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Speech intelligibility with binaurally linked hearing aids

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Conventional compression algorithms in bilateral hearing-aid fittings distort the interaural level differences (ILD's) due to independent gain characteristics at the two ears. By transmitting signals between hearing aids, the compression can be coordinated and the same gain can be applied to both ears, thus preserving the ILD's. The present study investigated the influence of such "binaurally linked" hearing aids on speech intelligibility. Hearing-impaired listeners with a symmetric hearing loss were fitted with hearing aids connected to a hearing aid research platform (HARP). Speech reception thresholds (SRT's) were measured in a loudspeaker setup with the target speech and the masker spatially separated. Slightly, but not significantly better SRT's were achieved when the hearing aids were binaurally linked and combined with slow compression than when unlinked fast compression was used. The difference between monaural and binaural speech intelligibility was independent of the hearing aid algorithm. Thus, the preservation of the exact ILD information does not seem to be critical for binaural processing and speech intelligibility in the considered conditions.

INTRODUCTION

Wireless technology has become an integral part of modern hearing aids. In a bilateral fitting it has become possible to link the hearing aids on the left and right ear wirelessly and to exchange information between them. The transmission of either data parameters or the raw audio data is possible. Transferring low bit-rate data parameters is used to synchronize settings in the two hearing aids, e.g. volume, program or microphone mode settings.

The transmission of the raw signal data is realized with near-field magnetic induction (NFMI) and has proven useful to restore binaural sound cues (Behrens, 2008). In particular, interaural level differences (ILD's), which would be altered by the compression algorithms of two independent hearing aids (Moore *et al.*, 1992), can be preserved by applying linked amplification. While spatial cues are obviously useful for the localization of sound they can also provide an advantage for speech intelligibility. When a masker signal is spatially separated from a speech signal, the

difference in the perceived location of the speech and the masker can improve speech intelligibility and particularly if the masker is a speech signal instead of a noise signal (Shinn-Cunningham, 2003). With independent compression and thus independent gain of the hearing aid signals at the two ears (which is the case in a bilateral fitting) ILD's decrease proportionally with the compression ratio (Keidser *et al.*, 2006). Hence, it seems beneficial to apply the same gain on both ears, provided that the hearing-impaired person has a symmetric hearing loss. The preservation of spatial cues with binaurally linked hearing aids has been studied in terms of localization and sound quality in one study by Sockalingam *et al.* (2009). They found that fewer localization errors were made when the binaural communication link was turned on and that the sound was rated as more natural in a café or street environment. No research has been published so far on the effect of binaurally linked hearing aids on speech intelligibility. The goal of the present study was therefore to investigate if the preservation of spatial cues with binaurally linked hearing aids could provide a benefit for speech intelligibility.

When using commercial hearing aids, the interaction of different signal processing algorithms is often difficult to control for the experimenter. Furthermore, different hearing aid manufacturers use different signal processing approaches, so that experiments carried out with a hearing aid from one manufacturer typically represent only one signal processing approach. A standardized platform which provides full control over independent signal processing algorithms was therefore used in the present study. All stimuli were presented to the listener in a loudspeaker setup. The HARP, together with loudspeaker presentation, represent an advanced approach for testing hearing aid algorithms.

METHODS

Listeners

Seven hearing-impaired listeners participated in the study. Their age was between 64 and 77 years with a median age of 68. Median hearing thresholds are shown in Fig. 1. All listeners had a sensorineural and symmetric hearing loss (interaural threshold differences averaged across audiometric frequencies were ≤ 5 dB). Hearing aid usage and experience differed between listeners.

Stimuli

The speech stimuli were sentences from the Danish sentence test Dantale II (Wagener *et al.*, 2003). Each sentence consists of five words with a fixed syntactical structure spoken by a woman. The listeners responded via a Matlab user interface by choosing the words they had understood on a hand-held touch screen. The level of the speech signal was varied adaptively with a maximum likelihood procedure (Brand & Kollmeier, 2002) for speech reception threshold (SRT) estimation.

The masker stimuli consisted of a stationary speech shaped noise masker (SSN₉₀) and a reversed two-talker masker (revTT₉₀). The SSN₉₀ was created by repeatedly superimposing sequences of the Dantale II sentences (Wagener *et al.*, 2003). The

revTT₉₀ consisted of reversed running speech from two female speakers with silent gaps longer than 250 ms removed. The broadband root-mean-square sound pressure was equalized across the two maskers and levels were measured with an omnidirectional microphone at the location of the center of the listener's head with the listener absent. Each masker was presented at a constant level of 70 dB SPL.

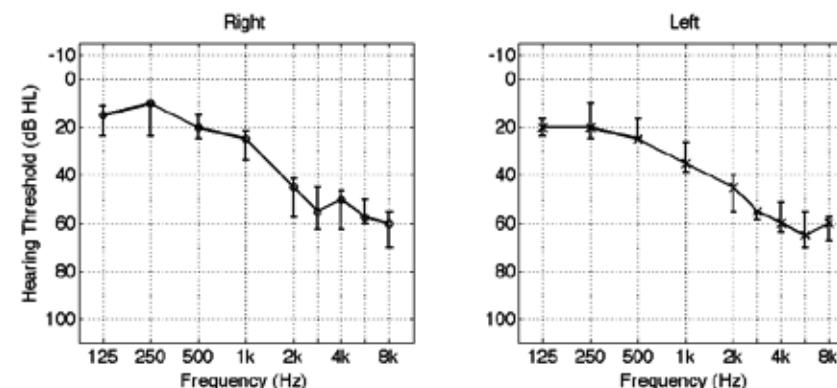


Fig. 1: Median hearing thresholds for the 7 hearing-impaired listeners. Error bars indicate the interquartile range.

Hearing Aid Research platform (HARP)

Setup and hearing aid signal processing algorithms

The HARP consists of a real-time target machine from Speedgoat (www.speedgoat.ch) which is programmed, controlled and monitored by a host computer. The host computer runs Matlab and SimuLink software to develop hearing aid signal processing models as well as to control the real-time processes on the target machine. Two BTE hearing aid satellites from Phonak were connected to the target PC.

The calibration of the different hardware components of the HARP, including the hearing aid satellites, was done with a PC using a high quality RME DIGI 96/8 sound card and Matlab. Where applicable, a hearing aid test box (Affinity 2.0 system) was used which was controlled via the hearing aid test (HIT) software from Interacoustics. Equalization filters were realized by IIR filters and fitted to the inverse absolute spectrum of the measured transfer functions using Matlab.

Three signal processing algorithms were implemented on the research platform: (i) a linear signal processing algorithm, (ii) a wide dynamic range compression (WDRC) algorithm and (iii) a binaural link algorithm. In the linear algorithm, all sound signals were processed linearly, i.e. the same gain was applied for all input levels. In the WDRC algorithm the input signal was first processed by a compressor using a peak level detector. Afterwards, spectral smoothing was applied to limit gain

variations between adjacent frequency bands. In the binaural link algorithm, the compressors of the left and right hearing aid were linked, i.e. the average gain of both compressors was applied to each hearing aid, thus retaining interaural level differences. An ideal binaural link was simulated through sample-by-sample transmission in all 24 channels introducing no additional time delay.

The independent compression on both hearing aids introduced a reduction in ILD's for both the target (presented from 0° azimuth) and the masker (presented from 90° azimuth) of approximately 4 dB and 5.1 dB, respectively (averaged over the 24 frequency channels and the two masker types). This will be discussed later.

Experimental procedure

Hearing aid fitting

The HARP was first calibrated such that, at the output of a 2cc coupler, a flat frequency response was achieved. Afterwards, the free field to BTE microphone transfer function was equalized (Bentler & Pavlovic, 1989, Table 1, column B) as well as the difference between the 2cc coupler and the real ear (RECD) for each individual listener. In this way, the gain provided by the HARP was directly equal to the real-ear insertion gain (REIG; Dillon, 2001) which could be derived from a generic fitting rule.

The "equalization" procedure provided with the CamFit software (version 1.0; Moore *et al.*, 1999) was used to derive individual REIG's and CR's for each listener based on their audiogram. The compression threshold (CT) in each frequency channel was defined such that all components of the speech signal were processed in the compressive region. Two compression strategies were employed: a fast and a slow one. The fast strategy used a compressor attack time (AT) of 5 ms and a release time (RT) of 50 ms. For the slow strategy the AT was 5 ms and the RT was 1000 ms.

Overall, five different conditions were tested: Binaurally unlinked combined with fast compression, slow compression and linear amplification and binaurally linked combined with fast and slow compression.

Speech intelligibility measurements

The listener was seated in the middle of a 29-loudspeaker array in an acoustically dampened room. Only two of the 29 loudspeakers were used for signal presentation. The speech signal was always presented from the front loudspeaker at 0° azimuth and the masker was presented from the loudspeaker at 90° azimuth (to the right of the listener).

SRT's were measured monaurally and binaurally with 20 sentences for each listener and condition. In the monaural condition, the right earmold was removed and the ear was plugged with an insert earphone (ER2 from Etymotic Research) delivering a white noise with a level of 75 dB SPL. Altogether, 20 SRT measurements were performed with the hearing aids (5 hearing aid algorithms x 2 maskers x

monaural/binaural). The masker conditions and the order of measurements for each masker were randomized. Before the first measurement, listeners performed a training with 20 sentences and were instructed to look at the front loudspeaker and to hold their head upright during sentence presentation.

RESULTS

Speech intelligibility data

Figure 2 (left panel) shows the mean SRT's averaged across the seven hearing-impaired listeners. In general, linked hearing aid conditions yielded better SRT's than unlinked conditions when combined with the same compressor speed (fast or slow). Slow compression yielded better SRT's than fast compression. Paired t-tests with Bonferroni correction for multiple comparisons were performed on the results. First, binaural SRT's were compared for the unlinked and linked condition and for the fast and slow compression times, respectively. The binaural link did not provide significantly better SRT's than the unlinked condition when fast compression was used. A significant difference between linked and unlinked SRT's was found for the slow compression ($p = 0.024$, $CI = 0.1073$ 1.3069), but it did not remain significant after Bonferroni correction. Finally, SRT's measured with linear processing were not significantly different from SRT's measured with a compression algorithm.

Binaural benefit

The difference between monaural and binaural SRT's is shown as the binaural benefit in Fig. 2 (right panel). Squares indicate the binaural benefit for the SSN₉₀ and circles represent the binaural benefit for the revTT₉₀. For both maskers, an analysis of variance (ANOVA) did not show a significant difference in binaural benefit between fast hearing aid algorithms. The average binaural benefit was 2 dB for the SSN₉₀ and 6.9 dB for the revTT₉₀.

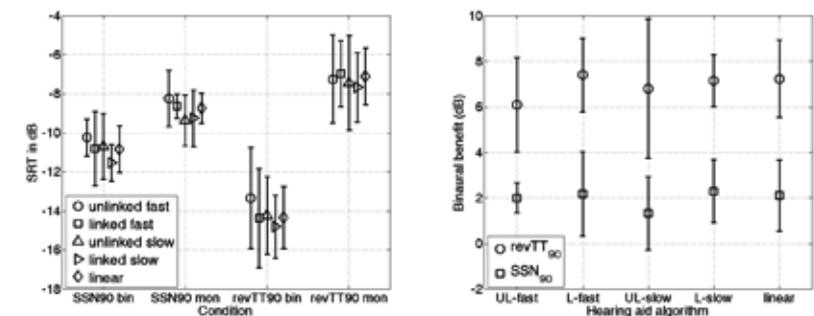


Fig. 2: Left panel: Mean SRT's for the different hearing aid processing algorithms and conditions. Right panel: Mean binaural benefit for the different hearing aid processing algorithms and maskers, calculated as the difference between the mean monaural and binaural SRT's. UL: unlinked, L: linked. Error bars indicate ± 1 standard deviation.

DISCUSSION

The aim of this study was to investigate if the preservation of ILD cues, as realized in binaurally linked hearing aids, can improve speech intelligibility compared to unlinked hearing aids. In the following it is discussed why the binaural link could not provide an advantage for speech intelligibility compared to conventional compression.

Gain differences at the two ears resulted in ILD's that were on average about half of the original ILD's. This was expected considering that the compression ratios derived from the CamFit software for the median audiogram were between 1.0 and 2.8 in the different frequency channels. With a reduction in ILD's, the perceived location of the masker was shifted in the direction of the target. However, the reduction in ILD's for the speech signal introduced a shift in perceived location away from the masker. The ILD's for the target were most likely introduced when the speech signal was recorded at the HATS which might not have been aligned precisely symmetric to the front loudspeaker. The shift of target and masker in the same direction (by slightly different amounts) thus only slightly decreased the spatial separation, but introduced an incorrect spatial representation of the two.

Even though unlinked compression reduces the ILD's, this might not influence the localization abilities of hearing-impaired listeners and hence, speech intelligibility might not be worse than for linked compression. Keidser *et al.* (2006) measured the localization error with WDRC hearing aids which almost halved the ILD's compared to a linear system. The reduction of ILD's had no significant effect on localization performance. Musa-Shufani *et al.* (2006) measured the influence of compression on just-noticeable-differences for ILD's with hearing-impaired listeners and compared the results to a localization task based on ILD's and interaural time differences (ITD's). They concluded that hearing-impaired listeners predominantly rely on ILD's for the localization of high-frequency stimuli and, even though they were reduced due to the compression, the localization accuracy was only decreased by 5° compared to normal-hearing listeners.

The relatively small difference in speech intelligibility between the linked and unlinked condition might also result from a limited correlation between localization abilities and speech understanding in noise. A study by Noble *et al.* (1997) investigated the relationship between localization, detection of spatial separateness and speech intelligibility in noise for hearing-impaired listeners. For the group of hearing-impaired listeners with sensorineural hearing loss, they did not find consistent relationships between the localization task, the spatial separateness task, and the speech task.

The AT of 5 ms for both, the fast and the slow compression algorithm, might have given the listener the possibility to analyze the ILD before it was compressed. Musa-Shufani *et al.* (2006) showed that just noticeable differences for ILD's increased with decreasing AT.

It should also be noted that the hearing-impaired listeners were not acclimatized to the hearing aids and some of them never or hardly wore their own hearing aids. Moore *et al.* (1992) pointed out, that “this is important because if a person has had a hearing impairment for many years, it may take some time for them to learn to use the new cues provided by a compression system.” Thus, even though the linked hearing aids provided measurable benefit in terms of preserved ILD's, the hearing-impaired listeners might have simply not been able to take advantage of it.

The binaural benefit determined from the monaural and binaural SRT's (see Fig. 2, right panel) was not significantly different across hearing aid algorithms, i.e. there was no benefit from linking the hearing aids in terms of improved binaural speech intelligibility. Moore *et al.* (1992) studied the influence of a compression hearing aid and a linear hearing aid on the binaural benefit for speech intelligibility. Averaged across hearing-impaired listeners they found a binaural benefit of approx. 2.5 dB for both processing strategies. They presented a babble noise from $\pm 90^\circ$ and speech from 0° azimuth. The monaural condition was realized by turning off the hearing aid at the non-test ear. The binaural benefit is in good agreement with the binaural benefit for the SSN₉₀ in the present study. Moore *et al.* (1992) did not determine to what extent the ILD's were reduced by the compression but simply concluded that the independent compression at the two ears did not adversely affect the binaural cues. The present study has shown that *despite* the reduction of ILD's introduced by independent compression the binaural benefit is not decreased compared to other hearing aid processing algorithms.

The hearing-impaired listeners might have relied on other cues than ILD's for binaural processing. ITD's, for example, are most useful at low frequencies and were fully available for the hearing-impaired listeners with the hearing aids. This is in agreement with Bronkhorst and Plomp (1988) who found that the binaural benefit is mostly determined by ITD's for a broadband signal like speech.

SUMMARY & CONCLUSION

Binaural hearing aids, as opposed to bilateral hearing aids, can preserve ILD's which are assumed to play a role for understanding speech in noise. In the present study, a hearing aid research platform (HARP) was used to investigate the benefit from binaurally linked hearing aids for speech intelligibility in hearing-impaired listeners. In a loudspeaker setup, where the target speech and the masker were spatially separated, the binaural link resulted in slightly, but not significantly better speech intelligibility than the unlinked hearing aid algorithm (for the same compression speed). The best speech intelligibility results were achieved when the linked hearing aid was combined with slow compression. Despite the altered ILD's that were introduced by the unlinked WDRC, binaural processing was not adversely affected, resulting in the same binaural benefit for unlinked and linked hearing aid signal processing.

Even though the present study cannot provide a clear recommendation for binaurally linked hearing aids to improve speech intelligibility, the binaural link might still be useful to improve sound quality in terms of naturalness and spatial awareness, as was shown in previous studies (Sockalingam *et al.*, 2009; Behrens, 2008).

The independent hearing aid research platform in combination with a loudspeaker setup as used in the present study are versatile tools to further develop outcome measures that show the benefit of hearing aids for hearing-impaired listeners.

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Testing listening effort for speech comprehension

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When listening in noise, an individual's cognitive capabilities seem to play an important role. The individual's limited working memory capacity will gradually be consumed by processing the auditory information in increasing background noise, leading to less spare capacity. Good fitting of hearing aids can be seen as a way to ease listening effort, and therefore an objective measure of listening effort would be a useful tool when fitting hearing aids. The aim of the present study was to develop a test of cognitive spare capacity to assess if worse signal-to-noise ratio (SNR) would result in greater objectively measured listening effort. In the Auditory Inference Span Test (AIST) sentences were presented in stationary speech-shaped noise, at three SNRs, and then questions generating different memory load levels were asked about the content of the sentences. Listeners with normal hearing showed decreasing accuracy with increasing cognitive load and slower responses at maximum cognitive load. However, no relation between SNR and cognitive spare capacity could be established in this study.

INTRODUCTION

Hearing-aid fittings are essentially based on the audiograms of the hearing impaired individuals. Evaluating the fitting using SNR thresholds is not sufficient since individuals with similar hearing impairments, as measured by the audiograms, might perform significantly different (Rudner *et al.*, 2011). There are probably many reasons for this, but it has been shown that differences in the individuals' cognitive capabilities may play an important role when hearing in noise (Gatehouse *et al.*, 2003; Lunner, 2003; Edwards, 2007; Akeroyd, 2008; Stenfelt and Rönnberg, 2009).

Studies have shown significant correlations between working memory performance and speech recognition in noise (Lunner, 2003; Foo *et al.*, 2007; Rudner *et al.*, 2009). When speech perception is degraded by background noise, speech comprehension requires more cognitive resources (Larsby *et al.*, 2005; Pichora-Fuller and Singh, 2006; Edwards, 2007). Every individual has a limited working memory capacity, which is gradually consumed by increasing background noise (Pichora-Fuller and Singh, 2006; Schneider, 2011). An individual with higher