Influence of wearing hearing aids on speech intelligibility in spatial scenarios for normal-hearing listeners

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Introduction

While hearing aids provide large benefits for hearing-impaired users by amplification, noise reduction and other signal processing features, they also have negative effects on perception that can be termed as "side-effects". These can include for example a poor sound quality, disturbed spatial perception and disturbed speech perception. While such side effects may be irrelevant or acceptable for users with a severe hearing impairment, they arguably limit hearing aid performance in users with only a mild to moderate hearing impairment, up to a point where the negative side-effects outweigh the positive effects. Such side effects are even more critical for the acceptance and performance of hearing devices targeted at normal-hearing users like hearables, active hearing protectors or augmented reality headsets.

Several previous studies assessed the negative aspects of hearing devices on perception in isolation in normal hearing subjects. Most contributions thereby focussed on spatial hearing [1, 2] or sound quality [3, 4], whereas the data on speech perception is very sparse. Recently, Cubick et al. [1] demonstrated both an impaired speech intelligibility and an altered spatial perception through behind-the-ear (BTE) hearing aids worn by normal-hearing subjects. They accounted the reduction in speech intelligibility to changes in energetic masking caused by the microphone position behind the ear, and could not identify an interaction between altered spatial perception and speech intelligibility. The present study is largely motivated by that of Cubick et al. [1] and assesses the impact of wearing hearing aids on speech intelligibility in normal-hearing listeners. To this end, normal-hearing subjects were equipped with BTE hearing aids in a transparent setting. Speech Reception Thresholds (SRTs) were measured using two different maskers that were either collocated or spatially separated from the speech creating a diffuse-like sound field, while the subjects either wore the hearing aids or not.

Methods

Hearing Aids

The hearing aids worn by the subjects were prototype research devices based on the Portable Hearing Lab, consisting of portable miniature computer running the open Master Hearing Aid and BTE receiver-in-canal hearing aid dummies that were coupled to the ear by closed double domes [5]. The platform provides state-of-the-art hearing aid hardware, and was operated in a way to approach open-ear listening as well as possible. Processing included a time-frequency-analysis, a feedback cancellation based on a frequency shifter, and a frequency-dependent gain at a sampling rate of 24 kHz, leading to a delay of approx. 10 ms. The firmware version 4.12 was used without modifications except for the modified equalization filter. This filter was adjusted such that the measured aided response on KEMAR approached the appropriate unaided response in a diffuse sound field created by 8 loudspeakers in the horizontal plane, i.e., the hearing aids were operated in a transparent setting [4]. On average across 5 tested reinsertions in KEMAR, the open-ear response was conserved by the hearing aids with an accuracy of 3 dB between 200 Hz and 10 kHz.

Setup and Procedure

Subjects were seated within a circle of eight loudspeakers equally distributed in the horizontal plane, set up in an acoustically treated listening room. Using this setup, three different speech-in-noise scenes were presented to the subjects for measurements of the SRT:

- **Collocated**: Speech and masker presented from the frontal direction (0°).
- **Diffuse, static**: Speech presented from the frontal direction (0°), while independent maskers were presented simultaneously from 45°, 135°, 225° and 315° to create a diffuse-like noise.
- **Diffuse, dynamic**: As Diffuse, static, but with the direction of the speech source varying randomly between 0°, 90° and 180°.

Maskers included noise and speech (four different female talkers), both with a long-term spectrum equal to that of the speech material. The female talkers were audiobooks in German language, where each talker was presented from one loudspeaker in the Diffuse scenes, or all presented from the frontal loudspeaker in the collocated condition. In the latter case, an error in the creation script resulted in one audiobook to have a 12 dB lower level than the other three, which means that the differences between the collocated and diffuse scenes with the speech masker have to be interpreted with care.

SRTs were measured using the female version of the Oldenburg sentence test [6], as implemented in the Oldenburg Measurement Applications version 2.2.2. Within each condition, the speech level was adaptively controlled to reach 50% speech intelligibility during presentation of a list of 20 sentences, while the masker was continuously presented at 65 dB SPL. In case of the Diffuse, dynamic scene, SRT measurements for the three incidence directions were interleaved and only the result for 0° speech incidence was evaluated.

SRTs were measured in all 12 combinations of scene, masker and wearing hearing aid. To limit the measurement time, these were split into two sessions where the subjects either wore the hearing aids continuously or not. Each session was started with two OLSA training lists. Thirteen normal-hearing subjects (hearing thresholds better than 25 dB HL between 500 Hz and 4 kHz) participated.

To enable a technical analysis, the stimuli (speech and noise separately) were also recorded on KEMAR. Technical analyses included a frequency-dependent analysis of levels and SNRs created at ear, as well as a modelling of the SRTs using a Binaural Speech Intelligibility Model (BSIM, [7]). The model includes an effective simulation of peripheral binaural processing consisting of an Equalization-Cancellation stage ($f < 1500$ Hz) and Better Ear Listening at higher frequencies. The output is an enhanced monaural signal, for which the Speech Intelligibility Index (SII) is calculated. SRT differences between conditions can then be modelled by finding the SNR that yields the same SII as the SRT in a reference condition.

Results

Figure 1 shows the resulting SRTs, separated by masker type (upper/lower panels), scenes (position on x-axis) and aided/unaided listening (red/black symbols). Note that lower values indicate better speech intelligibility.

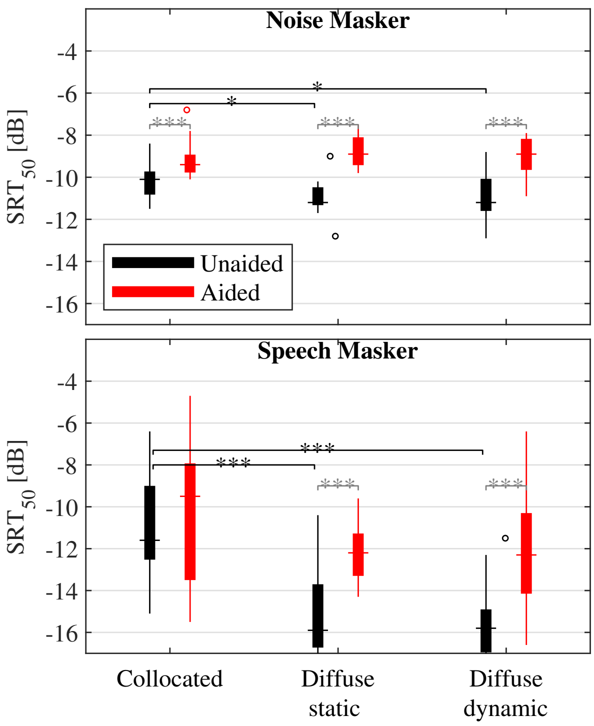

Figure 1: SNR at 50% speech intelligibility (SRT_{50}) results with speech-shaped noise masker (upper panel) and 4-talker speech masker (lower panel). Horizontal lines indicate the median across subject, thick vertical lines the range from 25% to 75% quantile, and thin vertical lines the full data range excluding outliers (denoted as circles).

A three-way repeated measures ANOVA with the factors above showed a significant influence of all factors (all $p < 0.001$), as well as significant interactions between scene and masker ($F(2,24) = 33.42, p < 0.001$) and between scene and aided/unaided listening ($F(2,24) = 9.69, p < 0.001$)). Simple effects were assessed by paired t-tests including a Bonferroni correction, and significant differences are denoted by brackets and stars in Fig. 1.

First, general differences between the masker types are expected due to the different temporal structure, and the statistical analysis showed that this difference is not influenced by the hearing aid. Second, statistically significant differences between the collocated and both diffuse scenes are seen with both maskers in the unaided condition. The SRT is lower in the diffuse cases, where speech and masker are spatially separated. Such a Spatial Release from masking (SRM) is either not observed (noise masker) or does not reach significance (speech masker) with the aided condition. No difference is noted between the static and dynamic diffuse scenes. Third, in all combinations of scene and masker, the SRTs in the aided case are larger than in the unaided condition, i.e. wearing the hearing aid resulted in poorer speech intelligibility in all tested conditions. Only in the collocated condition with the speech masker, this difference did not reach significance.

Fig, 2 shows the hearing aid disadvantage, i.e. difference between aided and unaided SRT in all conditions. While circles show the mean and standard deviation across subjects, the triangles show the SRT predictions from the BSIM model. The hearing aid disadvantage varies with the condition: in the collocated scene and with the noise masker it is 1 dB, and with the speech masker it lies at an average of 0 dB, however, with a large between-subject standard deviation of 3 dB. In the diffuse scene (static plotted only), it lies at 2 dB (noise masker) and 3 dB with the speech masker. The model predictions are generally well in line with the psychoacoustic data, especially in the diffuse scenes. In the collocated scenes, the HA disadvantage is underestimated by the model by approx. 1 dB.

Discussion

Hearing aid disadvantage and spatial release from masking

The disadvantage of the hearing aid in the diffuse scenes can be explained by altered sound transmission paths to the ear drum, which are altered differently for the speech at frontal incidence and the masker from the four separated conditions. The transmission through the external ear generally creates an effective SNR at ear that differs from the nominal SNR at free field, which is reported with the SRT. Figure 3 shows the SNR difference between free field and diffuse scenes, both for the unaided and aided conditions, as assessed from the KEMAR recordings. Besides the SNR in third octave levels, an average over frequencies with a speech importance weighting as defined in the SII (iSNR) is given in the dotted line. For both aided and unaided condition, the effective SNR at eardrum is decreased by the separation of speech and

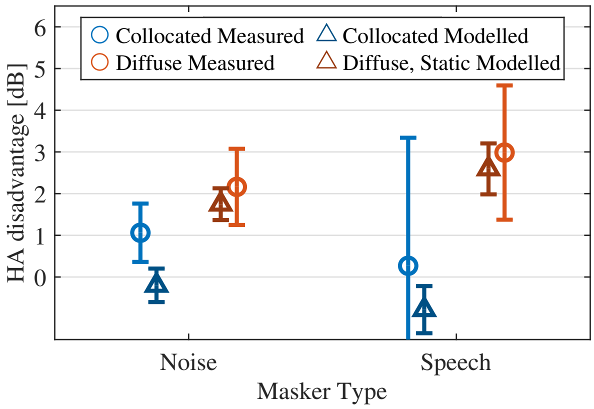

Figure 2: Hearing Aid disadvantage, i.e. difference in SRT_{50} between aided and unaided condition. Circles denote average and standard deviation across subjects, triangles the average and standard deviation of the model prediction.

masker. The reduction is larger in the aided condition, which is caused by the microphone location behind the ear [4]: Speech from the front is not collected by the pinna as with the open ear, whereas the influence of the microphone location is smaller for sound incidence from more lateral directions. The difference in iSNR between the aided and unaided condition in the diffuse scene is approx 1.7 dB, which explains most of the hearing aid disadvantage seen with the noise masker (c.f. Fig 2).

For the speech masker, the SNR difference at ear cannot fully explain the hearing aid disadvantage. However, the predictions with BSIM replicate it very well. These observations hint towards an additional detrimental effect of the hearing aid on binaural hearing by approx 1 dB. This is probably caused by the reduction of Interaural Level Differences (ILDs) seen at BTE microphones [2], a conclusion that was also drawn by Cubick et al. [1]. With the noise masker, the effects of the hearing aid on binaural hearing apparently play only a minor roll. This is understandable since the largest effect of the

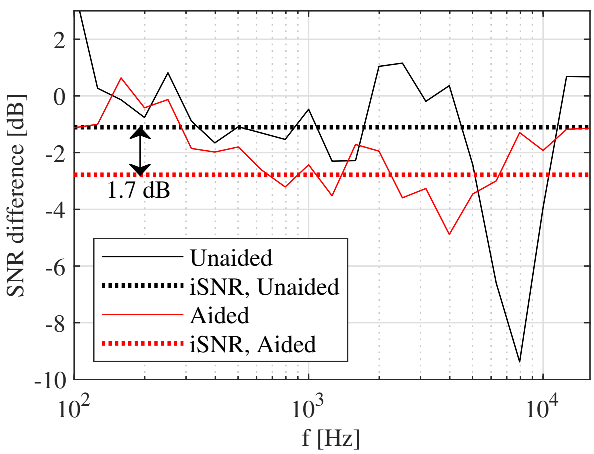

Figure 3: SNR difference between diffuse scene at ear and free field, unaided (black) and aided (red) condition, average between both ears. Solid lines denote the third-octave SNRs, dotted lines the average across frequency with a speech intelligibility appropriate weighting (iSNR).

hearing aid is present at frequencies above 2 kHz, where binaural processing is dominated by better-ear glimpsing [7]. Given the static, diffuse-like properties of the noise masker in the diffuse condition, better-ear listening can only be exploited with the speech masker. Consequently, a reduction of ILDs and thus a reduction of the benefit of better-ear glimpsing by wearing the hearing aid has no effect on the SRT seen with the noise masker in the diffuse condition. The present data contains no hints towards an impairment of binaural hearing at low frequencies, e.g. through equalization-cancellation processing.

Hearing aid disadvantage in collocated conditions

A hearing aid disadvantage was also observed in collocated conditions. This disadvantage was very consistent with the noise masker (approx. 1 dB), and varied largely between subjects with the speech masker. The large variations of the hearing aid disadvantage with the speech masker probably originates from the similarly large variation across subjects in the raw SRTs due to the variation of the masker with time. Therefore, for the discussion of collocated conditions we focus on the results with the noise masker.

The negative effect of the hearing aid in speech intelligibility is quite surprising here, since speech and masker always go through the same transmission path before reaching the eardrum. Therefore, no change in SNR or binaural cues can explain the hearing aid disadvantage as in the diffuse scenes. This expectation is consistent with the BSIM model predictions that are close to 0 dB hearing aid disadvantage.

Similar results for collocated conditions (1 and 0.5 dB disadvantage for speech and noise maskers, respectively) were observed by Cubick et al. [1], but not interpreted as a significant effect. We disagree with this interpretation and conclude that wearing hearing aids, even if high-quality set to a transparent mode, can reduce speech intelligibility also in collocated conditions. The underlying reasons cannot be identified from the present results but deserve further attention, since it may be the same causes that result in a poorer sound quality, higher listening effort and other negative effects of wearing hearing aids. Possible explanations could be the microphone noise, processing delays, a limited bandwidth or nonlinear distortions by the hearing aid driver, which may lead to a not well tangible change in perception (see also discussion below).

No effects of altered spatial perception or cognition on speech intelligibility (?)

Although not explicitly assessed in the present study, it can be safely assumed that the subjects experienced an altered spatial perception when listening through the hearing aids. Difficulties to localize sound sources as well as an apparent widening was demonstrated in previous studies with similar devices [1, 2] and is consistent with the authors' impression when wearing the devices from the current study. One research question of the present study as well in [1] was therefore, whether this impairment of spatial perception has an influence on speech intelligibility that goes beyond energetic masking effects.

The negative effects of a hearing aid on speech intelligibility in the diffuse scenes could be explained by an auditory model, i.e., they could be accounted to energetic masking effects. Likewise, a random change of the speech source direction did not have an effect on speech intelligibility. We conclude that in our data there is no apparent influence of higher cognitive effects like the impaired spatial perception on the impairment of speech intelligibility when wearing hearing aids. Our conclusion is consistent with that of Cubick et al. [1]. While our scene complexity was higher than that of Cubick et al. [1] by reducing the spatial separation between speech and masker and introducing the random variation of speech incidence direction, the results regarding an influence of spatial perception on speech intelligibility are the same. This means that either no such interaction exists, or the scenes were still not complex enough to elicit it.

However, an effect of the hearing aid on perception on a higher cognitive level, which could lead to a decreased ability to segregate the speech and noise streams, may be connected to the observed hearing aid disadvantage in the collocated condition. If it exists, it could have been hidden in the spatially separated conditions by more obvious and larger effects of energetic masking. Whatever the physical reason is, even if the linear transmission properties of the hearing aid are well-matched to that of the open ear, it is the personal experience of the authors and often informally reported by subjects that "something still sounds off". Such not well tangible differences in perception could be comparable to experiences in audio recording, for example that single instruments in a mix can not be perceived or isolated by a listener when the reproduction device is of low quality. Similarly, finding the reason for losing such a true transparent sound reproduction through hearing aids could improve perception for its wearers, hopefully eliminating many detrimental effects on perception like the seemingly minor 1 dB loss of speech intelligibility in collocated conditions.

Conclusions

1. Listening through BTE hearing aids in a transparent setting has a detrimental effect on speech intelligibility of 1-3 dB in normal-hearing listeners.
2. With spatially separated maskers, most of the reduction in speech intelligibility can be accounted to changes in the effective SNR at the ear. Additionally, wearing the hearing aid seems to reduce the effectivity of better-ear glimpsing through a reduction of ILDs.
3. An observed 1 dB reduction of speech intelligibility in collocated conditions could not be explained.
4. No interaction between (impoverished) spatial hearing and speech intelligibility could be demonstrated.

Our results are in excellent agreement with those reported by Cubick et al. [1]. However, we interpret the 1 dB poorer speech intelligibility with transparent hearing aids in collocated conditions as a non-negligible effect that deserves further attention.

Acknowledgement

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References

[1] Cubick, J. et al.: Listening through hearing aids affects spatial perception and speech intelligibility in normal-hearing listeners. The Journal of the Acoustical Society of America, 144 (2018), 2896-2905.

[2] Denk, F. et al:. On the limitations of sound localization with hearing devices. The Journal of the Acoustical Society of America, 146 (2019), 1732-1744.

[3] Killion, M. C.: Myths that Discourage Improvements in Hearing Aid Design-Part. Hearing Review, 11-1 (2004), 32-43.

[4] Denk, F. et al.: Adapting hearing devices to the individual ear acoustics: Database and target response correction functions for various device styles. Trends in Hearing 22 (2018), 2331216518779313

[5] Pavlovic, C. et al.: A High-Fidelity Portable Platform for Development of Novel Algorithms for Assistive Listening Wearables, presented at AAS 2020

[6] Wagener, K. C. et al.: Der weibliche Oldenburger Satztest." 17th annual conference of the DGA, Oldenburg, 2014.

[7] Beutelmann, R. et al.: Revision, extension, and evaluation of a binaural speech intelligibility model. The Journal of the Acoustical Society of America 127.4 (2010), 2479-2497.