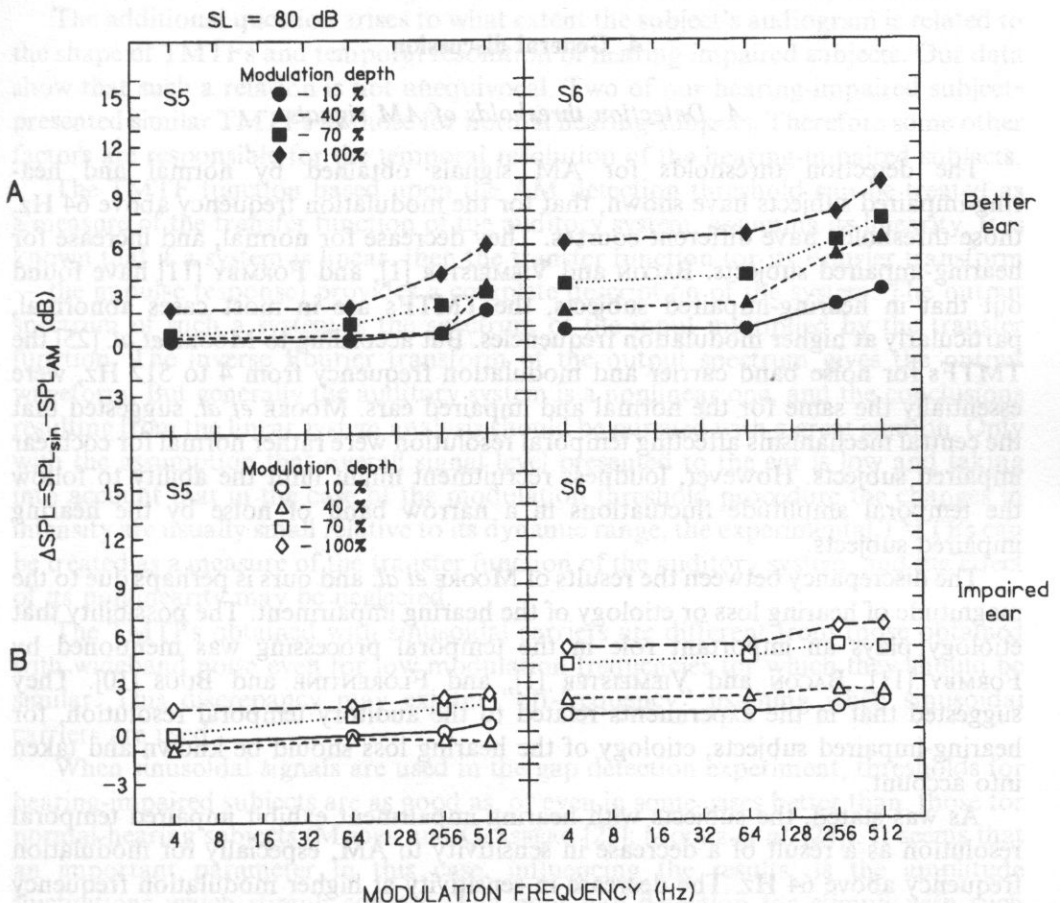

Fig. 7. As Fig. 6 but for SL = 80 dB.

successive modulation depths equal 10, 40, 70% amounts to: 1.7; 7.4 and 15.1 dB, respectively. Maximal intantaneous intensity level, for successive modulation depths (10, 40 and 70%), is equal to $SPL_{AM} + \Delta L/2$. For $SPL_{AM} = 50$ dB, it gives as a result the values: 50.9; 53.7 and 57.5 dB. The calculated instantaneous increments of intensity level caused by amplitude modulation amounted to: 0.9; 3.7 and 7.5 dB. Thus, changes in instantaneous intensity of the AM signals, produced by modulation should be related to changes in the resultant loudness of the signal. The increments of loudness of the AM stimuli relative to sinusoidal signal obtained in the psychoacoustic experiment are shown in Fig. 4−7. As can be seen from those figures, for the normal-hearing subjects and $SL = 50$ dB, increments of intensity levels for the AM the signal relative to sinusoidal one, determined subjectively, are larger than the increments calculated according to formula (3.1). A smaller discrepancy of the calculated and subjectively determined increments of intensity levels is observed for hearing-impaired subjects.

4. General discussion

A. Detection thresholds of AM signals

The detection thresholds for AM signals obtained by normal and hearing-impaired subjects have shown, that for the modulation frequency above 64 Hz, those thresholds have different courses. They decrease for normal, and increase for hearing-impaired subjects. BACON and VIEMEISTER [1], and FORMBY [11] have found out that in hearing-impaired subjects, the TMTFs are in most cases abnormal, particularly at higher modulation frequencies. But according to MOORE et al. [25] the TMTFs for noise band carrier and modulation frequency from 4 to 512 Hz, were essentially the same for the normal and impaired ears. MOORE et al. suggested that the central mechanisms affecting temporal resolution were rather normal for cochlear impaired subjects. However, loudness recruitment might limit the ability to follow the temporal amplitude fluctuations in a narrow band of noise by the hearing impaired subjects.

The discrepancy between the results of MOORE et al. and ours is perhaps due to the magnitude of hearing loss or etiology of the hearing impairment. The possibility that etiology plays an important role in the temporal processing was mentioned by FORMBY [11], BACON and VIEMEISTER [1], and FLORENTINE and BUUS [10]. They suggested that in the experiments related to the auditory temporal resolution, for hearing-impaired subjects, etiology of the hearing loss should be known and taken into account.

As was stated, the subjects with hearing impairment exhibit impaired temporal resolution as a result of a decrease in sensitivity to AM, especially for modulation frequency above 64 Hz. The decrease in sensitivity at higher modulation frequency results in steep high-frequency attenuation rate in a TMTF. For subjects with hearing impairment the rates can be twice those for normal hearing subjects (BACON and

VIEMEISTER [1]; FORMBY [11]). Abnormal TMTFs in the subjects with high-frequency hearing loss may reflect impaired temporal resolution or a restricted perceived bandwidth. It is also possible that the decrease in sensitivity to AM in hearing impaired subjects reflects a decrease in the SL of the carrier. It happens quite often that for subjects with high-frequency hearing impairment, energy at this frequency region, is just audible or even inaudible despite the high SL of the carrier. On the other hand, it is not possible to test these subjects at high SLs, because of the limited dynamic range of their hearing.

Some papers (PIERCE et al. [27]; HALL et al. [15]; HALL and GROSE [16]) suggest, that for high modulation rate, AM is not detected with time-domain cues but with combined spectro-temporal cues. The detection of AM at high modulation frequency may depend on across-frequency spectro-temporal cues rather than on time-based cues. It could account for the ability to detect high rates of modulation by the subject. But at a low modulation frequency, AM detection is mainly based on temporal cues. For intermediate modulation frequency the situation remains rather unclear.

The additional question arises to what extent the subject's audiogram is related to the shape of TMTFs and temporal resolution of hearing-impaired subjects. Our data show that such a relation is not unequivocal. Two of our hearing-impaired subjects presented similar TMTFs as those for normal hearing-subjects. Therefore some other factors are responsible for the temporal resolution of the hearing-impaired subjects.

The TMTF function based upon the AM detection threshold can be treated as a measure of the transfer function of the auditory system, assuming its linearity. It is known that if a system is linear, then the transfer function (or its Fourier transform — the impulse response) provides a complete description of the system. The output spectrum of such a system is the spectrum of the input multiplied by the transfer function. The inverse Fourier transform of the output spectrum gives the output waveform. But generally the auditory system is a nonlinear one, and the conclusions resulting from the linear system analysis should be pursued with a great caution. Only with the assumption that overall signal level presented to the ear is low and taking into account that in the case of the modulation threshold procedure the changes in intensity are usually small relative to its dynamic range, the experimental TMTFs can be treated as a measure of the transfer function of the auditory system, and the effect of its nonlinearity may be neglected.

The TMTFs obtained with sinusoidal carriers are different from those obtained with wideband noise even for low modulation frequencies for which they should be similar. This discrepancy may exhibit "off-frequency" listening when sinusoidal carriers are used.

When sinusoidal signals are used in the gap detection experiment, thresholds for hearing-impaired subjects are as good as, or even in some cases better than, those for normal-hearing subjects (MOORE and GLASBERG [23]; MOORE et al. [24]). It seems that an important parameter in this case, influencing the results, is the amplitude fluctuations which stimuli contain. The poor gap detection for stimuli with such fluctuations might result from the loudness recruitment.

B. Loudness of AM signal

Psychoacoustic data related to the estimation of loudness of the AM stimuli by normal and cochlear-impaired subjects indicated that the estimation, in the range of higher modulation frequency is different. The striking fact about hearing-impaired subjects is that ΔSPL is approximately independent of f_m in the whole range of the modulation frequencies tested. SCHARF and HELLMAN [32] also noticed a different loudness summation for normal and cochlear-impaired subjects. They investigated the loudness of complex sounds as a function of the frequency spacing (ΔF) between the lowest and highest components, and stated that loudness increased considerably with ΔF in the normal ear, whereas it remained independent of ΔF in the impaired ear. Thus, although an inner-ear pathology produces the same high thresholds and similar loudness functions for pure tone (HELLMAN and ZWISLOCKI [18]), they seem to affect the summation of loudness summation in the normal and cochlear impaired ear. Normally, increasing the bandwidth of a complex sound of fixed energy up to the critical band does not change its loudness, because the excitation pattern to which loudness is directly related, does not change. In this case the loudness depends only upon the overall SPL of the complex sound. But if the bandwidth increases out of the critical bandwidth, it involves a change in the excitation pattern, and the loudness of the complex sound starts to increase. This is the case for noise bands (ZWICKER et al. [42]) and complexes consisting of pure tones (SCHARF [31]). The similar rule may hold in cochlear pathology, the difference being that the critical bands are much wider for hearing-impaired subjects than for normal-hearing subjects (de BOER [3]; SCHARF and HELLMAN [32]). If the critical band is very wide in the impaired ear, narrow-band stimuli (e.g. AM signals with low modulation frequency) ought to produce the same large spread of excitation as wide-band stimuli (e.g. AM signals with high modulation frequency). So the total excitation remains approximately constant even as the stimulus bandwidth (modulation frequency) increases. Thus, if the critical-band mechanism did not analyze the excitation pattern in the cochlear-impaired ear, then the overall loudness of the AM stimulus would not depend on the stimulus bandwidth (modulation frequency), as was stated in this paper.

Perhaps in special cases of hearing loss, impairment of the critical-band mechanism may, without changing the excitation patterns, change the relation between loudness and excitation. Some impaired ears appear to be unable to integrate energy over intervals as long as those used by the normal ear (GENGEL and WATSON [12]). Also greater temporal masking in hearing-impaired listeners with large intrasubject variability has been reported (ELLIOTT [4]). Besides, hearing loss can also alter frequency selectivity of the auditory system and deform the auditory filter shapes (SOMMERS and HUMES [33], GLASBERG and MOORE [13]).

The loudness of AM signals, especially for low SPL, may also be affected by the loudness recruitment. It is known that for subjects with cochlear hearing loss, for low SPL, the loudness of sounds increases more rapidly with increasing SPL than for normal-hearing subjects. This rapid loudness growth continues until to a relatively

high SPL, and then reaches the normal increase. Thus, for hearing-impaired subjects, the instantaneous changes in intensity of AM signals might result in larger changes in instantaneous loudness compared with normal-hearing subjects. This hypothesis should be verified experimentally.

It is worth adding at the end, that perhaps the different mechanism of the loudness summation for normal and hearing-impaired subjects could be an additional diagnostic clue in a clinical application to distinguish the character of the ear impairment. It is also worth turning attention to the fact that as stated in the paper, for the cochlear-impaired subjects, the increase of the AM detection threshold in the range of higher modulation frequencies, and the likewise found for those subjects, loudness independence of amplitude changes rate of the signal, may appear to be useful at designing new hearing aids.

5. Conclusions

Detection threshold obtained with sinusoidal carriers AM modulated are roughly similar for normal and cochlear-impaired subjects but only for the low modulation frequency (below 64 Hz). However, for higher modulation frequency, the thresholds decrease for the normal-hearing subjects, whereas they tend to increase for the hearing-impaired subjects.

For modulation frequency f_m greater than the critical band, loudness of AM signals increased with f_m for the normal-hearing subjects, whereas it remained independent of f_m for the hearing-impaired subjects.

Acknowledgments

References

[1] S.P. BACON and N.F. VIEMEISTER, *Temporal modulation transfer functions in normal-hearing and hearing-impaired listeners*, Audiology, 24, 117–134 (1985).

[2] S.P. BACON and R.M. GLEITMAN, *Modulation detection in subjects with relatively flat hearing losses*, J. Speech Hear. Res., 35, 642–653 (1992).

[3] E. de BOER, *Measurement of critical bandwidth in case of perception deafness*. Proc. Int. Congr. Acoust. 3rd, Stuttgart, Amsterdam, Elsevier, 100–102 (1959).

[4] L.L. ELLIOTT, *Temporal and masking phenomena in persons with sensorineural hearing loss*, Audiology Basel, 14, 336–353 (1975).

[5] E.F. EVANS, *Cochlear nerve and cochlear nucleus*, in: *Handbook of Sensory Physiology. Behavioral Studies and Psychoacoustic*, [Eds.] W.D. Keidel and W.D. Neff Springer-Verlag, 1975, Berlin vol. 5, pt. 2, 4–108 (1974).

[6] P.J. FITZGIBBONS and F.L. WIGHTMAN, *Gap detection in normal and hearing-impaired listeners*, J. Acoust. Soc. Am., **72**, 761 – 765 (1982).

[7] P.J. FITZGIBBONS, *Temporal gap detection in noise as a function of frequency, bandwidth and level*, J. Acoust. Soc. Am., **74**, 67 – 72 (1983).

[8] H.F. FLETCHER and W.A. MUNSON, *Loudness, its definition, measurement and calculation*, J. Acosut. Soc. Am., **5**, 82 – 108 (1933).

[9] M. FLORENTINE and S. BUUS, *Temporal resolution as a function of level and frequency*, Proc. 11th Int. Congr. Acoust., **3**, 103 – 106 (1983).

[10] M. FLORENTINE and S. BUUS, *Temporal gap detection in sensorineural and simulated hearing impairments*, J. Speech Hear. Res., **27**, 449 – 455 (1984).

[11] C. FORMBY, *Modulation detection by patients with eight-nerve tumors*, J. Speech Hear. REs., **29**, 413 – 419 (1986).

[12] J.L. GENGEL and C.S. WATSON, *Temporal integration. I. Clinical implications of a laboratory study. II Additional data from hearing-impaired subjects*, J. Speech Hear. Disord., **36**, 213 – 224 (1971).

[13] B.R. GLASBEG and B.C.J. MOORE, *Auditory filter shapes in subjects with unilateral and bilateral cochlear impairments*, J. Acoust. Soc. Am., **79**, 1020 – 1030 (1986).

[14] B.R. GLASBEG, B.C.J. MOORE and S.P. BACON, *Gap detection and masking in hearing-impaird and normal-hearing subjects*, J. Acoust. Soc. Am., **81**, 1546 – 1556 (1987).

[15] J.W. HALL, A.C. DAVIS, M.P. HAGGARD and H.C. PILLSBURY, *Spectro-temporal analysis in normal-hearing and cochlear-impaired listeners*, J. Acoust. Soc. Am., **84**, 1325 – 31 (1988).

[16] J.W. HALL and J.W. GROSE, *Spectro-temporal analysis in cochlear hearing impairment: effects of frequency selectivity, temporal resolution, signal frequency, and rate of modulation*, J. Acoust. Soc. Am., **85**, 2550 – 62 (1989).

[17] R.P. HELLMAN and J.J. ZWISLOCKI, *Some factors affecting the estimation of loudness*, J. Acoust. Soc. Am., **33**, 687 – 694 (1961).

[18] R.P. HELLMAN and J.J. ZWISLOCKI, *Loudness function of a 1000-cps tone in the presence of a masking noise*, J. Acoust. Soc. Am., **36**, 1618 – 1627 (1964).

[19] R.P. HELLMAN, *Dependence of loudness growth on skirts of excitation patterns*, Acoust. Soc. Am., **63**, 1114 – 1119 (1978).

[20] W. JESTEADT, *An adaptive procedure for subjective judgments*, Percept. and Psychoph. **28**, 85 – 88 (1980).

[21] H. LEVITT, *Transformed up-down methods in psychoacoustics*, J. Acoust. Soc. Am., **49**, 467 – 477 (1971).

[22] E. LÜSCHER and J.J. ZWISLOCKI, *A simple method for indirect monaural determination of the recruitment phenomena. (Difference limen in intensity in different types of deafness)*, Acta Oto-laryngol. Suppl., **78**, 156 – 167 (1949).

[23] B.C.J. MOORE and B.R. GLASBERG, *Gap detection with sinusoids and noise in normal, impaired and electrically stimulated ears*, J. Acoust. Soc. Am., **83**, 1093 – 1101 (1988).

[24] B.C.J. MOORE, B.R. GLASBERG, E. DONALDSON, T. MCPHERSON and C.J. PLACK, *Detection of temporal gaps in sinusoids by normally hearing and hearing-impaired subjects*, J. Acoust. Soc. Am., **85**, 1266 – 1275 (1989).

[25] B.C.J. MOORE, M.J. SHAILER and G.P. SCHOONEVELDT, *Temporal modulation transfer functions for band-limited noise in subjects with cochlear hearing loss*, Brit. J. Audiol., **26**, 229 – 237 (1992).

[26] J.O. PICKLES, *The neurophysiological basis of frequency selectivity. Frequency selectivity in hearing.* B.C.J. Moore (Ed.) (pp. 51 – 121), Academic Press, London 1986.

[27] J.R. PIERCE, R. LIPES and C. CHEETHAM, *Uncertainty concerning the direct use of time information in hearing: Place cues in white spectra stimuli*, J. Acoust. Soc. Am., **61**, 1609 – 21 (1977).

[28] M. RODENBURG, *Investigation of temporal effects with amplitude modulated signals.* in: *Psychophysics and Physiology of Hearing*, [Eds.] E.F. Evans and J.P. Wilson, Academic, London 1977, pp. 429 – 437.

[29] D.W. ROBINSON and R.S. DADSON, *A re-determination of the equal-loudness relations for pure tones*, Brit. J. App. Physics, **7**, 166 – 181 (1956).

[30] S. ROSS, *Matching functions and equal-sensation contours for loudness*, J. Acoust. Soc. Am., **42**, 778 – 793 (1967).

[31] B. SCHARF, *Complex sounds and critical bands*, Psychol. Bull., **58**, 205 – 217, (1961).

[32] B. SCHARF and R. HELLMAN, *Model of loudness summation applied to impaired ears*, J. Acoust. Soc. Am., **40**, 71 – 78 (1966).

[33] M.S. SOMMERS and L.E. HUMES, *Auditory filter shapes in normal-hearing, noise-masked normal, and elderly listeners*, J. Acoust. Soc. Am., **93**, 2903 – 2914 (1993).

[34] J.A. STILLMANN, J.J. ZWISLOCKI, M. ZHANG and L.K. CEFARATTI, *Intensity just-noticeable differences at equal-loudness levels in normal and pathological ears*, J. Acoust. Soc. Am., **93**, 425 – 434 (1992).

[35] L. SWISHER, *Response to intensity change in cochlear pathology*, Laryngoscope, **76**, 1706 – 1713 (1966).

[36] C.W. TURNER, J.J. ZWISLOCKI and P.R. FILION, *Intensity discrimination determined with two paradigms in normal and hearing-impaired subjects*, J. Acoust. Soc. Am., **86**, 109 – 115 (1989).

[37] R.S. TYLER, *Frequency resolution in hearing-impaired listeners*, in: *Frequency selectivity in hearing*, B.C.J. MOore (Ed). (pp. 309 – 371), Academic Press, London 1986.

[38] N.F. VIEMEISTER, *Temporal factors in audition: a systems analysis approach*, in *Psychophysics and Physiology of Hearing*, [Eds.] E.F. Evans and J.P. Wilson, Academic, London 1977, pp. 419 – 428.

[39] N. F. VIEMEISTER, *Temporal modulation transfer function based upon modulation thesholds*, J. Acoust. Soc. Am., **66**, 1364 – 1380 (1979).

[40] E. ZWICKER, *Die Grenzen der Hörbarkeit der Amplitudenmodulation und der Frequenzmodulation eines Tones*, Acustica, **2**, 125 – 133 (1952).

[41] E. ZWICKER, *Die elementaren Grundlagen zur Bestimmung der Informationskapazitnt des Gehörs*, Acustica, **6**, 365 – 381 (1956).

[42] E. ZWICKER, G. FLOTTORP and S.S. STEVENS, *Critical bandwidth in loudness summation*, J. Acoust. Soc. Am., **29**, 548 – 557 (1957).

[43] E. ZWICKER and H. FELDTKELLER, *Das Ohr als Nachrichtenempfänger*, S. Hirzel Verlag, Stuttgart 1967.

[44] J.J. ZWISLOCKI, *Temporal summation in loudness*, J. Acoust. Soc. Am., **46**, 431 – 441 (1969).