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HEARING DAMAGE FROM EXPOSURE TO MUSIC

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Sound pressure levels and exposures in discotheques and youth clubs and during training sessions of music students were measured and analysed. Effects of exposure in the form of permanent and temporary threshold shift were determined in the samples of young discotheque attendants and in music students. The consequences of the threshold shift in the perception of pitch, loudness, and time are discussed.

1. Introduction

Music has been recognised as a source of acoustic trauma, and a danger of hearing loss from loud music has aggravated substantially over the past quarter of a century. Although live music can also be potentially dangerous to the hearing system, most traumatic effects observed in the samples of young population in Poland (and also western countries) were caused by music from portable cassette players, high power home sonic equipment and very high power electroacoustic systems in discotheques or pop and rock concert halls. Significant effects of overexposure were found in some music students due to very high sound pressure levels in training sessions.

Traumatic effects of acoustic overstimulation that have long been considered as a decrease in sensitivity only, manifest themselves in several psychophysical spaces. The decrease in sensitivity or hearing loss is thus usually associated with poorer frequency discrimination and frequency resolution. In the perception of intensity a distortion of loudness function, known as a recruitment is often observed. Severe distortions of signals caused by acoustic trauma result from the poorer perception of auditory events with time. In the proximity of an (elevated) hearing threshold and up to moderate sensation levels acoustic trauma often causes a lack of tonality and/or non-linear distortions. Cumulative effects of a pronounced acoustic trauma change the characteristics of signals incoming auditory pathways to such an extent that spoken messages cannot be understood.

The question of the danger of hearing loss in young people seems to be open to various interpretations and has recently brought conflicting answers. However, the findings from the audiometric laboratory examinations of statistically significant samples of young musicians in Poland show that 68% of them bear marks of acoustic overexposure while

50% of them show selective hearing loss of 20 dB or more in at least one ear. The observations seem to indicate that the danger of hearing loss from long term socially administered overexposures to music might have been underestimated yet.

2. SPL's and exposures

The deterioration of hearing from exposure to loud and to amplified music has been studied and described by large number of investigators over the past quarter of a century. Their efforts resulted in large supply of experimental data that has been critically reviewed by HUGHES *et al.* [40], WEST and EVANS [100], CLARK [13], DIBBLE [17] and in some measure by BRADLEY *et al.* [8], HELLSTRÖM and AXELSSON [39], AXELSSON *et al.* [1] and many others.

A number of investigators have measured and analysed data referring to music (noise) exposures, i.e. corresponding sound pressure levels and their frequency and time distributions and also to the duration and character of exposures.

Analysed were the data pertaining both to live and amplified pop/rock music, e.g. KOWALCZUK (1967), RINTELMAN and BORUS [83], RINTELMAN *et al.* [84], CABOT *et al.* [10], CLARK and BOHNE [14], CLARK [13], BORSCHGREVINK [7], ISING *et al.* [41], JAROSZEWSKI and RAKOWSKI [44], JAROSZEWSKI [56], and to live and recorded and/or amplified symphonic music e.g. LEBO and OLIFANT [65], AXELSSON and LINDGREN [2], WESTMORE and EVERSDEN [101], RABINOVITZ *et al.* [79], JANSSON and KARLSSON [42], FRY [29], SCHACKE [89], WOOLFORD *et al.* (1988), and CLARK [13], JAROSZEWSKI *et al.* [60].

Regrettably, the abundant published data from various authors show very large variance with reference to the sound pressure levels and their distribution in the frequency scale and in time and, consequently, also with reference to exposures.

However, almost all researchers report sound pressure levels that are potentially dangerous to hearing as for example: BIKERDIKE and GREGORY [5], $L_{\mathrm{Aeq}} = 88-113$ dB, DIBBLE (1988), $L_{\mathrm{Aeq}} = 94 - 99$ dB, while MAWHINNEY and MC CULLAGH [69] report SPL's in excess of 95–115 dB with peaks from approximately 105 dB to over 125 dB.

In investigations of sound pressure levels and their distribution in 10 Warsaw discotheques present authors found even larger values of SPL (JAROSZEWSKI *et al.* [57]). L_{Aeq} was found to be in the range from 90 to 116 dB. Long time average spectra in 1/3 octave bands in the tested discotheques are given in Fig. 1. SPL cumulative distribution functions for these discotheques are given in Fig. 2.

Impulsiveness of music noise tested, determined as a difference between the peak and equivalent level is given in Fig. 3 showing presence of peaks reaching 30 dB with median value of approximately 22 dB.

In investigation of sound exposures in Swedish symphonic orchestras JANSSON and KARLSSON [42] reported mean L_{Aeq} values from 89 dB up to 93 dB with maximum values reaching 98.6 dB. They have not observed peak values exceeding 125 dB. Similar data, L_{Aeq} from 85 dB up to 90 dB with weekly equivalent of 85 dB were reported by AXELSSON and LINDGREN [2]. SCHACKE [89] recorded sound pressure levels in orchestra

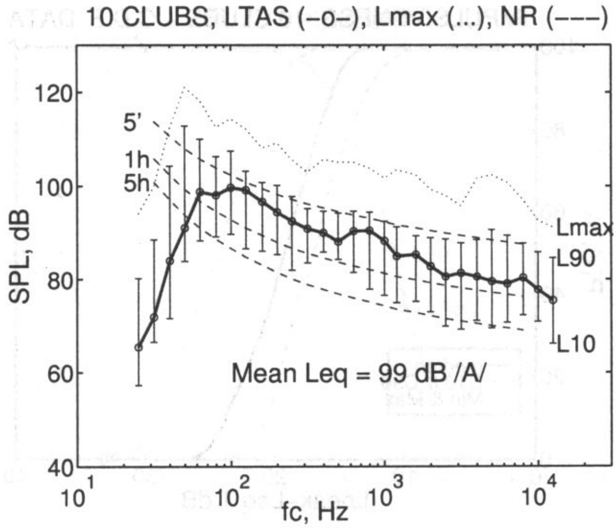


Fig. 1. Long time average spectra in 1/3-octave bands and noise rating curves for pop/rock music in 10 Warsaw discotheques.

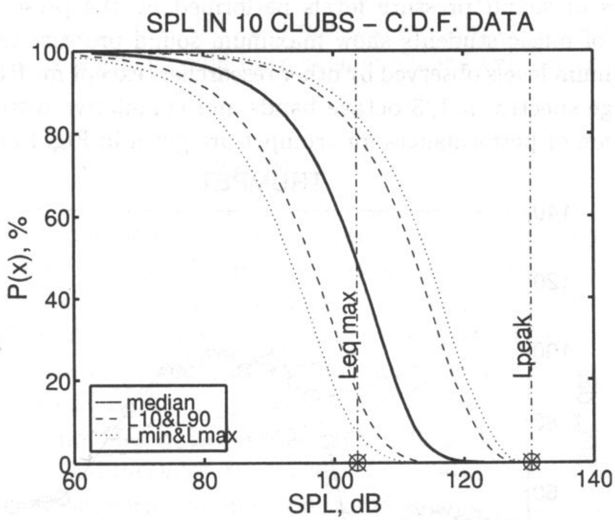


Fig. 2. SPL cumulative distribution functions for pop/rock music in 10 Warsaw discotheques.

of the Deutsche Oper Berlin and found average A levels for brass ranging from 87 dB to 96 dB with peaks reaching 122 dB, and average levels for woodwinds varying between 88 dB and 97 dB with peaks reaching 117 dB. In the report by SCHACKE [89] L_{Aeq8h} for wind instruments was determined at 87.7 dB which is about twice as much as maximum permissible exposure according to German regulations. Alarming data on L_{Aeq} values were reported by ROYSTER *et al.* [87]. They found L_{Aeq} values ranging from 74.7 to 94.7 dB with peaks in the range from 112 to 143 dB.

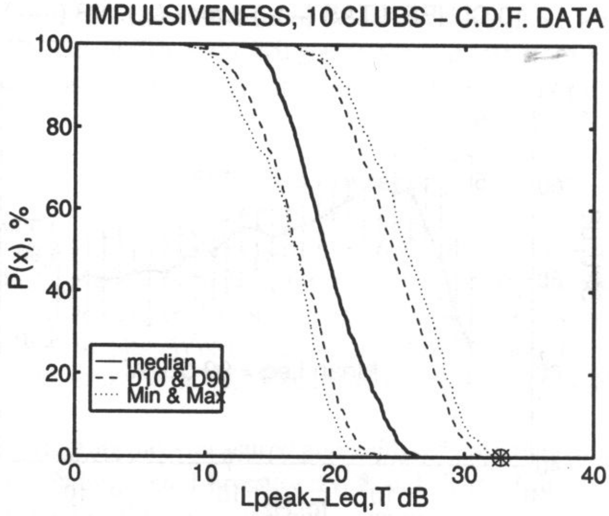


Fig. 3. Impulsiveness as a difference between peaks and equivalent SPLs of the tested discotheque music.

Measurements of sound pressure levels performed by the present authors during training sessions of music students show maximum sound pressure levels substantially higher than maximum levels observed by other researchers except for ROYSTER *et al.* [87]. Long time average spectra in 1/3 octave bands and cumulative distribution functions for a short selection of performances for trumpet are given in Fig. 4 and Fig. 5.

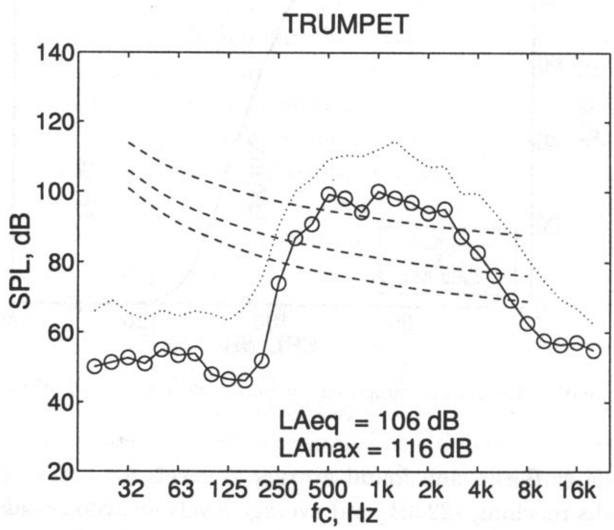


Fig. 4. LTAS in 1/3-octave bands of trumpet sound during daily practice of music student. Noise rating curves for 5 min, 1 hr and 5 hrs are also shown on the diagram.

Present findings indicate also that the exposures experienced by music students during their training sessions are far in excess relative to the permissible doses. Predictably,

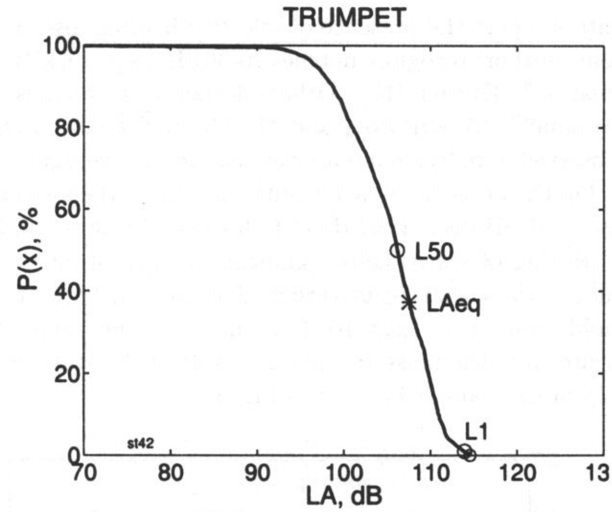


Fig. 5. SPL cumulative distribution functions of trumpet sound during practice hours of music student.

such exposures lead to aggregation of NIPTS acquired over a long period of time and as such should not be ignored. In 50% of brass and woodwind student players PTS of 10 dB to 25 dB was found which could have been explained only by acoustic trauma.

3. Hearing thresholds

In audiometric examination of classical musicians AXELSSON and LINDGREN [2], WESTMORE and EVERSDEN [101], RABINOWITZ *et al.* [79], KARLSSON *et al.* [63], WOOLFORD [105], JOHNSON *et al.* [61, 62], JANSSON *et al.* [43], OSTRI *et al.* [75], ROYSTER *et al.* [87], and others, all have found audiometric patterns corresponding to the noise induced hearing loss. The audiograms showed notches, mostly at frequency 6 kHz in 30% to over 50% of the tested sample.

The depth of these notches varied between HTL 10 dB (OSTRI *et al.* [75], ROYSTER [87]) and 20 to 25 dB (RABINOWITZ *et al.* [79]. The greatest hearing loss was found in musicians playing bassoon, horn, trumpet and trombone (e.g. AXELSSON and LINDGREN [23]). However, some investigators e.g. WESTMORE and EVERSDEN [101], AXELSSON and LINDGREN [2], have declared that only "slight degree of hearing loss was found in the average hearing thresholds", even that they also found notch shaped audiograms with the dip at 6 kHz in the tested samples.

To relate the exposure data from loud and amplified pop/rock music to the damage of hearing many authors measured and analysed the permanent and temporary threshold shift in music performers, personnel and attendants to discotheques and youth clubs e.g. LIPSCOMB [66], SKRAJNAR [92], CATALANO and LEVIN [11], FEARN [19], FEARN and HANSSON [20, 21], CLARK [13], JAROSZEWSKI and RAKOWSKI [44], JAROSZEWSKI *et al.* [57].

Many investigators report the presence of selective hearing loss of various depths at 6 kHz. However, some authors recognise notches 20-30 dB deep at 6 kHz as "not exceeding limits of normal hearing" (DIBBLE [17]). Others declare in such cases that "the hearing losses are relatively small" (MAWHINNEY and MC CULLAGH [69]) or show little concern that the notches observed in individual data were lost in the averaging procedure (WEST and EVANS [100]). On the other hand, some authors express their serious concern about the notches that are 7-10 dB deep at 6 kHz (FEARN and HANSON [20, 21], FEARN [19]).

In audiometric testing of statistically significant sample of music students, present authors arrived at the data that seem rather alarming. In 68% of a sample of 214, permanent threshold shift of at least 10 dB or more in one ear at 6 kHz was found which clearly indicates a music noise trauma. A result of the statistical analysis of the audiometric data from this sample is given in Fig. 6.

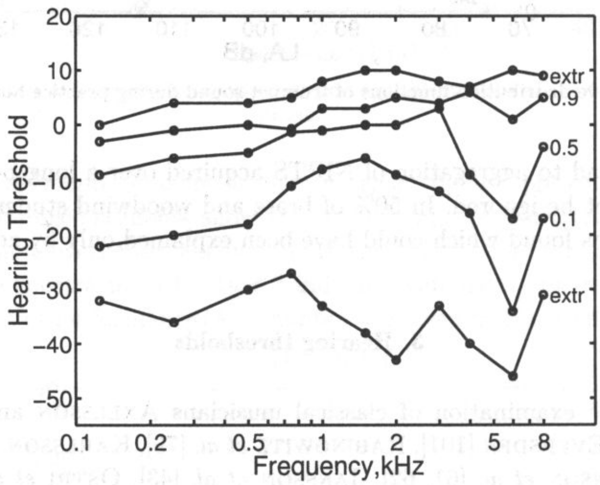


Fig. 6. Hearing threshold data. Sample of 214 subjects aged 16 to 27.

It has been learned from interviews that in all cases of notch shaped PTS the subjects were attendants to discotheques and/or used portable cassette or CD players and/or used home audio equipment at very high level.

Audiometric data from a group of 14 attendants to discotheques show similar results of overexposure to music in the form of the notches at 6 kHz, 20 dB deep, and a considerable amount of temporary threshold shift TTS2 measured immediately after cessation of over 6 hrs exposure in the discotheque, Fig. 7.

Quite dramatic audiometric data were obtained from 4 music performers in one of youth clubs. For example these data show hearing loss of 20 to 50 dB in both ears of one of the subjects tested while the temporary threshold shift measured 2 min. after 5 hrs exposure reaches from 50 to 81 dB, Fig. 8.

Also, both hearing loss and temporary threshold shift occupy wide range of frequencies. Maximum sound pressure levels in this night club were reaching 125 dB (JAROSZEWSKI and RAKOWSKI [44]).

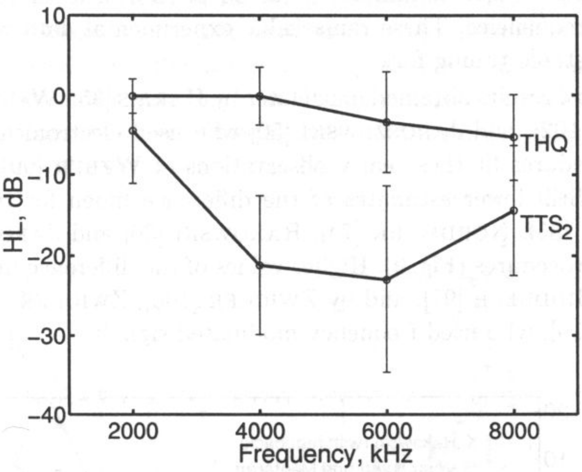


Fig. 7. Hearing threshold in quiet (THQ) and temporary threshold shift (TTS2) in 14 discotheque attendants after 6 hrs of exposure to music.

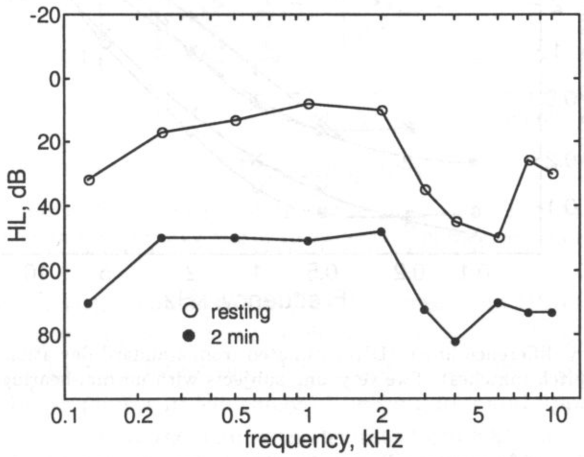


Fig. 8. Hearing threshold in quiet (open circles) and temporary threshold shift (closed circles) in one pop/rock musician after 5 hrs of exposure.

The data obtained seem to indicate that the hazard of listening to very loud music from high power electronic equipment in night clubs or discotheques or from low-power portable players delivering very high sound pressure levels may be substantially larger then it is generally assumed.

4. Frequency discrimination

It has long been known that the frequency discrimination in the hearing system is astonishing. Early observations by WEBER [99] and PREYER [78] showed that very experienced musicians can discriminate 64 to 83 pitches in a semitone in the middle range of audible frequencies. These remarkable experimental data were obtained with the use of an adjustable tuning fork.

The experimental results obtained much later by HARRIS [35], WALLISER [98], MOORE [70], WIER *et al.* [102], and JAROSZEWSKI [50] who used electronically controlled constant stimuli procedures fit these early observations of WEBER [99] and PREYER [78] surprisingly well. Still lower estimates of the difference limen for frequency were obtained by RITSMA [85], NORDMARK [74], RAKOWSKI [80] and JAROSZEWSKI [50] who used adjustment procedures (Fig. 9). Higher values of the difference limen were obtained by SHOWER and BIDDULPH [91], and by ZWICKER [106], ZWICKER and FELDTKELLER [107], and FASTL [19], who used frequency modulated signals.

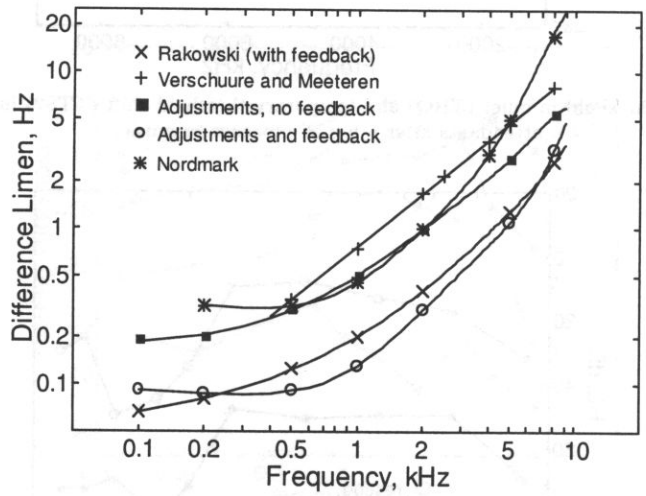


Fig. 9. Frequency difference limen (DL) estimated from standard deviation of adjustments (pitch matches). Twelve young subjects with normal hearing.

Numerous studies of frequency discrimination in hearing impaired subjects show that in majority of cases with sensorineural hearing loss frequency difference limens for pure tones are larger than in normal hearing subjects. In the data from e.g. TYLER, WOOD and FERNANDES [96], HALL and WOOD [32], FREYMAN and NELSON [27], which were obtained from subjects with comparatively large hearing loss of 30 to 60 dB and relatively flat over the range of audiometric frequencies, the DL estimates are on average several times larger than in normal hearing subjects. However, DL values obtained by these authors are rather large both for normal and for hearing impaired subjects. More recent data from FREYMAN and NELSON [28], show also several times worse DL's in hearing impaired than in normal hearing subjects, but the DL estimates are also large (e.g. 4.5 Hz/1200 Hz and 15 Hz/1200 Hz for normal and hearing impaired correspondingly) while the group of subjects is less consistent relative to the amount of hearing loss over the frequency scale.

Much lower DL values which were found in normal hearing young musicians by RAKOWSKI [80] and JAROSZEWSKI [50], expressed by approximately 0.1 Hz for frequencies below 1 kHz indicate the difference in hearing ability in musicians and in non musicians. Poorer DL estimates were found in elder but musically educated and musically trained subjects outside the range of frequencies at which hearing loss was measured in them, JAROSZEWSKI and FIDECKI [55], Fig. 10.

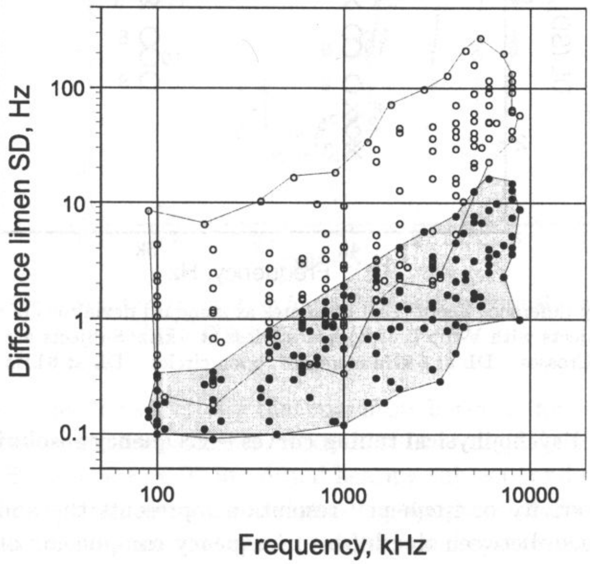


Fig. 10. Scatter diagram of difference limen (DL) for 12 subjects with normal hearing (closed circles) and for 12 subjects with large hearing loss of 60-70 dB in high frequency range (open circles).

On the other hand, larger contrast was found between the DL estimates in normal hearing and in hearing impaired subjects reaching 1 : 30 to even 1 : 90 in extreme cases, while it amounted to approximately only 1 : 10 in the data from other investigations. Also, the DL was always poorer in the range of hearing loss and approximately normal outside this range, which is in agreement with the data from FREYMAN and NELSON [28].

Severe loss in pitch discrimination ability pertains to the cases of large hearing loss which was observed in musicians active in pop and rock music performances (as shown in section 3) and in those involved in operation of discotheques. Less severe effects of hearing loss on pitch discrimination were found in musicians with selective hearing loss at 6 kHz. (so called "notch") of moderate and larger depth of 20 to 40 dB, Fig. 11.

While the difference limen is within normal limits outside the frequency of hearing loss, it is from 2 to 6 times worse at the frequency of impairment. In majority of cases the worse DL was associated with larger hearing loss. However, in some cases of notch shaped audiograms the DL estimates were approximately normal at the frequency of loss.

The present observations show that even moderate selective hearing loss acquired from overexposure to music often affects also other important characteristics of the hearing system and this effect on the DL is also selective.

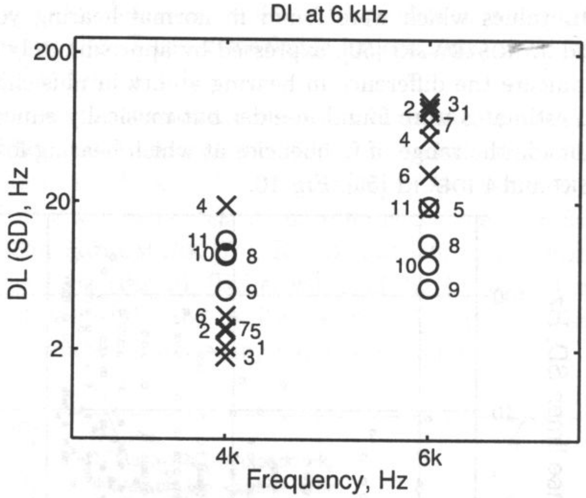


Fig. 11. Frequency difference limen (DL) estimates as standard deviations of adjustments (pitch matches) for subjects with V-dip (notch) hearing loss at 6 kHz. Subjects are depicted by their numbers. Crosses – DL at 6 kHz increased, open circles – DL at 6 kHz unaffected.

5. Psychophysical tuning curves – Frequency resolution

Frequency selectivity or frequency resolution represents the ability of the hearing system to distinguish between the different frequency components of a complex sound. Although different measures and procedures were used to determine the frequency resolution as described by FLORENTINE *et al.* [25], TYLER *et al.* [95], MOORE and GLASBERG (1987), LUTMAN and WOOD [68], LUTMAN *et al.* [67], COX and ALEXANDER [15], the psychophysical procedure described by CHISTOVICH [12] and SMALL [93] seems to be most widely used. In this procedure a faint test tone signal at fixed frequency and level is masked by variable frequency masker. The level of masker necessary to mask a test tone as a function of frequency results in the so called psychophysical tuning curve.

Psychophysical tuning curves measured in normal hearing subjects have extremely steep flanks, reaching 3×10^3 dB/oct or 3 dB/Hz in the upper flank when measured in forward masking and with off-frequency listening. The measure of frequency selectivity or frequency resolution is usually represented by the slope of the upper flank of the tuning curve or by a Q value defined as the center frequency divided by the bandwidth of the tuning curve at certain arbitrary level above the level of the test tone.

The first demonstrations of extremely steep flanks of psychophysical tuning curves in normal hearing subjects in forward masking (Fig. 12) were given by JAROSZEWSKI and RAKOWSKI [59] and JAROSZEWSKI [45, 46] and by MOORE [71].

Contemporarily, psychophysical tuning curves were measured in normal-hearing and hearing-impaired subjects by e.g. FLORENTINE *et al.* [25], TYLER *et al.* [95, 96] showing, regardless of the procedure, pronounced differences in frequency selectivity between these groups. However, these authors, similarly as later LUTMAN and WOOD [68] and LUTMAN *et al.* [67] used but continuous maskers of various characters. Since, their data do not

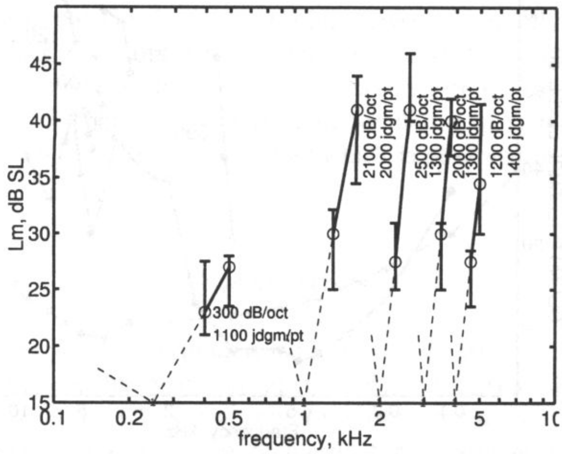


Fig. 12. Psychophysical tuning-curves in forward masking in normal hearing subjects. (2-IFC procedure. Lm = 15 dB SL).

reflect the utmost frequency selectivity that manifests better in forward masking. Using pulsed test tone and continuous masker, FLORENTINE *et al.* [25] for example, reported Q values at 4000 Hz of 6.06 to 6.92 in normal hearing subjects and only 3.0 in subjects with noise induced hearing loss and corresponding steepness of the upper flank of approximately 180 dB/oct. for normal hearing subjects, and approximately 100 dB/oct for hearing impaired. The Q value for young normal hearing musicians measured in forward masking reached 16.7 to 29.0, JAROSZEWSKI ET AL. [57], which is in agreement with the data from WIGHTMAN *et al.* [104], and the slope of upper flank 1.2×10^3 dB/oct, JAROSZEWSKI and RAKOWSKI [59], JAROSZEWSKI [45, 46].

In musicians with large sensorineural noise induced hearing loss a substantial decrease of both the steepness of tuning curves and of the Q values was observed, JAROSZEWSKI [47]. Contrary to the frequency discrimination estimates which were decreased in the range of hearing loss and preserved at normal level where threshold hearing level was normal, the decrease of Q values and of the steepness of upper flank occured in the frequency range of large hearing loss and also outside these frequencies, Fig. 13. These data are consistent with the data reported by FLORENTINE *et al.* [25], and early data from WIGHTMAN *et al.* [104]. However, conflicting data have been reported in studies, which demonstrated frequency discrimination performance at normal level in subjects, who were performing abnormally in frequency resolution, e.g. WIGHTMAN [103], TYLER *et al.* [96].

The psychophysical tuning curves measured in young musicians with only relatively small and/or moderate selective sensorineural hearing loss at 6 kHz, show somewhat lower values of Q and less steep upper flank at the frequency of loss (6 kHz), than above and below this frequency, JAROSZEWSKI *et al.* [52]. This observation indicates that even small amount of selective hearing loss affects also frequency resolution similarly as frequency discrimination. However, the performance of subjects in these tasks does not

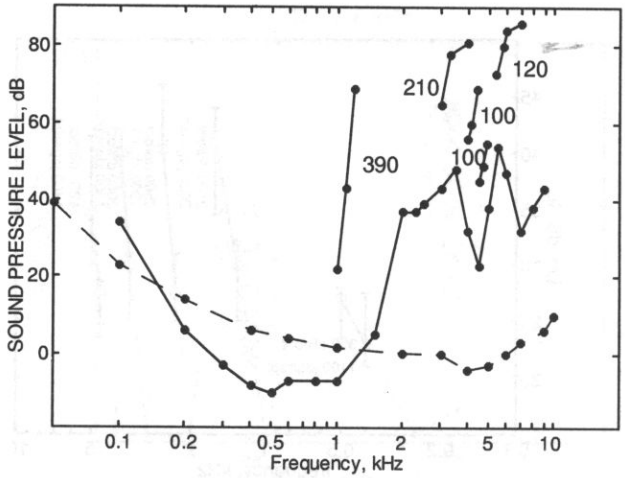


Fig. 13. Slopes of the upper flank of the psychophysical tuning-curves in hearing impaired with noise-induced sloping high frequency hearing loss as indicated by heavy line. Dashed line – normal threshold in quiet.

conform to a rigid pattern as follows from the evidence reported by e.g. WIGHTMAN *et al.* [107], FLORENTINE *et al.* [25], JAROSZEWSKI [47], JAROSZEWSKI *et al.* [57].

As indicated by TYLER *et al.* [96] frequency resolution and frequency discrimination may operate on the basis of different mechanism: frequency discrimination may depend on temporal coding while frequency resolution on place coding. FLORENTINE *et al.* [25] observed that, cit.: "the most sensitive measures of reduced frequency selectivity are the Q values of the tuning curves", even that they used pulsed test tone and continuous

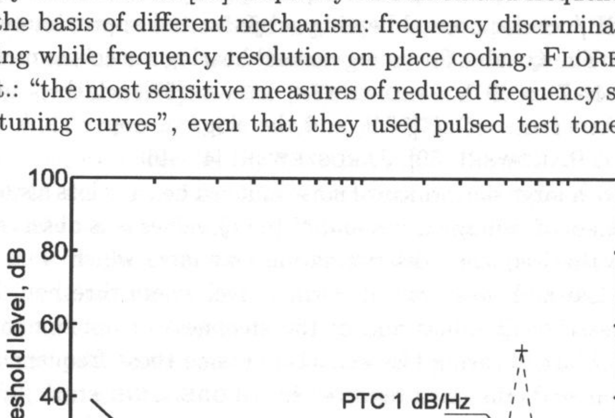


Fig. 14. Hearing threshold in quiet for subjects with V-dip (notch) hearing loss at 6 kHz and the slopes of the upper flank of psychophysical tuning-curve for V-dip 50 dB and 15 dB.

masker. The data from WIGHTMAN *et al.* [104] and JAROSZEWSKI [47], JAROSZEWSKI *et al.* [54], seem to indicate that Q value of the tuning curves measured in forward masking may be still more sensitive measure which "not only reveals even small amounts of hearing impairment, it also provides a measure of the degree of cochlear impairment" (after FLORENTINE *et al.* [25]). The slopes of upper flanks of psychophysical tuning curves are also affected by selective hearing loss which is observed in many subjects at 6 kHz, see Fig. 14.

6. Constant errors

Constant errors in frequency discrimination received little attention of the researchers exploring operation of the auditory system in spite of the fact that their existence was discussed already by FECHNER [22] at the end of the past century. Later constant errors were revisited by KELLOG [64] in a remarkable doctoral dissertation cited up to the present day.

Constant errors measured in normal hearing subjects, were present in the results of pitch adjustment to unison in the experiments of RAKOWSKI and HIRSH [81, 82], and more recently by the senior author of the present report, JAROSZEWSKI [49, 50]. It is interesting to note that small errors were observed in the procedures with feedback and large ones in the procedures without it.

One of the better illustration of the constant error manifestation are response density functions in the adjustment procedure. These functions, represent the ensembles of the values of frequency in which in the experimental run the subject decided that the pitch of the adjusted (matched) signal is too large or that it is too small, JAROSZEWSKI [52], Fig. 15 a, b, c.

The widths of these functions, which are usually normal in their nature, determine the dispersion of decisions or standard deviation in the final result. The ratio of one of the density functions over the sum of both is by definition the psychometric function, Fig. 15 c, while their situation along the frequency scale is the constant error or systematic time error.

As demonstrated earlier, JAROSZEWSKI [53, 54] constant errors are small in normal hearing subjects and comparatively large in hearing impaired with noise induced sensorineural hearing loss. Also constant errors reflect the amount of cochlear impairment being relatively small at frequencies where normal hearing is preserved and increasing dramatically at frequencies of hearing loss. The CE often increases by a factor of 10 to 100, see Fig. 16.

In the case of noise induced high frequency sloping hearing loss e.g. such as in Fig. 16 a, it means that while 1 kHz is perceived by the subject at its normal pitch, the pitch of 5.5 kHz is shifted by 100 Hz (i.e. 1/5 of a semitone). It seems to be interesting to note that in some cases, in the range of hearing loss, constant error changes abruptly its sign as demonstrated in the examples in Fig. 16 a, b. The intersubject change of sign in constant errors was observed in the earlier experiments by RAKOWSKI and HIRSH [81, 82]. The intersubject abrupt change of sign in constant errors from frequency to fre-

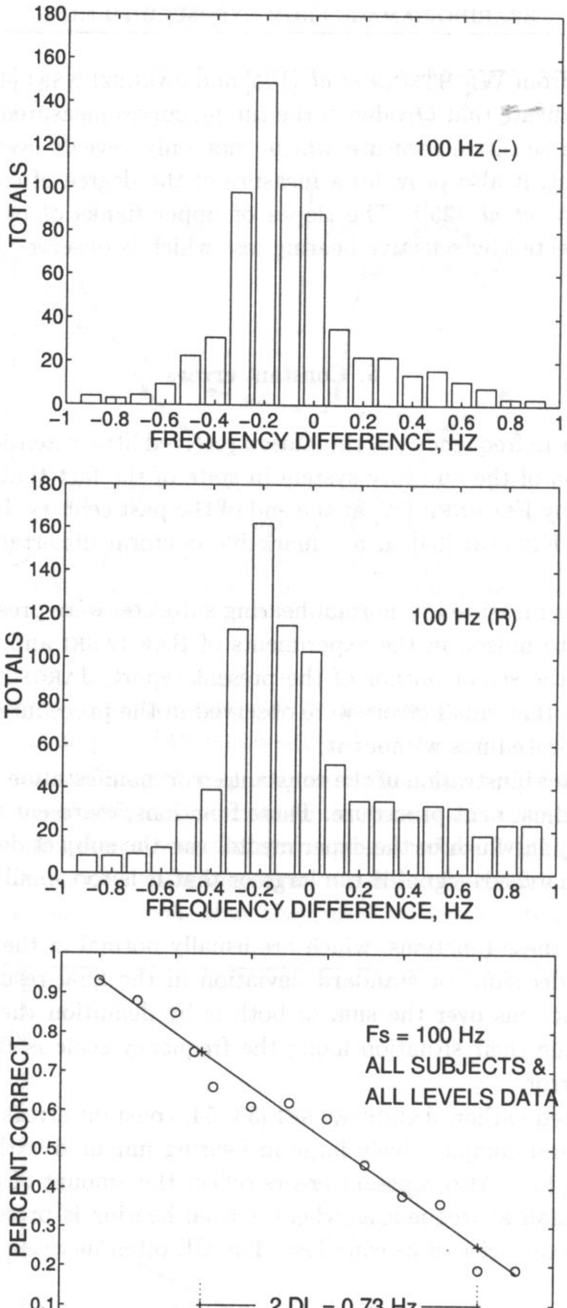
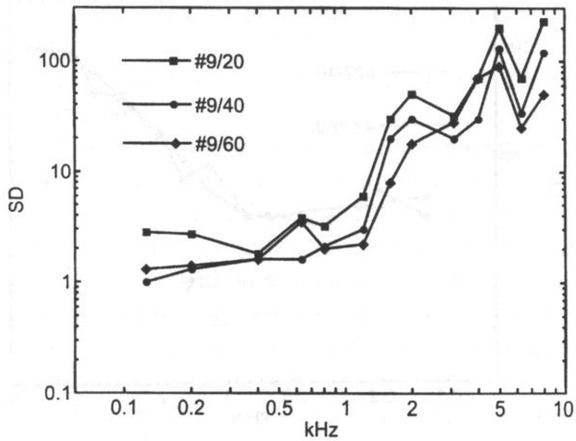
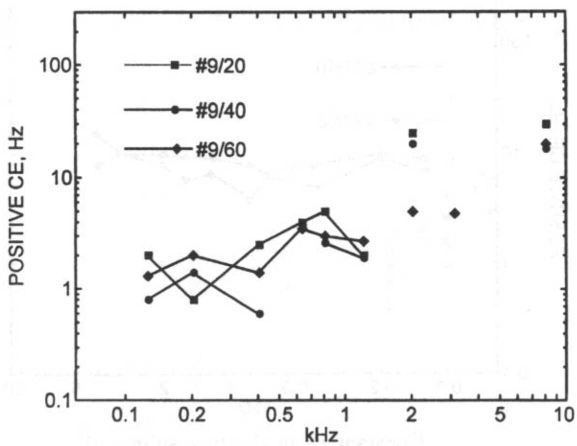


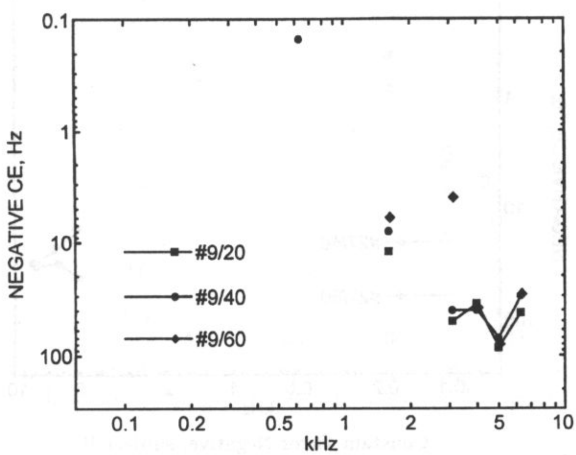
Fig. 15. a) Response density function for 100 Hz averaged over 12 subjects. Total number of "moves" made from the situation in which the variable signal was estimated as "too low" in pitch. b) Response density function for 100 Hz averaged over 12 subjects. Total number of "moves" made from situation in which the variable signal was estimated as "too low" and "too high" in pitch. c) Psychometric function derived from the response density functions given in Fig. 15 a and 15 b.



Frequency difference limen (DL), subject A

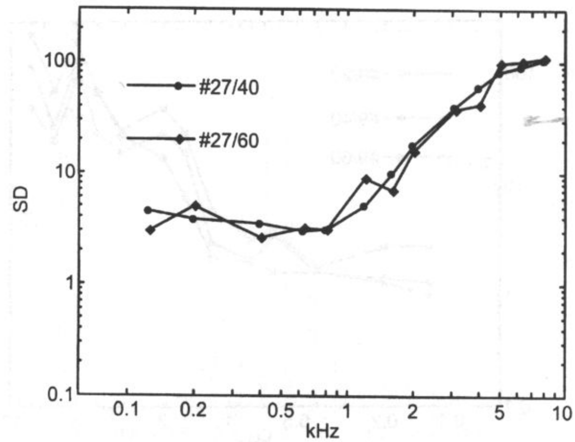


Constant Error Positive, subject A

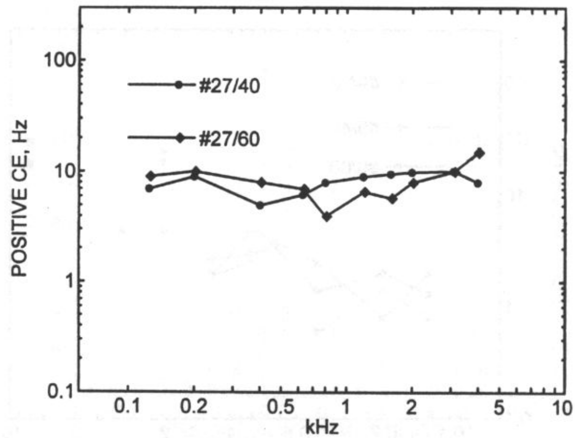


Constant Error Negative, subject A

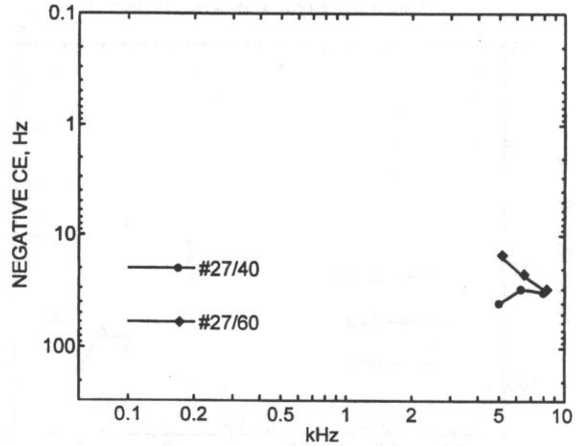
Fig. 16.



Frequency difference limen (DL), subject B



Constant Error Positive, subject B



Constant Error Negative, subject B

Fig. 16. Frequency dependence of the frequency difference limen DL and of the constant error CE for two subjects A and B, with large high frequency sloping hearing loss and with abrupt change in CE sign. The data for sensation levels 20, 40 and 60 dB for subject A and for 40 and 60 for subject B.

quency was reported only recently, JAROSZEWSKI [53, 54], and the origin of this strange phenomenon is totally unclear.

In all cases of normal hearing an absolute magnitude of constant errors was strongly positively correlated with the difference limen estimator for frequency. The same dependency was observed in cases of impaired hearing of sensorineural nature both in cases of deep impairment and in relatively moderate hearing loss, JAROSZEWSKI [53, 54]. Therefore, constant errors should be recognised as indicators of cochlear impairment reflecting one more deficiency of the auditory system resulting from, or accompanying the noise induced decrease of sensitivity. This deficiency shifts the pitches of perceived signals and it may add to their distortion.

In cases of presently often measured in young musicians and non-musicians selective noise induced hearing loss at 6 kHz ("notch"), the constant errors confirm the principle observed in large hearing loss, being small outside the frequency of hearing loss and larger by a factor of 3 to 8 at the frequency of impairment, Fig. 17.

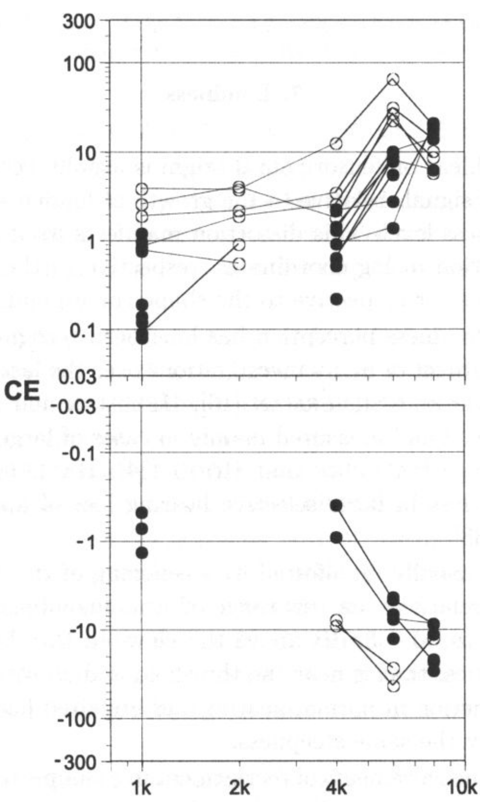


Fig. 17. Scatter diagram of constant errors CE data in subjects with V-dip ("notch") hearing loss at 6 kHz, at the frequency of loss and outside of this region.

However, this is true only for the "notches" or selective hearing loss exceeding HL 20 dB. For smaller selective hearing loss of approximately 10 dB in 60% of cases the CE was found to be the same or comparable to the CE outside hearing loss.

Whilst it is doubtful if relatively small or moderate constant error can affect the perception of pitch in normal human communication i.e. speech, music or warning signals in a detectable degree, it doubtless reflects the state and the operation of the auditory system which is abnormal. Even small deviations from what should be normal must be regarded as an evidence of the initiated process of degradation.

Statistical analysis of the large data base for frequency discrimination and constant errors indicates that both are independent from the sensation level within the whole range of frequencies investigated i.e. from 100 Hz to 9 kHz. This result is statistically significant at level of 0.01 for sensation levels 20 and 40 dB SL and at level 0.03 for sensation level 60 dB, which is in agreement with the earlier observations. However, significant intrasubject and intersubject variability was found with reference to the magnitude of constant error and its dependence on frequency. Analysis of the data base indicated that the dependence of constant error on frequency reflects individual characteristics of the auditory system, JAROSZEWSKI [53, 54].

7. Loudness

Hearing loss of cochlear or sensorineural origin is usually accompanied by distortion of perception of sound signals relative to the growth of loudness as a function of sound pressure level or loudness level. This distortion manifests itself often in increase of the slope of loudness function in log coordinates, respective to the slope observed outside the region of hearing loss or respective to the shape corresponding to normal hearing.

Such distortion of loudness perception has long been recognised as the so called recruitment and was a subject of many investigations over the last 70 years (e.g. FOWLER [26], BÈKÈSY [4], DAVIS and SILVERMAN [16], HELLMAN and MEISELMAN [37]). The recruitment was observed and measured mainly in cases of large, over 40 dB, and widespread hearing loss (e.g. HALLPIKE and HOOD [34], HALLPIKE [33], HELLMAN and MEISELMAN [37, 38]), less in large selective hearing loss of approx. 70 dB, HELLMAN and MEISELMAN [37, 38].

The recruitment is usually manifested by steepening of the loudness function in log coordinates only over relatively narrow range of stimulus intensity, which spreads from approx. 5 – 15 dB up to 30 – 35 dB above the elevated threshold. Below this limited range of sound intensities, that is near the threshold and above 30 dB over the elevated threshold, loudness function in normal-hearing and impaired-hearing with sensorineural hearing loss has usually the same steepness.

The data from the measurements of recruitment in a sample of 149 hearing – impaired subjects with noise induced hearing loss show that in the range of recruitment the slope of loudness function is always in excess of approx. 0.5 and reaches 6.0 in some cases, showing substantial intersubject variability, Fig. 18.

In normal hearing, or in hearing impaired subjects in the frequencies where normal hearing was preserved, the slope of loudness function is usually lower than 1.5 and sometimes is as low as 0.5, as reported by JAROSZEWSKI *et al.* [58]. These data are rather

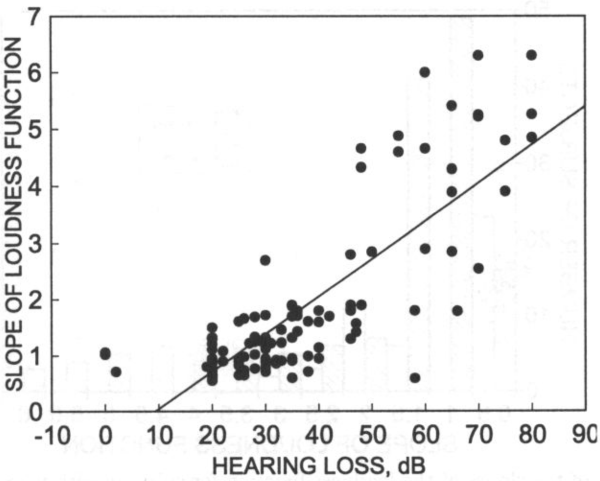


Fig. 18. Scatter diagram of the slope of the loudness function relative to the degree of hearing loss in 149 subjects with noise-induced hearing loss.

in agreement with the recent data from HELLMAN [36] and HELLMAN and MEISELMAN [37, 38], and also with the early data from HALLPIKE [33].

In normal hearing subjects and in hearing impaired outside of hearing loss, inter-subject variability of the shape of loudness function is much smaller than in hearing impaired with wide-spread hearing loss or in hearing impaired with selective hearing loss, at frequencies of loss.

Statistical analysis of the data from the sample of 76 subjects with high frequency sloping noise induced hearing loss clearly indicates that steeper slopes of loudness function are strongly positively correlated with the amount of hearing loss. The same holds for the slopes of loudness function measured in subjects with selective V-dip or notch shaped hearing loss. While the slope is correlated with the amount of hearing loss, the variance of slope values observed reflect the variability of the depth of hearing loss. It is obvious thus, why the variance of the slopes for normal hearing that is also demonstrated in histogram in Fig. 19 is much smaller than in hearing impaired.

An example of typical behaviour of loudness function in musician with large sloping high frequency hearing loss is given in Fig. 20, and similar behaviour was observed in 50 subjects in a sample of 76 with high frequency sloping hearing loss.

Typical slopes of the loudness function in normal hearing subject are given for comparison in Fig. 21.

Individual data on recruitment in selective V-dip music noise induced hearing loss in young musician are given in Fig. 22, showing significant change of the slope of loudness function at the frequency of hearing loss and at sensation level of 15 dB. At sensation level of 50 dB and at the same frequency of hearing loss (4 kHz) the slope of loudness function is less than at adjacent frequencies at both sides of the impairment.

This kind of recruitment was observed in 30% of the sample of 76 examined ears with noise induced selective hearing loss at 6 kHz or at 4 kHz.

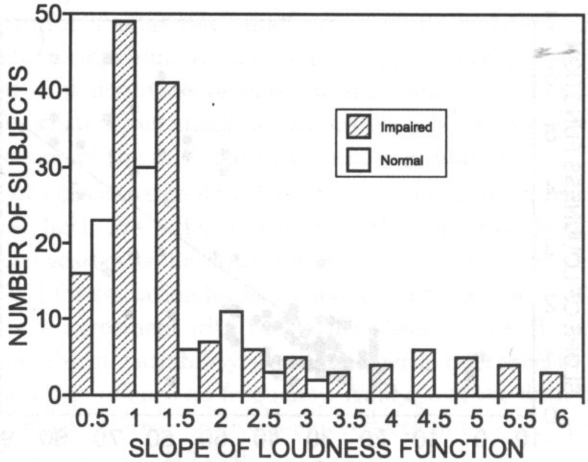


Fig. 19. Distribution of the slopes of the loudness function for subjects with noise induced hearing loss and with normal hearing.

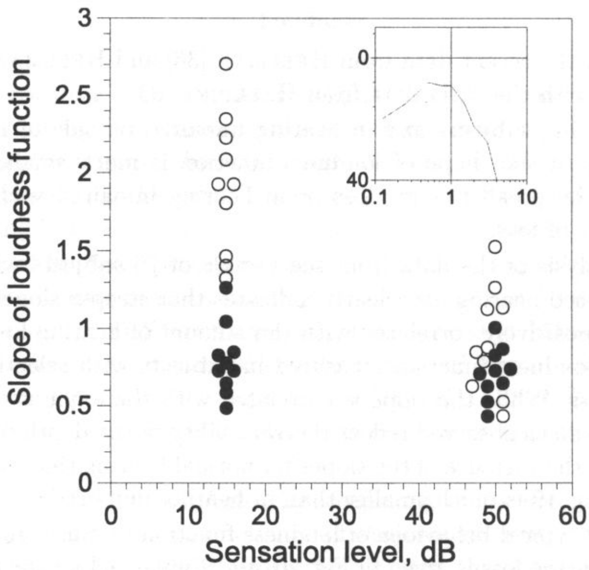


Fig. 20. The slope of the loudness function in musician with sloping high frequency hearing loss.

In some cases of selective noise induced hearing loss measured in young musicians a distortion of loudness function of the nature reversed respective to the recruitment was observed. This type of distortion is manifested, similarly as the recruitment, in the range of approximately 5 dB up to 35 dB SL above the elevated threshold. This type of distortion of the loudness function was also observed in other laboratories and is known as a "decruitment". Typical example of "decruitment" accompanying music noise induced hearing loss of V-dip "notch" type, 35 dB deep at 4 kHz is represented in Fig. 23.

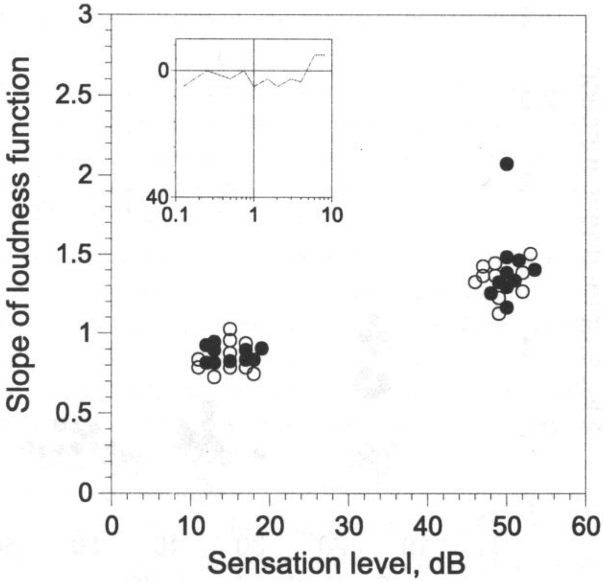


Fig. 21. Typical slope of the loudness function in normal hearing subject.

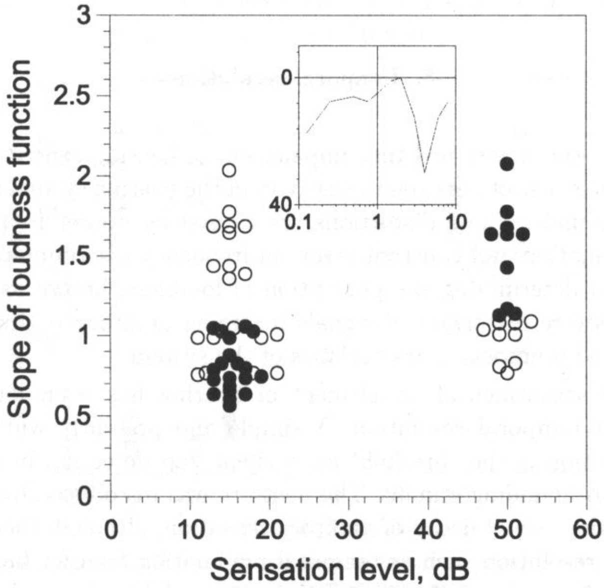


Fig. 22. Recruitment in the selective V-dip ("notch") music-induced hearing loss.

While flattening of the loudness function is largest at 15 dB, in a smaller degree flattening is also present at 35 dB and at 50 dB. Unfortunately, no data are available for sensation levels larger than 50 dB. It should also be observed that in some cases of recruitment at 15 dB SL a decruitment was measured at 50 dB SL.

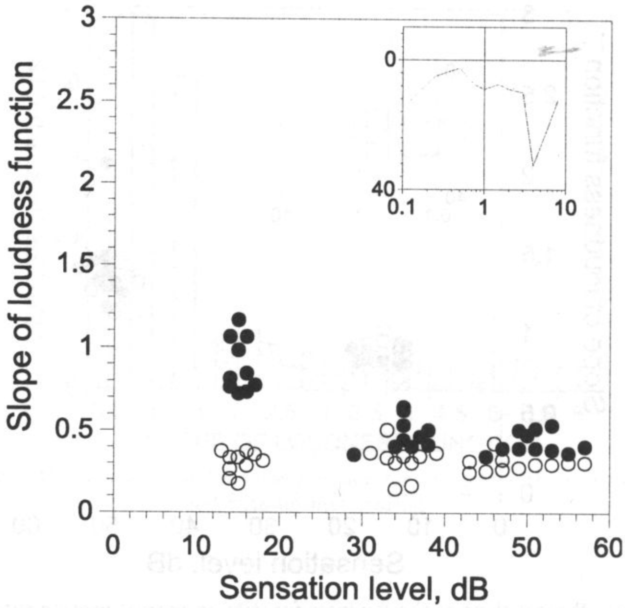


Fig. 23. "Decruitment" in the selective V-dip ("notch") music-induced hearing loss.

8. Temporal resolution

It has already been mentioned that impairment of hearing caused by acoustic overstimulation results in loss of pure tone sensitivity of the hearing system and in distortions of the incoming signals. These distortions are caused by poorer frequency resolution, frequency discrimination and constant errors in frequency discrimination and by deformation of function determining the perception of loudness, known as recruitment and as decruitment. Severe distortion of signals incoming auditory pathways may also be produced by altered temporal characteristics of the system.

Noise induced sensorineural impairment of hearing has been found by some researchers to affect temporal resolution. A simple and presently widely used measure of temporal resolution is the threshold for a silent gap detection in a continuous signal or between two bounding stimuli. The measure was introduced by PENNER [76] for determination of the rate of decay of auditory sensation, although there are other measures of temporal resolution such as temporal modulation transfer function introduced by VIEMEISTER [97], or discrimination of time-reversed signals, used by RONKEN [86], or gap difference limen, RUHM *et al.* [88], TYLER *et al.* [95].

Many researchers e.g. BOOTHROYD [6], TRINDER [94], FITZGIBBONS and WIGHTMAN [23, 24], BUUS and FLORENTINE [9], GLASBERG *et al.* [30] have found that gap detection thresholds are larger in subjects with cochlear impairment than in normal hearing. On the other hand MOORE and GLASBERG [72], MOORE *et al.* [73] observed that, for sinusoids at least, gap detection thresholds in normal and in impaired hearing are about the same, while TYLER *et al.* [95] obtained worse scores in gap detection for some hearing impaired listeners.

With reference to these data GLASBERG *et al.* [30], MOORE and GLASBERG [72], and PLACK and MOORE [77] declared that poorer gap detection in hearing impaired could result from distortion of loudness perception. This interpretation was supported by experiments with simulated effect of loudness recruitment, GLASBERG and MOORE [31]. On the other hand, PLACK and MOORE [77] found reduced temporal resolution in impaired hearing in one of the three subjects tested.

Gap detection in narrow band noise but without notched noise masking at center frequency performed with normal hearing music students shows a little lower gap detection thresholds than those reported by SHAILER and MOORE [90]. The experiment was performed at only 4, 6 and 8 kHz to avoid the influence of fluctuations of noise and at sensation level of 20 dB SL. Thresholds in 6 normal listeners were almost all lower than 3 ms.

The same experiment was performed with 9 hearing impaired musicians with severe noise induced high frequency sloping hearing loss of 50 to 65 dB for frequencies above 1 kHz. They had normal hearing at frequencies lower than 1 kHz except for one who had normal hearing below 750 Hz only. In seven cases the measured gap detection thresholds were substantially worse than in normal hearing young subjects, reaching from 5.0 to 25.0 ms, see Fig. 24. In two cases gap detection was close to the threshold measured in young normal hearing musicians, amounting to 3.0 and 4.0 ms.

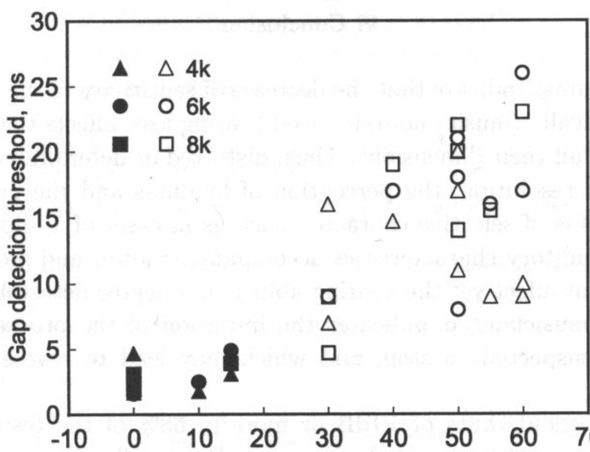


Fig. 24. Gap detection threshold in normal and hearing impaired subjects related to the degree of hearing loss at the test frequency.

Measurements of the gap detection thresholds in 2 music students with "notch-shaped" selective noise induced hearing loss at 6 kHz performed at the frequency of loss and at two adjacent frequencies above and below 6 kHz gave the results comparable to those for normal-hearing subjects. No difference was obtained between the data at the frequency of loss and outside of it.

It seems to be not easy to interprete these results with existing major controversy, Moore (1993), as to whether noise induced sensorineural impairment of hearing affects temporal resolution. Present data clearly suggest that such dependence exists at least in cases of relatively deep and wide-spread cochlear hearing loss. The present data, JAROSZEWSKI *et al.* [57] are in some conflict with the data from GLASBERG *et al.* [30] and MOORE *et al.* [73] and with suggestions by PLACK and MOORE [77], who recognised "gap detection as not adequate way of measuring temporal resolution". However, the data are consistent with findings by TYLER *et al.* [95, Fig. 1, p. 749] who also found large proportion of their impaired subjects performing worse than normal hearing.

Much better gap detection thresholds at high frequencies result, as it was pointed out by FITZGIBBONS and WIGHTMAN [23] and by TYLER *et al.* [95], from the small time constants and large bandwidths of high frequency auditory filters.

Referring to the present consideration whether gap detection experiment is a good or worse measure of temporal resolution, it is evident that in a good number of reports (and the present) the data for the gap detection threshold show marked differences between normal and hearing impaired subjects. No indication of worse temporal resolution from the gap detection experiment with noise induced hearing loss in music students is ambiguous. It may be that temporal resolution in cases of selective noise induced hearing loss is preserved at normal level. However, the gap detection threshold procedure applied may be not sensitive enough.

9. Conclusion

The present findings indicate that the decrease of sensitivity of the hearing system or hearing loss, specifically (music) noise-induced hearing loss, affects the perception of the auditory signals in all their dimensions. Thus, distorted or deteriorated is the frequency discrimination and resolution, the perception of loudness and the perception of time, even if hearing loss is of selective character, such as in cases of V-dips at 6 kHz. While the distortion of auditory characteristics accompanying lower and moderate degrees of hearing loss may not affect yet the hearing ability in a degree detectable in professional activity of young musicians, it indicates the initiation of the process of impairment, which cannot be suspected to stop, and which may lead to severe disability of the hearing system.

Permanent threshold shifts of 10 dB or more in 68% of the tested sample of 214 (and 30 dB or more in 10%) are quite alarming. Practically there is less than 10% of the population of young musicians in which no marks of overexposure were found. Main sources of acoustic trauma are discotheques, portable cassette or CD players, high power home sonic equipment and very loud training sessions of young musicians.

Acknowledgement

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