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Speech intelligibility deterioration for normal hearing and hearing impaired patients with different types of tinnitus

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ABSTRACT

Objectives: Many tinnitus subjects report problems with communication, in particular, difficulties with the intelligibility of speech when it is presented in the background of noise. The type of tinnitus (tone-like, noise, etc.), its location and range in the frequency domain, and the type and degree of accompanying hearing loss can affect speech intelligibility in noise in different ways. The main purpose of this study was to determine the effects of tinnitus and degree of hearing loss on the intelligibility of speech when it is presented in a background noise.
Methods: A group of 128 patients participated in the study. There were persons with tinnitus and sensorineural hearing loss as well persons with tinnitus without hearing loss. All participants were patients of the Laryngological Centre of Rehabilitation, Medical University in Poznań. The age of patients ranged from 31 to 84 years. An additional group of 10 subjects (24–50 years) with normal hearing and without tinnitus took part in this study as a control group. An initial experiment was concerned with the determination of the tinnitus type. A band of noise of different widths (Q-factor, goodness), with varying centre frequency (f) was used to match the perceived tinnitus type. The Q factor is the ratio of the centre frequency to the noise bandwidth. In the main experiment, the Speech Reception Threshold (SRT) was measured using The Polish Sentence Test (PST). In this test, short sentences were presented in a background of a so-called babble-noise reflecting the averaged spectrum of Polish speech.
Results: among the different types of signal used by patients to match their tinnitus, the ones most often used were broadband noise in the medium frequency range (BM) and tone-like high-frequency noise (TH). The average Speech Reception Threshold (SRT) for tinnitus patients with normal hearing was 3 dB higher than that for the control group. The highest deterioration in speech intelligibility was observed for broadband tinnitus, located in the mid-frequency band (1.5–5 kHz).
Conclusions: Tinnitus patients with normal hearing threshold have significantly higher speech reception thresholds (SRT, on average by 3 dB) than normally hearing subjects (control group, without tinnitus), when the speech is presented in a background of babble-noise. Patients with flat audiograms had SRT values on average about 2.5 dB lower than patients with sloping type audiograms (with greater loss at higher frequencies). On average patients in the age group up to 60 years had 4 dB higher SRT values than the control group, and in the older group of patients (above 61 years) - values were 5 dB higher than in the control group. A significant effect of tinnitus located in the medium and high frequency band on the increase of SRT was noted in normally hearing patients and also in patients with mild hearing loss. For higher degrees of hearing loss, the factor that determines the deterioration of speech intelligibility is the hearing loss (moderate and severe), not tinnitus.

1. Introduction

Tinnitus is a phantom auditory sensation in one or both ears in the absence of an external acoustic stimulus. The term 'tinnitus' derives from the Latin *tinnitre*, which means 'to ring'. The perceived tinnitus sounds can be tone-like or noise-like but common descriptions of the tinnitus percept given by patients are 'ringing', 'whistling', 'humming', 'buzzing', or 'rustling'. The data published so far show that about 15% of

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the world's population complain of tinnitus symptoms and at least 8% report that this disease is difficult for them as it interferes with work or leisure. The incidence of tinnitus increases with age, especially after 40 years in women and 50 years in men (Møller, 2011). Due to the large number of people with this type of ailments as well as their nature, tinnitus has been recognized as a social disease (Langguth, 2011). It is often one of the factors contributing to the onset of depression (Aazh and Moore, 2017) and may contribute to suicidal ideations (Aazh and Moore, 2018). A very important factor contributing to an increased risk of the appearance of tinnitus is exposure to noise (industrial, traffic, associated with loud music or impulse noise) (Guest et al., 2017).

The main purpose of the presented study was to determine the effect of the tinnitus and degree of hearing loss on speech intelligibility presented against a background noise in two groups of participants (patients with tinnitus and sensorineural hearing loss as well as patients with tinnitus without hearing loss).

Currently, the literature presents different models for as possible mechanisms of tinnitus generation. For example: an animal model, a physiological-behavioural model of tinnitus (Eggermont, 2012; Jastreboff, 2007), a model based on cochlear dysfunctions (Jastreboff, 2007), a model based on neural synchrony (Eggermont and Roberts, 2004) or a model referring to the phenomenon of central auditory gain (Norena and Farley, 2013). It seems that the most important one is the neurophysiological model, proposed by Jastreboff (2007). In this model, the primary activating cause of tinnitus is dysfunction of the cochlea. Improper functioning of the cochlea results in abnormal neuron activity. This activity affects the limbic system which is responsible for emotions. As a consequence, tinnitus is produced, causing anxiety and nervosity. Schaette and McAlpine (2011) found that individuals with tinnitus had low amplitude wave I but normal amplitude wave V, which inspired the "central gain" theory as a possible cause for tinnitus generation. They demonstrated that patients with tinnitus and normal hearing threshold have a deficit in auditory nerve (AN) function manifested as a reduction in nerve output at high sound levels, indicating deafferentation of high-threshold AN fibers. Consistent with the central gain theory, Valderrama et al. (2018) found that individuals with tinnitus had statistically greater scores in the waves I and V amplitude ratio compared to individuals without tinnitus.

Tinnitus is also closely related to hearing loss. The majority of tinnitus patients are also affected by hearing loss (Nicolas-Puel et al., 2002) and the occurrence of tinnitus is usually related to steep audiogram slopes (Konig et al., 2006).

The general knowledge of tinnitus as well as direct reports of tinnitus patients strongly suggests that tinnitus markedly influences speech intelligibility (Andersson et al., 2009, Degeest et al., 2017; Wicher et al., 2010). However, speech signals across different languages, even those composed of similar phonemes, are markedly different. The phoneme content of each language is different and in some languages the number of fricatives, i.e. phonemes carrying much less acoustic energy than vowels, is markedly higher (e.g. Polish language). However, the energy of the fricatives is concentrated mainly in high frequency band and therefore a hearing loss (usually higher in high frequency band) as well as tinnitus (in mid- and/or high-frequency area) may markedly influence the speech intelligibility. Because the tinnitus is recognized as an audible signal, it may produce a sort of masking effect that reduces audibility of hearing external signals and what is more important, reduces the intelligibility of speech signals. Therefore the tinnitus masking effect can be considered, at least in part, as an energetic masking effect (Pollack, 1975).

The majority of energy of many phonemes in the Polish language is located in a high frequency band (5–10 kHz) as Polish language is fairly rich in fricatives and stops. These two types of phonemes are very often used in spoken language (as taken all together). In the case of 2–3 successively occurring phonemes in Polish language one of them is either a stop or fricative. The levels of these particular phonemes are at least a dozen decibels lower than the other phonemes. However it would be irrational to assume that they do not influence the speech intelligibility. Therefore it was assumed that for tinnitus patients with normal hearing the tinnitus may significantly decrease speech intelligibility especially in the case of the high-frequency tinnitus type. In other words, if the frequency range of the tinnitus occurrence coincides with the frequency range of speech signals the speech intelligibility may be reduced.

As for the speech intelligibility, the two first formants of the speech signals seem to be the most important frequency components for vowels. Therefore it is expected that for tinnitus patients with moderate and severe hearing loss the speech intelligibility reduction will be markedly high.

2. Method and equipment

The Polish Sentence Test (PST) was used as the speech material (Ozimek et al., 2009; Wicher et al., 2010). The PST consists of 37 lists of 13 sentences in each list. Each list is phonemically balanced for Polish language. All sentences in the test are related to everyday language and are used in the public life, literature, press, theatre, radio and television. Moreover each sentence in the test contains grammatically correct and semantically neutral utterances and consisting of 4 to 6 words. In the test there are no interrogative sentences, imperatives, proverbs or names. Each sentence contains up to 9 syllables, and each word contains no more than 3 syllables (Ozimek et al., 2009; Wicher et al., 2010). The speech intelligibility was measured in a background of a so-called babble-noise, that optimally matches averaged power spectra of test sentences as well as Polish natural speech. The babble-noise was produced by summing up all of the test sentences with random time shifting and reversing half of them in the time domain. The average spectrum of the babble-noise is presented in Fig. 1. The energy of the babble-noise is maximum in the 0.2 to 1 kHz band, corresponding with that of the speech signal. (O'Shaughnessy, 1999).

However, due to many fricatives and stops used in Polish language there is also a lot of energy above 5 kHz.

Specially designed software, implemented in Matlab environment, was used for measurement of speech intelligibility. An adaptive procedure (1-down/1-up) was used to determine the Speech Reception Thresholds (SRTs). The SRT is the signal-to-noise ratio (SNR) for which a listener achieves 50% correct responses (in this case 50% of correctly repeated sentences). The subjects' task was to repeat the heard sentence. The answer was recognized as correct if, and only if, the whole sentence was repeated correctly (including order of words).

Initially, at the beginning of a single test, a correct answer caused a reduction of the SNR by 2 dB, while an incorrect answer caused an increase of 2 dB. After two incorrect answers the software reduced the step of the SNR change to 1 dB and it remained the same to the end of the test. Changes in the SNR were obtained by adjusting the level of the speech signal while the babble-noise level was kept constant at a level of 65 dB SPL.

In order to determine a single SRT value for a subject, three tests were performed, each containing a randomly selected list of 13 sentences, and the three estimates of the SRT were averaged. The tests were performed monaurally and were performed independently for the right and the left ear.

The signals were generated by a PC Sound Blaster audio card via Sennheiser HD 580 headphones. The system was calibrated using an artificial ear simulator B&K type 4152. The system calibration procedure also took into account the compensation of changes in the signal level resulting from non-flat frequency response of the headphones by applying a correction curve in the frequency range from 25 Hz to 10,000 Hz.

2.1. Participants

Tinnitus in patients taking part in the present study was precisely determined in the frequency and the level domain. This has been done

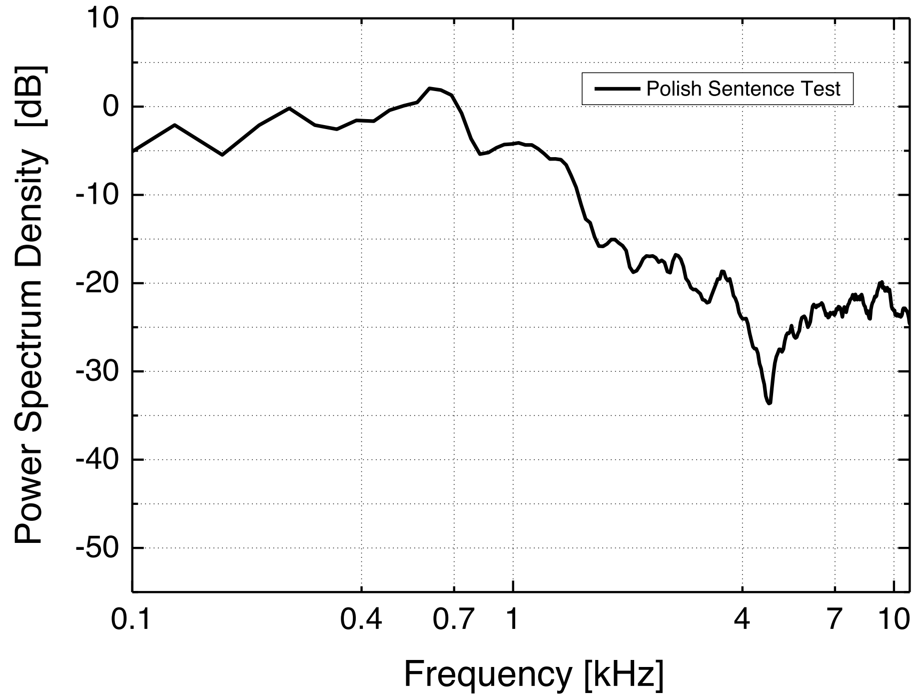

Fig. 1. The long-term power spectrum of the babble noise used in the present study.

using a tinnitus sound matching procedure in which a patient's task was to adjust both the centre frequency (Moore et al., 2010) and bandwidth as well as the level of the monaurally presented signal to be as close as possible to the tinnitus sensation. The study involved 128 participants. There were patients with tinnitus and sensorineural hearing loss as well as patients with tinnitus without hearing loss. All participants were patients at the Laryngological Centre of Rehabilitation, Medical University in Poznań. If any of the patients used hearing aids or any other hearing device, they were asked to turn off and remove the device during the examination. The age range of patients was 31 to 84 years. Participants were divided into four age groups: G1 (up to 50 years) – 31 patients, G2 (51–60 years) - 42 patients, G3 (61–70 years) - 38 patients and G4 (over 71 years) – 17 patients. Moreover, a control group of 10 normally-hearing subjects (up to 50 years) without tinnitus was also used.

Prior to the main measurement, tympanometry and standard audiometry tests were carried out. Tympanometry test results confirmed an absence of conductive hearing loss as results gathered in all participants were type A. Patients were also divided into four groups according to the average value of the absolute threshold determined at the frequencies of 0.5, 1, 2 and 4 kHz (hearing threshold level (HTL) 0.5, 1, 2, 4 kHz) as recommended by the WHO-1997. In addition, different shape of audiograms enabled a selection of two types of subjects. The difference of the absolute threshold at 4 kHz and 0.5 kHz, (i.e. HTL4 kHz - HTL0.5 kHz) was taken into account. If the difference did not exceed 25 dB then the audiogram was classified as "flat", but if the difference exceeded (positive) 25 dB then the audiogram was classified as "sloping".

There were no significant differences in the number of patients (31 to 42) in different age groups except for the oldest patient group in which there were 17 patients. Considering the size of the hearing loss, the largest groups of patients where those with mild and moderate hearing loss. A group of normally-hearing patients consisted of 39 persons while the smallest group were patients with a severe hearing loss.

2.2. Patients' tinnitus characteristics

In order to characterize tinnitus in each patient, apart from standard tympanometry and standard audiometry tests, an initial experiment was conducted whose purpose was to compare tinnitus perceived by the patient with a sound delivered by the headphone. As tinnitus is a subjective phenomenon, it is impossible to measure its physical parameters directly. It is also difficult to evaluate its parameters indirectly and create a signal which would evoke exactly the same sensation as the tinnitus sensation of patients. The only way to assess the tinnitus parameters is to present an acoustic stimulus to the tinnitus patient and adaptively change its parameters to get a signal that creates a sensation as similar as possible to that of the tinnitus. Each patient performed the test, which consisted of listening to signals of different spectral structure and intensity. The structure of the signal was characterized by three adjustable parameters:

- *freq.* – centre frequency of the noiseband,
- Q – factor which describes of the shape of spectrum (actually its bandwidth, goodness), the Q factor is the ratio of the centre frequency to the noise bandwidth,
- L – the level of the signal.

These parameters were changed gradually and the patient's task was to point out the signal which would sound as closely as possible to his/her tinnitus (Niewiarowicz and Kaczmarek, 2011). Noise bands of different widths (Q-factor, goodness), and different centre frequencies (f) were used.

It has been assumed that the noise was treated as broadband (B) when Q-factor was in a range of ⟨0.5, 2⟩, narrowband (N) when Q-factor was in a range of ⟨2, 6⟩ and tonal (T) when Q-factor was greater than 10. When the centre frequency of the band was less than or equal to 1.5 kHz, the noise was classified as a low-frequency noise (L). When the centre frequency of the noise was from the range of 1.5 - 5 kHz than the noise was classified as a mid-frequency (M) noise. For centre frequencies above 5 kHz the noise was classified as a high-frequency noise (H). The level of perceived tinnitus was determined for the selected Q value (goodness) and the centre frequency. When the level did not exceed 25 dB, it was defined as normal level. If it was in the range of 26–40 dB, it was defined as mild level. When it was in the range of 41–60 dB, it was marked as moderate level. However, when it was in the range of 61–80 dB it was marked as severe level. A list of all abbreviations used for noise being the most similar to perceived tinnitus is presented in Table 1. For example, "TL" means a tone-like low-frequency noise.

3. Results

The purpose of the initial part of this study was to identify the type and the level of tinnitus of each patient. The results are presented in Fig. 2, which shows the percentage distribution of tinnitus type according to centre frequency (L, M, H) and quality value (T, N, B), grouped according to tinnitus level (normal level, mild level, moderate level and severe level) for all tinnitus patients. The data presented in Fig. 2 show that the most common tinnitus types were narrowband and broadband in the medium frequency range (M) with a mild level, as well as tonal in the medium (M) and high (H) frequency ranges with mild and moderate levels.

Another analysis of the percentage distribution of tinnitus type with respect to the degree of hearing loss has also shown that the most common type of tinnitus is BM and TH for normal hearing and mild hearing loss (26% of all cases). Analysis of the percentage distribution of the tinnitus type with respect to the shape of the audiogram has also shown the dominance of the tinnitus type BM and TH, for audiograms of the sloping type (23% of all cases). In summary, the most common types of tinnitus in the entire group of patients studied were BM and TH. These cases relate to sloping audiograms, mild and moderate tinnitus levels, and hearing thresholds in the normal range and mild hearing loss.

The mid-frequency band is fairly important for speech intelligibility as many vowel formants fricative noise peaks are within this frequency band. It seems therefore that an energetic type of masking by means of the tinnitus signal may play an important role in this case.

The purpose of the main part of the study was to analyse the effects of tinnitus on speech reception thresholds. To begin this analysis, the level of speech reception threshold (SRT) was compared between the control group (NH-no tinnitus) and the group of patients with tinnitus and normal hearing thresholds (NH-tinnitus). Participants from the most similar age group, i.e. G1, were selected for this comparison. The comparison was made using linear mixed-model (LMM) analysis, based on IBM SPSS Statistics ver. 26.0.1.0. The dependant variable was the "SRT", while fixed effects were "ear" ("left", "right") and "group" ("NH-no tinnitus", "NH-tinnitus"). Random effect was “subject id”. The results of the analysis showed that the “ear” factor was not statistically significant, [F (1276) = 0.94, p = 0.757]. On the other hand, the "group" turned out to be a statistically significant factor [F (1, 58) = 57.08, p <0.001]. The presence of tinnitus in patients with normal hearing was associated with increase of the average SRT by 3.2 dB. The results of this analysis are presented in Fig. 3.

The analysed group (G1) of patients was dominated by tonal tinnitus (T, 42%) in the medium (M) and high (H) frequency bands (76%) with a mild tinnitus level (72%). It should be emphasized that in this case the only factor that decides about statistically significant differences between control group and NH-tinnitus group (i.e. tinnitus with no hearing loss) is the occurrence of the tinnitus. This means that tinnitus in patients with a hearing threshold considered as normal significantly affects (i.e. impairs) the speech intelligibility when speech is presented in a background of babble-noise.

Table 1
Notation of the character of patients’ tinnitus with respect to the physical parameters of the matching signal.

symbol	type of signal	signal parameters (f, Q)
T	tone-like signal	$Q > 10$
N	narrowband noise	$Q = 2$ - 6
B	broad band noise	$Q = 0.5$ - 2
L	low-frequency	< 1,5 kHz
M	mid-frequency	– 5 kHz
H	high-frequency	>5 kHz
normal level	–	< 26 dB
mild level	–	26 – 40 dB
moderate level	–	41 – 60 dB
severe level	–	61 – 80 dB

Subsequent analyses concerned the entire group of 128 tinnitus patients in various age groups, without hearing loss and with hearing loss of various degrees. All analyses were made using the LMM method. The dependant variable was the "SRT", while fixed effects were: "age group" (G1, G2, G3, G4), "HTL group" (normal, mild, moderate, severe), "tinnitus level group" (normal, mild, moderate, severe), “tinnitus Q group” (T, N, B), “tinnitus centre freq. group” (L, M, H) and “audiogram shape” (“flat”, “sloping”). Random effect was “subject id”. Interactions between fixed effects were also investigated Table 2. summarizes all fixed effects.

The results in Table 2 show that the mean hearing threshold (HTL group) has the greatest impact on the SRT values in the study group, [F (3, 732) = 55.12, p <0.0001], followed by audiogram shape [F (1, 684) = 27.11, p <0.0001], then tinnitus frequency (tinnitus centre freq. group) [F (2, 112) = 7.98, p = 0.001] and the age group [F (3, 96) = 4.01, p = 0.01]. In addition, a statistically significant impact on the SRT values was also shown by factors interaction (HTL group * tinnitus centre freq. group) [F (6, 729) = 17.04, p <0.0001], (tinnitus centre freq. group * audiogram shape) [F (2, 673) = 10.76, p <0.0001], and (HTL group * audiogram shape) [F (2733) = 4.72, p = 0.009]. The estimates of fixed effects are presented in the Table III in the supplementary materials. In further analysis, the relationship between SRT and degree of hearing loss was determined. This is shown in Fig. 4.

The mean values of SRT for the tinnitus patients with normal hearing and mild hearing impairment are actually the same and equal to about −3 dB. For moderate hearing loss only, there was a slight increase in SRT to about −2 dB. The highest increase in SRT was found for severe hearing loss. In order to find the statistical significance of the differences between the SRT values in each degree of hearing impairment, pairwise contrast analysis was additionally used at the significance level p = 0.05. The analysis showed that the SRT values for normal hearing versus mild hearing loss are not significantly different. However, for the remaining combinations the differences between the SRT values are statistically significant.

The next stage of analysis focussed on the HTLs at 0.5, 1,2, and 4 kHz. A high degree of variability in these data was noticed. While most of these audiograms showed a significant increase in hearing loss in the frequency range from 0.5 to 4 kHz, there were many cases in which the audiogram pattern was approximately flat showing no or very small increase in hearing loss in this frequency range. It was assumed that, if the hearing loss at 4 kHz is higher than the one at 0.5 kHz by at least 25 dB, then an increase in hearing loss within this range may be a significant factor that strongly influences the SRT. Therefore, all audiograms were divided into two groups with respect to the difference between the threshold for 0.5 and 4 kHz. The audiograms with the difference less than 25 dB were called “flat” while the others were called “sloping”. In the analysed group of patients 40% of audiograms were found to be “flat” and 60% were found to be “sloping”. Average SRT values for these two types of audiogram are presented in Fig. 5.

The data in Fig. 5 shows that the average SRT for “sloping” audiograms is approximately 2.5 dB greater than the SRT for “flat” ones. This is a statistically significant difference. Therefore, it can be concluded that a greater loss of speech information in the frequency range of 2–4 kHz causes more deterioration of speech intelligibility than a flat hearing loss with a comparable average HTL value at lower frequencies. In the case of not only the Polish language, as used in this research, the third (F3) and fourth (F4) vowel formants and part of the consonants’ spectra are located in the 2–4 kHz frequency range. Therefore, these formats may be partially masked resulting in much poorer speech intelligibility.

Age of the patients is also an important factor that determines the value of the SRT Fig. 6. shows the dependence of the mean SRT on individual age groups (G1-G4).

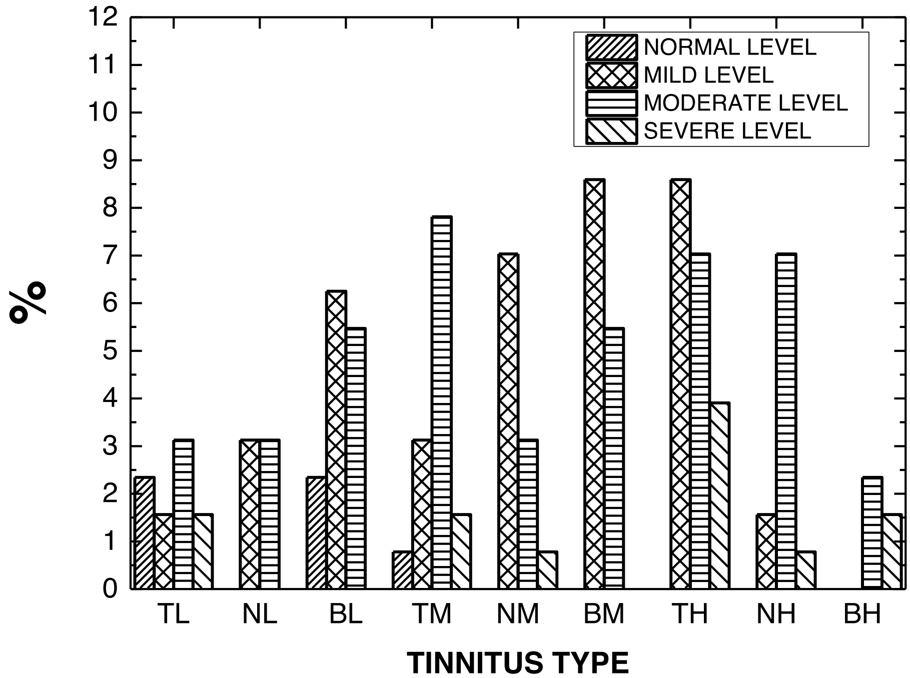

Fig. 2. Histogram of tinnitus types for all patients, by tinnitus level (normal, mild, moderate and severe level – see also Table 1).

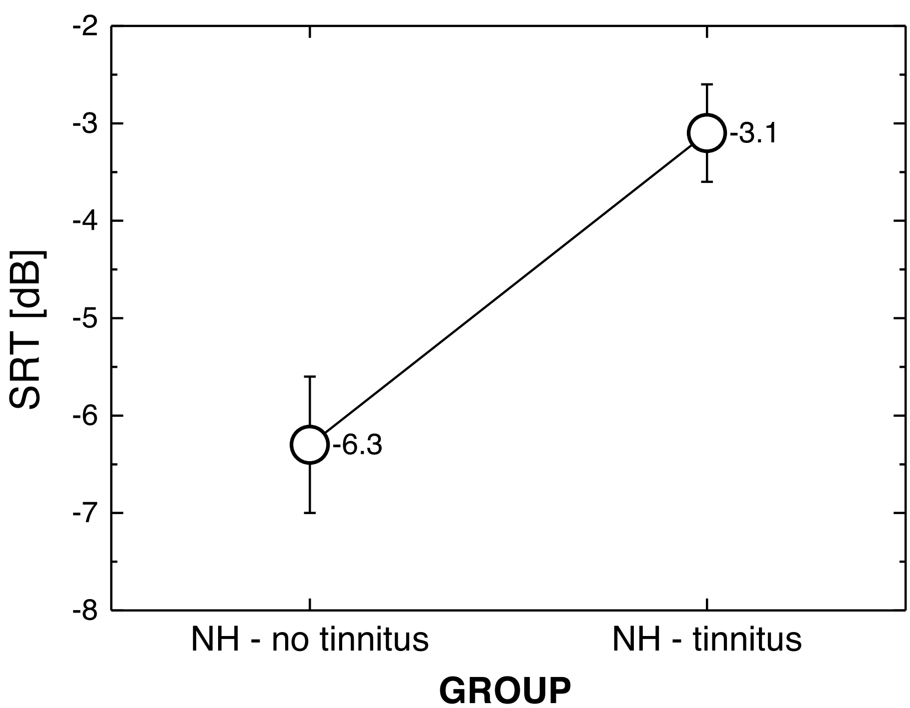

Fig. 3. Mean SRT values for NH – no tinnitus and NH – tinnitus (group G1). Error bars show 95% confidence interval.

As expected, an increase in patient's age is associated with poorer speech intelligibility. For the G1 and G2 groups the mean values of SRT are practically the same, and values for the G3 and G4 groups are also similar to each other. A significant change in the SRT value was observed between the G2 and G3 groups. This means that a significant deterioration in speech intelligibility occurs when patients with tinnitus are over 60 years of age. Additionally, an analysis of pairwise contrasts was performed, which showed that statistically different values of SRT occur between the G1-G3, G2-G3, G1-G4, and G2-G4 groups. Significance level was 0.05. It is also worth pointing out that the 'dynamic range' of the SRT change with age (Fig. 6) and that with increase of hearing loss degree (from to normal to severe) (Fig. 4) are significantly different. In the case of hearing loss from normal to severe the range is about 6 dB while in the case of age it is only 2 dB. Nevertheless, an increase in both age and hearing loss size brings qualitatively the same result, namely increase in the SRT.

LMM analyses showed that the interaction of constant factors (HTL group * tinnitus centre freq. group) is also statistically significant. Therefore, a comparison was made of the mean SRT as a function of degree of hearing loss for each location of the tinnitus centre frequency

Table 2
The results of the linear mixed-model (LMM) statistical analysis: fixed effects.

Fixed Effects, target: SRT				
Source	F	df1	df2	Sig.
Corrected Model	16.964	33	180	0.000
age group	4.011	3	96	0.010
HTL group	55.120	3	732	0.000
tinnitus level group	2.513	3	98	0.063
tinnitus Q group	0.857	2	95	0.428
tinnitus centre freq. group	7.983	2	112	0.001
audiogram shape	27.104	1	684	0.000
HTL group * tinnitus centre freq. group	17.037	6	729	0.000
tinnitus centre freq. group * audiogram shape	10.758	2	683	0.000
tinnitus centre freq. group * tinnitus level group	2.112	5	100	0.070
tinnitus centre freq. group * tinnitus Q group	2.198	4	96	0.075
HTL group * audiogram shape	4.723	2	733	0.009

Probability distribution: Normal
Link function: Identity.

(L, M, H). This is shown in Fig. 7.

In the case of normally hearing patients, no effect of tinnitus centre frequency on SRT value was found. This conclusion was confirmed by pairwise contrasts analysis. For mild degree of hearing loss, the highest increase in SRT was found for tinnitus in the medium (M) and high (H) bandwidths. For the moderate degree of hearing loss, the lowest tinnitus effect was recorded for the low (L) and high (H) bands. However, a significantly greater effect was found for tinnitus located in the medium (M) band. For the highest hearing loss (severe), the highest increase in SRT was found when tinnitus was located in the low (L) and medium (M) bands. It should be emphasized that in the case of tinnitus located in the highest frequency band (H), the SRT value was constant and close to −2 dB, regardless of the degree of hearing loss. When tinnitus was located in the lowest frequency band, the lowest SRT values were observed in the range of hearing losses not exceeding moderate degree. It can be concluded, then, that low-frequency tinnitus does not markedly influence speech intelligibility thresholds.

As shown earlier, the frequency range in which the tinnitus is located is an important factor influencing the values of SRT. It is interesting to compare the influence of the tinnitus frequency and the type of audiogram on the SRT values. The interaction of these two factors, (i.e. tinnitus centre frequency group * audiogram shape), was statistically significant. This interaction is graphically presented in Fig. 8.

For both types of audiogram, the highest SRTs were found when tinnitus was located in the mid-frequency range (M), i.e. in the 1.5–5 kHz bandwidth. Pairwise contrast analysis showed that for all three tinnitus frequency bands, flat audiograms were associated with lower SRTs (by approximately 1.5 to 3 dB) than sloping audiograms. These differences are all statistically significant. In the cases of the analysed frequency bands there are vowel formants (F3 and F4) and some consonants.

4. Discussion

About 15% of the world's population is affected by the problem of tinnitus. In some cases, tinnitus significantly influences on the daily functioning of a person in many areas of life. People with tinnitus may suffer from insomnia and chronic stress, which significantly reduces their quality of life. Research results also indicate a negative effect of tinnitus on speech intelligibility, both in the case of people without hearing loss (Gilles et al., 2016; Liu et al., 2020; Van Eynde *et al.*, 2016; Vielsmeier et al., 2016), and with hearing loss (Andersson et al., 2009; Oosterloo et al., 2020; Wicher et al., 2010). Therefore, this paper is concerned with the speech intelligibility in noise determined by means of the SRT for patients that suffer with symptoms of tinnitus. The main aim of this study was to determine the effect of the tinnitus and degree of hearing loss on speech intelligibility presented against a background noise in two groups of participants (patients with tinnitus and sensorineural hearing loss as well as patients with tinnitus without hearing loss). The patient groups were analysed in different ways with respect to size of hearing loss, tinnitus type, gender, audiogram type, etc. This large group of tinnitus patients was complemented by young normally hearing persons to be able to compare the SRTs across these two groups.

First of all, the results gathered in this study confirmed a negative effect of tinnitus on speech intelligibility, even in the absence of hearing loss. They showed that normally-hearing patients with tinnitus had poorer speech intelligibility in noise in comparison to the control group. The deterioration of speech intelligibility in the NH-tinnitus patients' group was reflected by an increase in the value of SRT by 3 dB. This

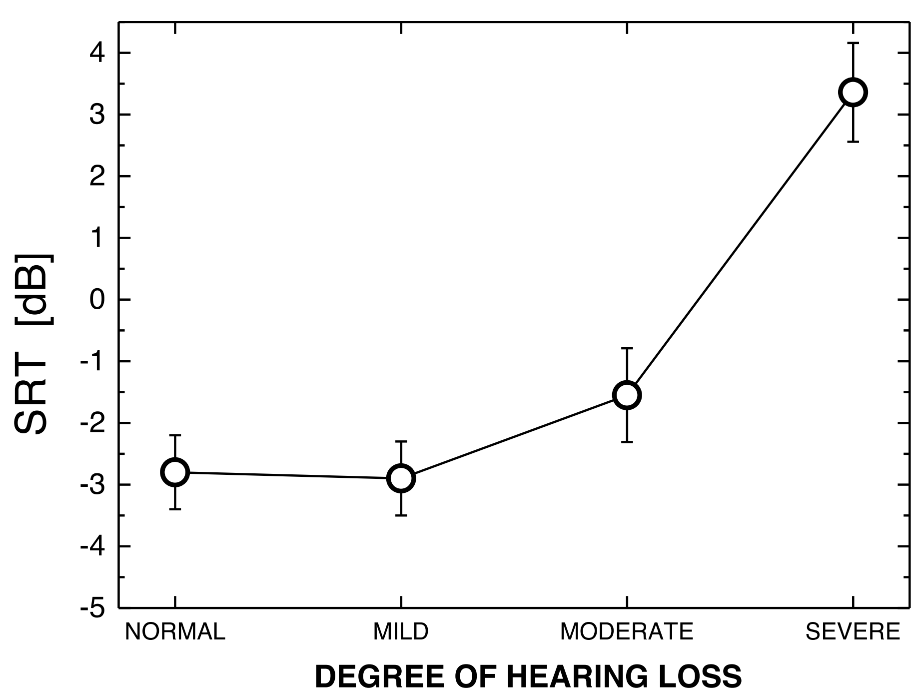

Fig. 4. Mean SRT as a function of hearing loss degree. Error bars show 95% confidence intervals.

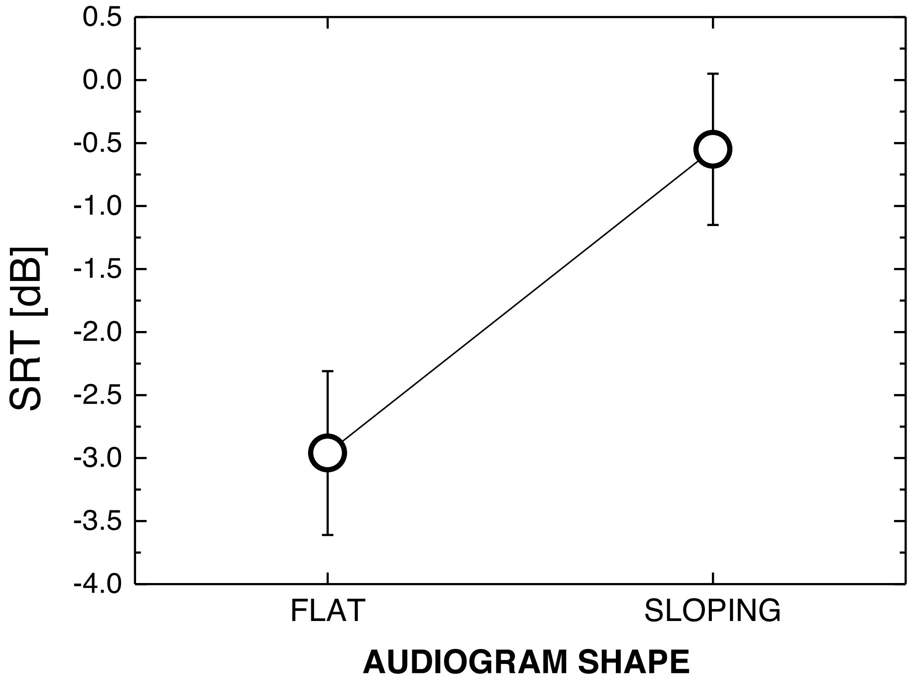

Fig. 5. Mean SRT as a function of the audiogram shape. Error bars show 95% confidence intervals.

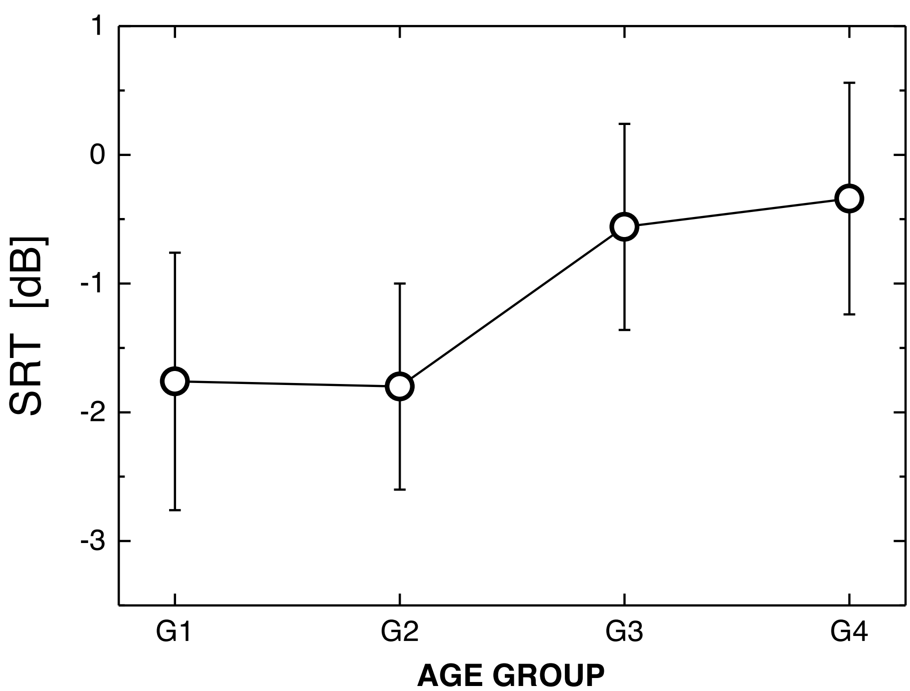

Fig. 6. Mean speech reception thresholds (SRTs) for each age group. Error bars show 95% confidence intervals.

comparison is concerned with groups of participants in a similar age range and is consistent with most reports in the literature. Moreover, the results of this study partly confirm the hypothesis about the negative influence of tinnitus located in the medium (M) and high (H) frequency bands. It can be suspected that the increase in the SRT value was particularly influenced by the middle frequency band, as it coincides with the 3rd and 4th vowel formants and the frequency band in which many consonants are located. The problem of speech intelligibility in normally-hearing persons with tinnitus was analysed in quite a few studies (Degeest et al., 2017; Gilles et al., 2016; Liu et al., 2020; Melcher et al., 2009; Tai and Husain, 2019; Van Eynde et al., 2016; Vielsmeier et al., 2016) Gilles et al. (2016). also studied speech intelligibility in young normally hearing people with tinnitus without hearing loss. They showed that the presence of tinnitus could possibly suggest more centrally located deficits. Moreover, deficiencies in higher-order cortical networks have been found by Melcher et al. (2009) in tinnitus patients with normal hearing thresholds Liu et al. (2020). on the other hand, analysed speech intelligibility for normally hearing people with and without tinnitus. Speech reception thresholds were measured for target speech in the presence of multi-talker babble noise or competing speech. For competing speech, the speech reception thresholds were measured for different cue conditions (i.e., with and without target-masker, sex

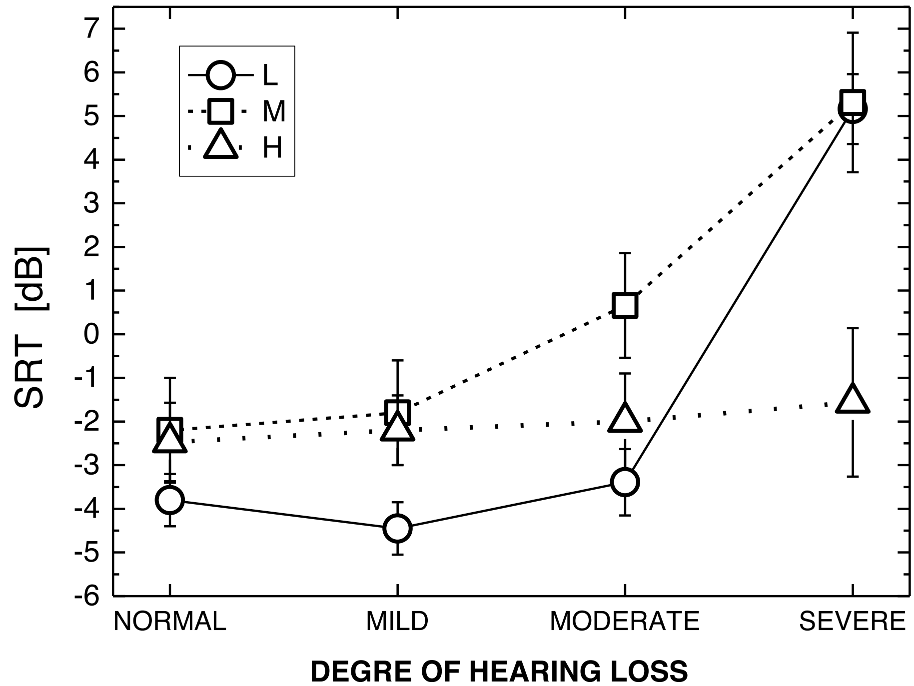

Fig. 7. Mean SRT values as a function of degree of hearing loss for different location of the tinnitus centre frequency in frequency range (low - L, medium - M, and high - H). Error bars show 95% confidence intervals.

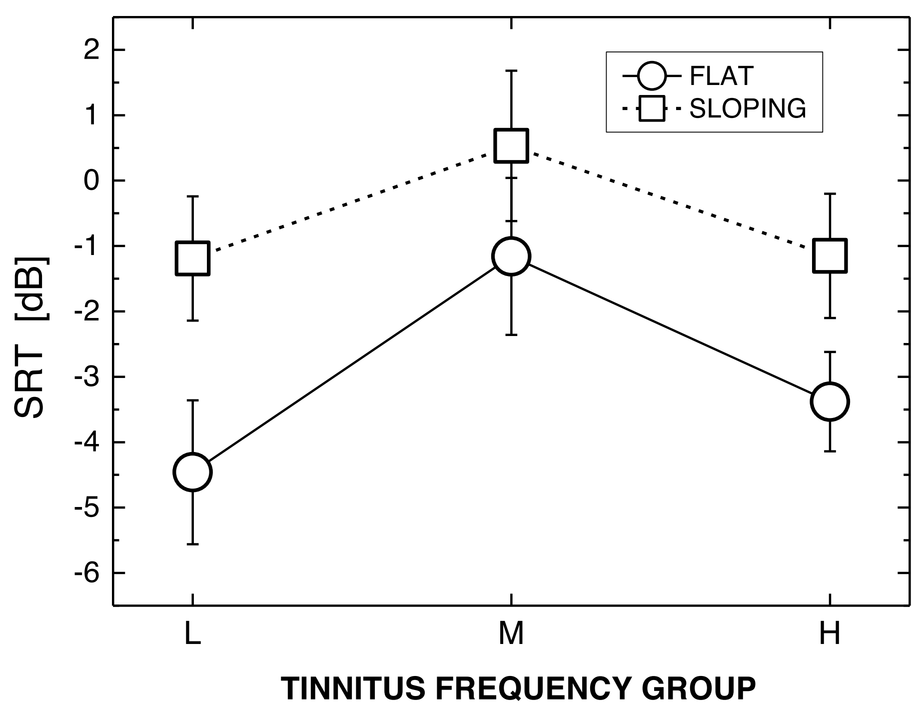

Fig. 8. Mean SRT values as a function of the tinnitus frequency for different audiogram shapes (flat, sloping). Error bars show 95% confidence intervals.

differences and/or with and without spatial cues). The present data suggest that tinnitus negatively affected masked speech recognition even in individuals with no measurable hearing loss Tai and Husain (2019). also reported an impact of tinnitus on speech in noise performance. They observed a poorer recognition of speech in noise in tinnitus patients compared to a control group. They also stated that tinnitus can alter cognitive control processing Van Eynde et al. (2016). also studied people with tinnitus and normal hearing thresholds. The participants of this study reported various problems with speech intelligibility after noise exposure. The Digit Triplet Test (DTT) was used for the speech intelligibility measurements, i.e. three digits spoken at a background of speech-like noise. The results of the study showed a statistically significant deterioration of speech intelligibility in noise for 35% of the participants. Degeest *at al.* (2017) also showed that an internal noise (tinnitus) resulting from dysfunction of the auditory system markedly influences (impairs) speech intelligibility Vielsmeier et al. (2016). also studied speech intelligibility in tinnitus patients without hearing loss. They concluded that whereas speech comprehension deficits in quiet environment are primarily related to the peripheral hearing loss, speech comprehension deficits in noisy environments are related to both peripheral hearing loss and dysfunction of central auditory processing. Disturbed speech comprehension in noisy environments might be modulated by a central inhibitory deficit. Therefore, it can be stated that the results obtained in this study for the NH-tinnitus patients' group are consistent with the results of other studies cited above. Moreover, in this study, the quantitative index of deterioration of speech intelligibility, expressed in the change of the SRT value, was determined.

It is worth to add that despite the normal hearing thresholds, dysfunctions of the auditory system may sometimes occur. Then, we are dealing with the so-called hidden hearing loss Schaette and McAlpine (2011). found that hidden hearing loss and a neurological processes, called "central gain mechanisms", were responsible for the mechanism of tinnitus development and its negative impact on speech intelligibility Schaette and McAlpine (2011). investigated the amplitudes of auditory brainstem responses (ABR) in normal hearing patients with tinnitus. Their results showed a significant reduction in the amplitude of the I wave and a normal amplitude of the V wave. Subjects with tinnitus and normal hearing threshold had a deficit in auditory neurone (AN) function manifested as a reduction in nerve output at high sound levels, indicating deafferentation of high-threshold AN fibers. This phenomenon suggests physiological evidence of hidden hearing loss. This deficit appears to be compensated at the level of the brainstem, supporting an idea that tinnitus is promoted by homoeostatic mechanisms that are able to stabilize levels of neural activity in the central auditory system. It also means that the hidden hearing loss could lead to pathological activity patterns in the auditory brainstem that potentially activate the tinnitus Schaette and McAlpine (2011). suggest that deafferentation of high-threshold AN fibers may be considered as a mechanism for the increased hearing thresholds for tones presented against the noise. This statement correlates with the results gathered in the experiments and presented here: the speech intelligibility in noise for normally hearing patients with tinnitus was about 3 dB higher than the standard values Valderrama et al. (2018). similarly explained the mechanism of tinnitus generation and its influence on speech intelligibility. They indicated that noise-induced cochlear synaptopathy may be responsible for the mechanism of tinnitus formation. This could be a potential cause of tinnitus and decline of speech intelligibility, especially in noisy conditions. Cochlear synaptopathy increased a gain of central parts of the auditory system. In order to take into account possible cases of hidden hearing loss in the NH-tinnitus patients' group, future studies should include such methods as the previously mentioned auditory brainstem responses (ABR) or electrocochleography. It would not be fully clear whether hidden hearing loss or tinnitus was more responsible for the deterioration of speech intelligibility, but it would provide a more complete information of the hearing status of the examined patients. analysing the results of this research by means of LMM analysis for all patients with tinnitus and hearing loss, it was shown that the degree of hearing loss had the most prominent and statistically significant impact on the deterioration of speech intelligibility. The shape of the audiogram as well as the tinnitus frequency and age of the patients also had a significant impact on the values of SRT. However, regardless of the shape of the audiogram (flat or sloping), the highest increase in SRT was found for tinnitus located in the medium frequency band, i.e. from 1.5 to 5 kHz Oosterloo et al. (2020). showed a decrease in speech intelligibility in patients with tinnitus and hearing loss. They also compared the above-mentioned results with results obtained for people with very similar hearing thresholds, but with no tinnitus. Using the Digits in Noise Test (DIN) in their research, they showed a significant statistical effect of tinnitus on SRT in the case of patients with average hearing thresholds $HTL_{0.5–4}$ from 20 to 50 dB. The increase in SRT in people with tinnitus was less than 1 dB, but the difference was highly statistically significant Ayodele et al. (2021). studied the quality of life of people with hearing loss suffering from tinnitus. They tried to determine the quality of life of adult tinnitus patients and the effect of hearing loss has on the quality of life. They stated that tinnitus had a significant health burden which tends to increase with co-existing hearing loss Andersson et al. (2009). also showed that for a given hearing loss, the presence of tinnitus additionally worsens speech intelligibility. The data gathered in the present study have also shown that tinnitus, in most cases, gives exactly the same symptoms as 'a regular' hearing loss without tinnitus. An elevated hearing threshold as well as the reduced speech intelligibility shown here are fully consistent with the cited data Vielsmeier et al. (2016). also showed that in people with hearing loss, the presence of tinnitus causes an additional deterioration in speech intelligibility. This was demonstrated by applying the sentence test presented without an interfering noise.

The results of this study and literature reports indicate that still one of the main problems associated with the diagnosis and rehabilitation of tinnitus is to determine whether tinnitus is of peripheral or central origin. However, recent literature reports generally two stages of the tinnitus mechanism of formation. The first stage is concerned with the development of dysfunction in synaptic connections of the auditory neurons with the inner hair cell, which results in a reduction in nerve output at high sound levels. This also indicates the deafferentation of high-threshold auditory neurons. Then, in the second stage, this deficit appears to be compensated at the level of the brainstem, supporting the idea that tinnitus is promoted by homoeostatic mechanisms, (Schaette and McAlpine, 2011; Valderrama et al., 2018).

5. Conclusions

In summary, the results of this study support formulation of the following general conclusions:

- For tinnitus patients without hearing loss (NH-tinnitus) there is a 3 dB increase in SRT compared to the control group of subjects without tinnitus and hearing loss, within similar age groups.
- The group of normally hearing (NH) tinnitus patients was dominated by tonal tinnitus (T, 42%) in the medium (M) and high (H) frequency bands (76%) and with a mild level (72%).
- The broadband noise tinnitus located in the mid frequency range (BM) as well as tone-like tinnitus located in the high frequency band (TH) were the most common types of tinnitus in the entire group of patients studied in the presented experiments. These cases related to an sloping type of audiograms, mild and moderate tinnitus levels, normal hearing thresholds and mild hearing loss.
- For all patients taking part in the study the following parameters had the most significant influence on the speech reception threshold: hearing threshold level (HTL [$F(3, 732) = 55.12$, $p < 0.0001$]); audiogram shape ([$F(1, 684) = 27.11$, $p < 0.0001$]); tinnitus frequency ([$F(2, 112) = 7.98$, $p = 0.001$]); and patient's age ([$F(3, 96) = 4.01$, $p = 0.01$]).
- For patients with normal hearing thresholds and for mild hearing loss, an increase in SRT was around 3 dB.
- Patients with flat audiograms had on average about 2.5 dB lower SRT values than patients with sloping type of audiograms.
- The frequency location of the tinnitus (frequency band) is an important factor for the increasing value of SRT. Regardless of the shape of the audiogram (flat or sloping), the highest increase in SRT (about 1.5 - 2 dB) was found for tinnitus located in the medium bandwidth, i.e. from 1.5 to 5 kHz.
- Patients in the G1 and G2 age groups (up to 60 years) had a higher SRT values (by about 4 dB) than people in the control group. Also, the older patients (groups G3 and G4) had a higher SNR by about 5 dB than people in the control group.
- A significant effect of tinnitus located in the medium and high frequency band on the increase in the value of SRT was noted in normally hearing and mild hearing loss patients. For higher degrees of hearing loss, the factor that determines the deterioration of speech intelligibility is the hearing loss (moderate and severe), not tinnitus.

CRediT authorship contribution statement

Marek Niewiarowicz: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision, Resources. **Andrzej Wicher:** Writing – original draft, Writing – review & editing, Visualization, Formal analysis. **Aleksander Sęk:** Writing – review & editing, Methodology, Software. **Tomasz Górecki:** Writing – review & editing, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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