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# The Benefit of Binaural Hearing Among Listeners with Sensorineural Hearing Loss

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The performance of binaural processing may be disturbed in the presence of hearing loss, especially of sensorineural type. To assess the impact of hearing loss on speech perception in noise regarding binaural processing, series of speech recognition measurements in controlled laboratory conditions were carried out. The spatial conditions were simulated using dummy head recordings played back on headphones. The Intelligibility Level Difference (ILD) was determined by measuring the change in the speech reception thresholds (SRT) between two configurations of a masking signal source (N) and a speech source (S), namely the S0N90 condition (where numbers stand for angles in horizontal plane) and the co-located condition (S0N0). To disentangle the head shadow effect (better ear effect) from binaural processing in the brain, the difference between binaural and monaural S0N90 condition (so-called Binaural Intelligibility Level Difference, BILD) value was calculated.

Measurements were performed with a control group of normal-hearing listeners and a group of sensorineural hearing-impaired subjects. In all conditions performance of the hearing-impaired listeners was significantly lower than normal-hearing ones, resulting in higher SRT values (3 dB difference in the S0N0 configuration, 7.6 dB in S0N90 and 5 dB in monaural S0N90). The SRT improvement due to the spatial separation of target and masking signal (ILD) was also higher in the control group (8.1 dB) than in hearing-impaired listeners (3.5 dB). Moreover, a significant deterioration of the binaural processing described by BILD was found in people with sensorineural deficits. This parameter for normal-hearing listeners reached a value of 3 to 6 dB (4.6 dB on average) and decreased more than two times in the hearing-impaired group to 1.9 dB on average (with a deviation of 1.4 dB). These findings could not be explained by individual average hearing threshold (standard in audiological diagnostics) only. The outcomes indicate that there is a contribution of suprathershold deficits and it may be useful to consider binaural SRT measurements in noise in addition to the pure tone audiometry resulting in better diagnostics and hearing aid fitting.

**Keywords:** hearing; speech audiometry; speech perception; audiology.

## 1. Introduction

Speech perception in real life conditions is much more demanding than in silence. The influence of the presence of interfering signals is even more crucial in people with hearing loss, especially of sensorineural type – damage of the hair cells in the inner ear (cochlear sensorineural hearing loss) or the nerve pathways that lead from the inner ear to the brain (retrocochlear hearing loss) (ASHA). It results in much higher speech reception threshold (SRT) in hearing-impaired people than in normal-hearing listeners (Wagener, Brand, 2005). Among people with hearing deficits of the first mentioned type it is common to observe a growing speech intelligibility in quiet with increasing speech signal level. Speech curves usually reach maximum without degradation at highest tolerable sound intensities, but it is very rare to observe it on the 100% level. This kind of hearing impairment, connected mainly with improper functioning of hearing cells in the cochlea (or their loss) was the main observed among listeners taking part in described experiments. In patients with retrocochlear hearing loss, which is another type of sensorineural hearing loss, discrimination increases with speech presentation level, reaches plateau at a specific intensity and then decreases with further increase of speech signal level (rollover curve) (Pruszewicz, 2010).

Binaural hearing is crucial for auditory perception in acoustically complex scenarios since it is involved in sound source separation, suppression of reverberation and, in general, reduction of the influence of interferences on the target signal reception. Many studies showed benefit from spatial separation of the speech and noise source on speech recognition (see Bronkhorst, 2000 for an overview; Sęk *et al.*, 2004 for studies considering Polish language). This ability is reduced in hearing-impaired listeners (e.g. Beutelmann *et al.*, 2010; Bronkhorst, Plomp, 1989).

The solution that would improve the auditory functioning of an individual in the environment, especially in the aspect of the communication process, is correctly fitted hearing supporting devices that account for listening in the complex acoustic conditions. Unfortunately, the current technical possibilities used in diagnostics of hearing loss as well as in the fitting procedures of hearing devices rely mainly on the data obtained in measurements performed in silence, using tonal signals or single words in the monaural conditions. Therefore current solutions do not bring satisfactory benefits. In order to increase ecological validity of diagnostic tools a number of speech tests dedicated for accurate assessment of speech intelligibility in noise have been developed (Kollmeier *et al.*, 2015; Soli, Wong, 2008) including speech tests for the Polish language (Ozimek *et al.*, 2010; 2009). This study aims at assessment of binaural speech perception in noise in hearing-impaired listeners using Polish Matrix sentence test.

Speech intelligibility measurements are conducted via headphones using virtual acoustics, i.e., spatial conditions are obtained by convolution of speech and noise signals with desired Head Related Transfer Function (HRTF) recorded with a dummy head. With this approach, it is possible to reflect the effect of diffraction and reflections on the head, as well as the resonance of the system formed by the ear and the external auditory canal. The listener is thus provided with a comprehensive spatial and perceptual impression of a natural listening experience. Simulation of spatial conditions with dummy head HRTFs recordings are assumed to provide similar results in terms of speech intelligibility as when using individually recorded HRTFs (Peissig, 1992; Mandel *et al.*, 2010; Orduña-Bustamante *et al.*, 2018). Efficiency of binaural processing in terms of speech intelligibility is characterized by two parameters: Intelligibility Level Difference (ILD) and Binaural Intelligibility Level Difference (BILD). The ILD parameter is related to the benefit that the listener draws from spatial separation of target and masking signal sources. ILD corresponds to SRT difference between two binaural configurations of sound sources: (a) both speech and noise sources are located in front of the listener (S0N0), (b) speech signal source in front of the listener (azimuth 0°) and masker source at 90° azimuth (S0N90). Due to the head shadow effect and binaural processing, the speech and masker separation leads to an improvement in SRT. The scheme of ILD measurement configuration is shown in the left panel of Fig. 1.

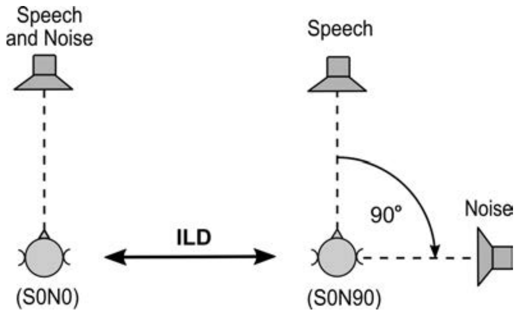


Fig. 1. Scheme of target and masker spatial position in the Intelligibility Level Difference (ILD) measurement setup. ILD is a difference between SRT in S0N0 and S0N90 configuration.

In order to distinguish the impact of the head shadow effect and binaural processing at the central level of auditory pathway, a BILD test is performed, in which SRT is measured in S0N90 binaural condition, and then in the same setting but excluding the ear which is aimed at the masker source – S0N90 (MON). BILD (Fig. 2) is the difference between SRT S0N90 measured monaurally (with "better ear" only, namely with the one on the opposite side of the noise source) and binaurally. Due to the benefits achieved by binaural processing and acoustic head shadow occurrence, the results obtained in the binaural S0N90 condition

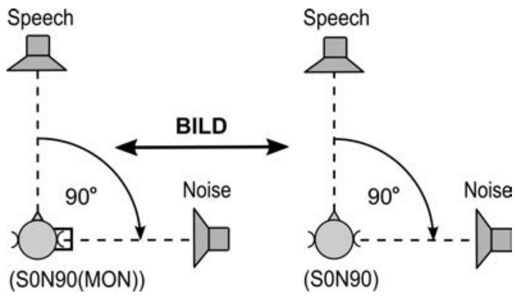


Fig. 2. Scheme of spatial position of target and maskiner in the Binaural Intelligibility Level Difference (BILD) measurement setup.

are better than in the monaural presentation as long as normal-hearing listeners are considered.

ILD and BILD measurements can be seen as an intermediate step towards measuring speech recognition in conditions reflecting real life scenarios that may include more complex settings like moving sound sources, reverberation and multiple sound sources. Although such complex scenes will be important for ecologically valid assessment of hearing loss or benefit from hearing devices, development of reliable methods of speech recognition measurements in such scenes is still subject of current research.

## 2. Method

### *2.1. Aim*

The aim of this study was to focus on speech intelligibility by means of ILD and BILD parameters for hearing-impaired listeners in a simulated spatial conditions (using headphones and recordings from a dummy head) in comparison to the group of normal-hearing listeners.

### *2.2. Stimuli*

In order to simulate the conditions of everyday communication, speech audiometry should be conducted together with the masking signal. The measurement procedure carried out in this manner provides not only information related to the loss of amplification, but also to the supra-threshold auditory processing, taking into account individual factors. Here, the Polish Matrix sentence test and a stationary speech-shaped PolMat noise were used as a speech material and masker, respectively (Ozimek *et al.*, 2010). The masking signal was generated on the basis of multiple superposition of the speech items of the Polish Matrix test, hence the long-term spectrum of the resulting noise corresponded to the spectrum of the speech material. The use of this type of noise is therefore mainly aimed at the energetic masking. Such a test formula was first used for the Swedish language by Hagerman (1982) and it is currently available in about 20 languages (Kollmeier *et al.*, 2015). The so-called Matrix sentence test, consisting of a 50-word base matrix, allows to generate 100,000 five-word, semantically unpredictable sentences with a constant syntax (name verb numeral adjective object). An important feature of the Matrix sentence test is that the test lists are phonetically balanced and are equivalent in speech recognition, which guarantees high reliability of the measurements. All speech recognition measurements were conducted using test lists of 20 sentences. The speech material of the Polish Matrix sentence test is presented in Fig. 3.

| | | | | |
|---|---|---|---|---|
| Adam | bierze | pięć | białych | dzwonów |
| Anna | daje | sześć | czarnych | gazet |
| Ewa | kupi | siedem | dobrych | klocków |
| Julia | ma | osiem | drogich | koszy |
| Maciej | nosi | dziewięć | dziwnych | okien |
| Maria | robi | sto | nowych | opon |
| Michał | sprzeda | tysiąc | pięknych | piłek |
| Paweł | widzi | kilka | starych | soków |
| Tomasz | woli | dużo | tanich | stołów |
| Zofia | wygra | wiele | żółtych | toreb |
| Anna | ma | sto | pięknych | opon |

Fig. 3. Speech material of the Polish Matrix sentence test with an example of a sentence. Each sentence is created by taking one word from each column (name, verb (predicate), numeral, adjective, noun (object)).

### *2.3. Measurement procedure*

Hearing loss was characterized using pure tone audiometry based on the WHO guidelines (WHO/PDH/97.3, 1997), i.e., by calculating the average hearing loss as the arithmetic average of the pure tone hearing threshold for frequencies: 500, 1000, 2000 and 4000 Hz (PTA 4). PTA 4 was used in the analysis in order to link the degree of hearing loss and speech recognition in noise.

In the speech recognition measurements, the default noise level was 65 dB SPL. For 9 hearing-impaired listeners who reported that the noise at 65 dB SPL during the training could not be perceived or was perceived as very soft, the noise level was increased (for eight listeners to 70 dB SPL and for one to 80 dB SPL). Increasing the masker level allowed to measure speech recognition in the presence of audible noise. Individual noise level was set at a level reported by the listener as comfortable, i.e., above the hearing threshold and below the uncomfortable level.

In order to avoid the training effect, the actual measurements were preceded by two training lists presented in a closed-set response format. The first one was presented binaurally at a fixed signal-to-noise ratio (SNR) of 0 dB (for listeners with PTA 4 not exceeding 40 dB HL) and 10 dB (for listeners with PTA 4 higher than 40 dB HL). The second training list was measured adaptively using the 1-up/1-down procedure introduced by Brand and Kollmeier (2002). The noise level was fixed and the speech level was adjusted according to the listener's responses and converged to 50% correct responses, i.e. to SRT. The noise signal started 500 ms before and ended 500 ms after the presentation of each sentence; gated with 50 ms rising and falling ramps using a Hann window. The answers were judged using word-scoring, i.e. each word in a sentence was scored separately as correct or incorrect. The step size of the adaptive procedure depended on the number of correctly repeated words in the previous sentence (Brand, Kollmeier, 2002). The speech level of the subsequent sentences was changed by

$$\Delta L = -\frac{f(i) \cdot (prev - tar)}{slope}, \tag{1}$$

where *tar* denotes the target recognition rate at which the procedure should converge (50% in this study), *prev* indicates the recognition rate obtained in the previous sentence and is used as input for the adaptive procedure setting. The parameter $f(i)$ controls the rate of convergence with $i$ denoting the index of the reversal. The step size is parameterized using the exponential function $f(i) = a \cdot b^{-i}$, with $a$ and $b$ set at 1.5 and 1.41, respectively. These values of parameters $a$ and $b$ have been shown to yield the best convergence to the target (Brand, Kollmeier, 2002). The step size decreases exponentially after each reversal. The final value of $f(i)$ is limited to 0.1. The slope is set at 15%/dB which corresponds to median slope for the sentence test used in this study. The starting SNR was set at 0 dB. The SRT was estimated from the psychometric function (represented by the logistic function) which was fitted to all collected data using the maximum likelihood procedure.

The actual experiment consisted of three adaptive SRT measurements for each participant (S0N0, S0N90 and S0N90(MON)). Those results were used to determine ILD and BILD.

Speech recognition measurements were carried out using the PC-based Oldenburg Measurement Application software (HörTech GmbH, Oldenburg, www.hoertech.de). The measurement setup consisted of a notebook, EarBox (Auritec, Hamburg, Germany) high power sound card, and free-field equalized Sennheiser HDA200 headphones (ISO 389-8 2004). The setup was calibrated to the dB SPL using Brüel & Kjær instruments, i.e. artificial ear type 4153, microphone type 4134, preamplifier type 2669 and amplifier type 2610. Speech and noise signals were filtered with the anechoic HRTFs to simulate desired direction. The HRTFs were taken from a publicly available data base (Algazi *et al.*, 2001) and were recorded with a KEMAR manikin.

### *2.4. Listeners*

The control group consisted of 9 adults aged from 18 to 35 years. All of them were native speakers of Polish language and did not report hearing problems (that was additionally verified by pure-tone audiometry).

The group of hearing-impaired listeners consisted of 16 adults aged from 22 to 85 years (mean age $70.2 \pm 17.2$ years). The listeners voluntarily participated in the experiment and were native speakers of Polish language. All listeners were diagnosed with sensorineural hearing loss of cochlear type, which manifested, among others, in the fact, that speech-perception curves in quiet rarely achieved 100%. For each listener, indications for hearing prosthesis were made according to the BIAP guidelines (BIAP, 1996): the average hearing characterized by PTA 4 exceeded 40 dB HL in the better ear. The mean PTA 4 in the hearing-impaired group was 56.7 dB HL (SD: 9.4 dB) and PTA 4 difference between ears reached on average 6.6 dB.

## 3. Results and discussion

The assessment of binaural phenomena consisted of SRT measurements in three spatial scenarios (S0N0, S0N90 and S0N90 (MON)), which made it possible to determine the ILD ($SRT_{S0N0}$–$SRT_{S0N90}$) and BILD ($SRT_{S0N90(MON)}$–$SRT_{S0N90}$) parameters. The mean SRTs (averaged across listeners) with corresponding standard deviations for control and hearing-impaired group in each measurement condition are presented in Fig. 4.

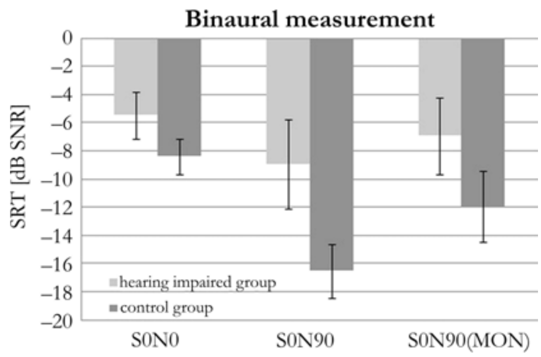


Fig. 4. Comparison of mean SRTs (averaged across listeners) with corresponding standard deviations for three spatial configurations of target and masker for hearing-impaired (light grey) and control group (dark grey).

The mean values of ILD and BILD with corresponding standard deviations (for the hearing-impaired and control group) are shown in Fig. 5.

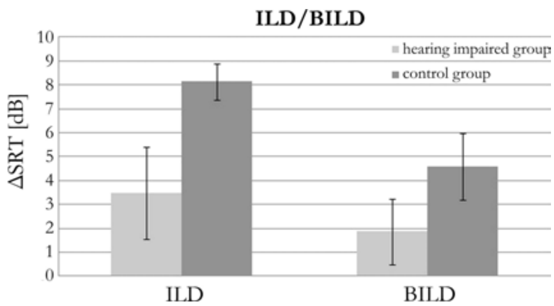


Fig. 5. Comparison of mean Intelligibility Level Differences (ILD) and Binaural Intelligibility level differences (BILD) with corresponding standard deviations obtained for hearing-impaired listeners (light grey) and control group (dark grey).

In order to compare measured SRTs across conditions and listener groups, repeated-measures ANOVA was conducted with a between listener factor 'listener group' and within listener factor 'measurement condition'. The results obtained indicate that hearing-impaired listeners performed significantly worse than control group ($F(1, 23) = 425.3$, $p < 0.001$). The difference between these two groups was 3 dB in the S0N0, 7.6 dB in S0N90, and 5 dB in S0N90(MON) condition. Significant differences in SRTs were also found across measurement conditions ($F(2, 46) = 185.4$, $p < 0.001$). Moreover, the interaction between both factors was statistically significant ($F(2, 46) = 29.6$, $p < 0.001$) indicating different trends across measurement conditions for control and hearing-impaired group.

A one-way repeated measures ANOVA and post-hoc comparisons with Bonferroni correction were performed separately for control and hearing-impaired group. For the control group, SRTs differed significantly across all three measurement conditions ($F(2, 16) = 192.1$, $p < 0.001$; post-hoc comparisons: $p < 0.001$ for S0N0 vs S0N90, $p = 0.003$ for S0N0 and S0N0(MON) and $p < 0.001$ for S0N90 and S0N90(MON)) with lowest SRTs in the S0N90 settings (on average $-16.5 \pm 1.9$ dB SNR). The highest SRTs were observed in the co-located condition S0N0 (on average $-8.4 \pm 1.3$ dB SNR). Monaural condition with spatially separated speech and noise sources (S0N90(MON) resulted in the mean SRT of $-11.9 \pm 2.5$ dB SNR. Post-hoc analysis of the results obtained for listeners with a sensorineural hearing loss showed statistically significant differences between S0N0 (mean SRT $-5.4 \pm 1.7$ dB SNR) and S0N90 (mean SRT $-8.9 \pm 3.2$ dB SNR) conditions only ($p = 0.001$). There was no statistically significant SRT difference for the pair S0N0 and S0N90(MON) (mean SRT $-6.9 \pm 2.7$ dB SNR, $p = 0.36$) and the pair S0N90 and S0N90(MON) ($p = 0.1$). The results showed improvement in SRT after spatial separation of target speech and masking noise for normal-hearing as well as hearing-impaired listeners. However, the differences across listening conditions were smaller in the group of subjects with hearing loss than in the control group indicating that hearing-impaired listeners cannot benefit as much from the spatial separation of the speech and noise as normal-hearing listeners. Also the variability across listeners is higher in the group of hearing-impaired listeners than in normal-hearing listeners as indicated by higher standard deviation of SRT.

Improvement in SRT due to head shadow effect and binaural processing (ILD) was on average $8.1 \pm 1.8$ dB in the control group and $3.5 \pm 1.9$ dB in the hearing-impaired group. The BILD parameter, describing the effect associated with the binaural processing, which for normal-hearing listeners reached a value of 3 to 6 dB (4.6 dB on average), decreases in the hearing-impaired group to 1.9 dB on average (with a deviation of 1.4 dB). This is more than two times less than in the control group.

In line with the previous studies (e.g. Bronkhorst, Plomp, 1989; Beutelmann *et al.*, 2010), the above presented data prove therefore that in people with sensorineural hearing loss, a less effective use of spatial separation of simultaneously presented target and masker signals is observed in the terms of speech intelligibility improvement. This observation also concerns the BILD parameter – the gain in speech intelligibility resulting from the two-ear signal perception, compared to the monaural presentation, is much lower than for normal-hearing people. The reference data obtained with the control group is in line with the results described by the literature for other languages, which indicates that the benefit resulting from spatial separation of target and noise signals, expressed through the ILD parameter, should oscillate between 6 and 12 dB (Wagener, Brand, 2006).

In order to better understand the underlying mechanisms of reduced binaural advantage in the group of hearing-impaired listeners, the SRTs measured in different configurations were compared to individual hearing threshold characterized by PTA 4. Figure 6 shows the dependency between SRTs in a given spatial condition (S0N0, S0N90, and S0N90(MON)) and PTA 4 for the better ear.

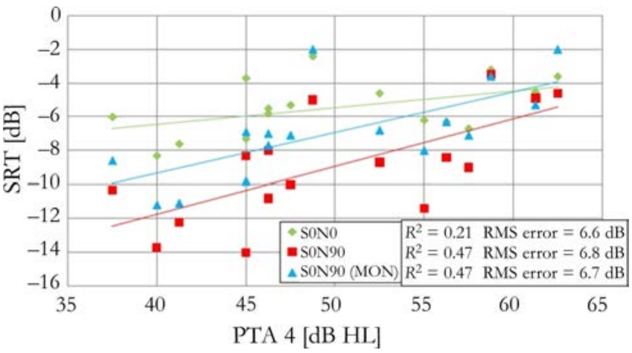


Fig. 6. Scatter plot of SRT measured in three spatial conditions (S0N0 – diamonds, S0N90 – squares, and S0N90(MON) – triangles) and mean hearing loss indicated by PTA 4 for hearing-impaired listeners. $R^2$ values are given for a linear fitting model.

As shown in Fig. 6, with spatial separation of target and masking signal (in S0N90 configurations), the level of hearing loss is better correlated with speech intelligibility than in spatially co-located condition (S0N0), i.e., SRT increases with increasing degree of hearing loss defined by PTA 4. However, in general, the relationship between the observed intelligibility and hearing loss is relatively low (less than 50% of the variance in the SRT data can be explained by the PTA 4). A weak correlation between SRT in S0N0 condition and PTA 4 indicates that speech intelligibility in noise cannot be accurately predicted from individual hearing threshold level what is in line with previous findings (e.g. Festen, Plomp, 1983; Kollmeier *et al.*, 2016). Audibility seems not to be a dominant factor determining performance of hearing-impaired on speech in noise task. Other mechanisms like suprathreshold deficits (e.g. reduced spectral and temporal resolution, Larsby, Arlinger, 1998; Summers *et al.*, 2013) seems to have a strong contribution.

It can be seen in Fig. 6 that, in addition to comparable RMS error values, the regression lines for the spatially separated conditions are parallel to each other. It indicates similar changes of SRT with increasing hearing loss degree in the binaural and monaural S0N90 condition. Therefore, no purely binaural deficits can be found or if they occur then their influence is strongly correlated with the monaural processing deficits. Otherwise another slope of regression line would be expected in the S0N90 and S0N90(MON) condition. Changes in the binaural SRT in co-located condition with increasing hearing loss degree differ from the changes in the spatially separated conditions which is indicated by different slope of the regression line. Generally, the SRT changes in the co-located condition are smaller with increasing hearing loss degree than in the spatially separated conditions.

Analyzing ILD and BILD data, reduction of both parameters with increasing PTA 4 can be observed. For listeners with PTA 4 higher than about 60 dB HL, no benefit can be found from spatial separation of speech and noise source. About 55% of the variance in the ILD data can be explained by the individual average hearing loss (PTA 4). For the BILD parameter this relationship is weaker and drops to 11%. This indicates that the true binaural effects as described by the BILD cannot be characterized based on the audiogram only. Furthermore, a significant correlation with $R^2$ of 0.45 is observed between ILD and BILD, i.e. the better the improvement of speech intelligibility in the measurement of the ILD parameter, the higher the BILD binaural effect value. However, this correlation is not very strong and therefore, the accurate estimation of the BILD parameter based on the amount of gain in the ILD is not possible.

Since speech intelligibility in noise (S0N0 condition) seems to be determined mainly by suprathreshold processing deficits (and not loss in audibility), SRT results obtained in the co-located condition are used to analyse influence of the suprathreshold hearing deficits on the performance in the spatially separated condition. To assess whether listeners who perform well on speech in noise task (low SRT values in S0N0 condition) can derive a greater benefit from a binaural processing than listeners with more prominent suprathreshold deficits (indicated by higher (worse) SRT values in S0N0 condition), S0N0 SRTs are correlated with SRTs in S0N90 and S0N90(MON) conditions (Fig. 7).

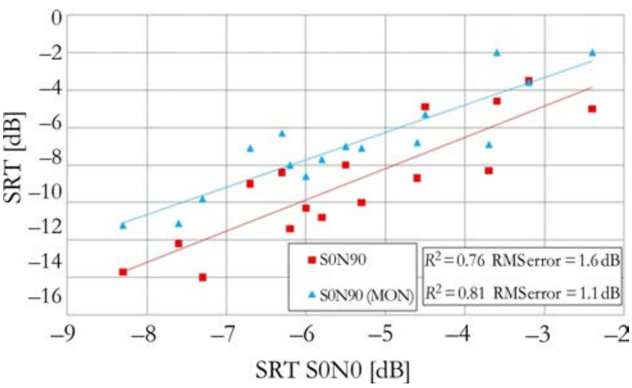


Fig. 7. Relation between SRT in spatially separated conditions (S0N90 – squares, S0N90(MON) – triangles) and SRT in co-located condition (S0N0). $R^2$ values are given for a linear fitting model.

The analysis revealed high correlations of the SRT when speech and noise come from the same direction and spatially separated conditions with $R^2$ of 0.81 and RMS error of 1.1 dB for S0N90(MON) and $R^2$ of 0.76 and RMS error of 1.6 dB for S0N90. Listeners performing well in the S0N0 condition (low SRTs) had bigger binaural advantage than listeners with poor speech intelligibility in the co-located condition. It indicated that the same suprathreshold deficit may determine speech intelligibility in co-located and spatially separated condition which may have important consequences for hearing diagnostics and enhancement of speech in hearing aid algorithms. Identification of the suprathreshold deficit responsible for speech in noise performance may help to design better algorithms that improve speech intelligibility in different conditions. Here it was shown that the same deficit may influence speech in noise performance in spatially co-located and spatially separated conditions. In addition to that, previous studies shown that the same suprathreshold deficit may be responsible for speech intelligibility in different types of masking noise (Kollmeier *et al.*, 2016; Pastusiak, 2018).

Further measurements are required, taking into account the wider and more diverse research group, for instance listeners with asymmetrical hearing-impairment. Moreover, broader spectrum of tests including the psychoacoustic experiments would allow to precisely characterize the hearing loss and contribute to better understanding of the deficits observed in speech intelligibility task. This is particularly important for the BILD effect which was not correlated with the degree of hearing loss as well as with the perception in co-located condition (S0N0). Furthermore, one must also bear in mind that there are other deficits which seem to contribute to the reduction of BILD in hearing-impaired listeners, but may not be of the auditory nature. Identification of the suprathreshold deficits and development of appropriate methods for their restoration is important for improvement of benefit from hearing aids and by that for better communication abilities of hearing-impaired listeners in everyday life.

## 4. Conclusions

Examination and determination of factors (even those of non-auditory nature) that affect everyday speech perception is important for ecologically valid diagnostics and fitting of hearing aids. It is natural to consider binaural effects and masking signals, due to their unquestionable impact on speech intelligibility under real conditions. Outcomes of this study showed:

- affected speech intelligibility in noise in hearing-impaired listeners that cannot be explained by the outcomes of tests conducted in quiet (pure tone audiometry);
- reduction of binaural benefit obtained by spatial separation of speech and noise source in hearing-impaired group;
- no relationship between degree of hearing loss defined based on pure tone audiometry and binaural deficits in speech intelligibility in noise.

These outcomes suggest that binaural speech intelligibility in noise measurements should be included in the diagnostic test battery in addition to the tests in quiet like pure tone audiometry in order to better characterize individual hearing deficit in terms of speech intelligibility.

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