Adapting bilateral directional processing to individual and situational influences

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This study examined differences in benefit from bilateral directional processing. Groups of listeners with symmetric or asymmetric audiograms <2 kHz, a large spread in the binaural contribution to speech-in-noise reception (i.e., the binaural intelligibility level difference, BILD), and no difference in age or overall degree of hearing loss took part. Aided speech reception was measured using virtual acoustics together with a simulation of a linked pair of closed-fit behind-the-ear hearing aids. Five processing schemes and three acoustic scenarios were used. The processing schemes differed in the trade-off between signal-to-noise ratio (SNR) improvement and binaural cue preservation. The acoustic scenarios consisted of a frontal target talker and two lateral speech maskers or spatially diffuse noise. For both groups, a significant interaction between BILD, processing scheme and acoustic scenario was found. This interaction implied that, for lateral speech maskers, users with BILDs >2 dB profited more from low-frequency binaural cues than from greater SNR improvement, while for smaller BILDs the opposite was true. Audiometric asymmetry reduced the BILD influence. In spatially diffuse noise, the maximal SNR improvement was beneficial. Moreover, binaural tone-in-noise detection performance (N_0S_π threshold) at 500 Hz predicted the benefit from low-frequency binaural cues effectively. These results provide a basis for adapting bilateral directional processing to the user and the scenario.

INTRODUCTION

Although hearing-impaired listeners can differ substantially in their speech-in-noise abilities, the responsible factors are yet to be fully understood. As a consequence, ways of addressing these differences with hearing devices remain scarce. The current study aimed to shed more light on the factors driving benefit from binaural information for speech-in-noise reception, and to identify ways of tailoring directional hearing aid (HA) processing to individual hearing abilities. In a previous study, we

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screened almost 80 elderly hearing-impaired listeners with a large spread in the absolute across-ear difference in low-frequency (<2 kHz) pure-tone average hearing thresholds (ΔPTALF) in terms of the binaural contribution to speech-in-noise reception (Neher, 2017). To that end, we used the so-called binaural intelligibility level difference (BILD). The BILD is a measure of the improvement – or lack thereof – in speech-in-noise reception due to binaural processing (e.g., Kollmeier, 1996). Using virtual acoustics, we simulated a frontal target talker in the presence of a lateral speech-shaped noise masker and amplified the resultant stimuli according to the 'National Acoustic Laboratories–Revised Profound' (NAL-RP) fitting rule (Dillon, 2012). By taking the difference between the binaural and the monaural (i.e., better-ear) speech reception thresholds (SRTs), we then quantified the BILD, reflecting the change in signal-to-noise ratio (SNR) due to binaural interaction. Typically, normal-hearing listeners obtain BILDs of ~4 dB (e.g., Santurette and Dau, 2012).

In the current study, we tested a carefully selected subset of these listeners further. Using a computer simulation of a linked pair of behind-the-ear (BTE) HAs, we performed aided speech reception measurements with five directional processing conditions in three acoustic scenarios. The processing conditions differed in the trade-off between SNR improvement and binaural cue preservation. The acoustic scenarios differed primarily in terms of the noise characteristics (lateral speech maskers vs. spatially diffuse noise). Our aims were (1) to relate ΔPTALF and BILD to performance with the different directional processing schemes, and (2) to investigate if a simple binaural tone-in-noise detection measure can be used to predict the benefit from binaural cue preservation.

Below, we provide a summary of our methods and results. More detailed information can be found in (Neher *et al.*, 2017).

METHODS

Participants

Forty listeners aged 62-80 yr (mean: 73 yr) participated in the current study. Their pure-tone average hearing loss calculated across 0.5, 1, 2 and 4 kHz and left and right ears (PTA4) ranged from 35 to 69 dB HL (mean: 52 dB HL). The participants had either 'symmetric' ΔPTALF (N = 20; mean: 3 dB; range: 0-6 dB) or 'asymmetric' ΔPTALF (N = 20; mean: 23 dB; range: 15-39 dB). Furthermore, the two groups exhibited substantial and comparable spread in the BILD (ranges: 0.2 to 5.2 vs. –0.4 to 4.7 dB; means: 2.6 vs. 2.5 dB). To control for potentially confounding effects, we made sure that the two groups were matched in terms of age (means: 74 vs. 72 yr) and PTA4 (means: 52 vs. 53 dB HL).

In the study of Neher (2017), the 40 participants were characterised further using some psychoacoustic and cognitive tests. These included binaural tone-in-noise detection measurements (i.e., N_0S_0 and N_0S_π thresholds) at 0.5 and 1 kHz. Furthermore, they included a reading span test for the assessment of working memory capacity (Carroll *et al.*, 2015) and a 'distractibility' test for the assessment of selective attention

(Zimmermann and Fimm, 2012). Statistical analyses showed that the BILD was strongly correlated with the N_0S_π detection threshold at 500 Hz (Pearson's r correlation coefficient = –0.72, $p < 0.00001$) and that the two groups only differed in terms of ΔPTALF ($p < 0.00001$) and reading span ($p = 0.036$).

HA conditions

For simulating the different HA conditions, we used impulse response measurements made with a head-and-torso simulator equipped with two behind-the-ear (HA) dummies (Kayser *et al.*, 2009) together with the Master Hearing Aid research platform of Grimm *et al.* (2006). The directional processing conditions were all based on fixed, forward-facing microphone arrays, i.e., they were non-adaptive and steered towards 0° azimuth. The first (*pinna*) condition simulated two unilateral BTE devices with a modest degree of directivity above ~1 kHz. This resulted in a dichotic stimulus with binaural cues available across the entire frequency range. The second (*beamfull*) condition achieved maximal SNR improvement (~4.5 dB speech-weighted re. pinna) at the cost of binaural cue preservation. It resulted in a diotic stimulus across the entire frequency range. The third (*beam>0.8k*) and fourth (*beam<2k*) conditions were hybrid versions of the pinna and beamfull conditions. The beam>0.8k condition corresponded to the pinna condition below 0.8 kHz and to the beamfull condition above 0.8 kHz. The beam<2k condition corresponded to the pinna condition above 2 kHz and to the beamfull condition below 2 kHz. Thus, the beam>0.8k condition resulted in a dichotic stimulus in the low-frequency range and in a diotic stimulus in the mid- and high-frequency range. In contrast, the beam<2k condition resulted in a diotic stimulus in the low- and mid-frequency range and in a dichotic stimulus in the high-frequency range. Compared to the beamfull condition, the beam>0.8k and beam<2k conditions achieved less SNR improvement (~2 dB and ~3 dB speech-weighted re. pinna). The fifth (*beambetter*) condition was identical to the beamfull condition except that only the ear with the better speech-in-noise reception was stimulated (corresponding to bilateral contralateral routing of signals; BICROS). It therefore resulted in a monaural stimulus. Figure 1 shows polar patterns of the different directional processing conditions. Following the directional processing, we applied NAL-RP amplification to ensure adequate audibility.

Acoustic scenarios

We evaluated the different HA conditions in three acoustic scenarios. The scenarios comprised a frontal target talker uttering sentences from the Oldenburg sentence test (OLSA; Wagener *et al.*, 1999). As maskers, we used three types of signals: (1) a recording of another male speaker uttering OLSA sentences, (2) a modified version of the International Speech Test Signal (ISTS; Holube *et al.*, 2010), and (3) a recording made in a large cafeteria (T_{60} = 1.25 sec) during a busy lunch hour (Kayser *et al.*, 2009). The OLSA masker consisted of 10 sentences that were concatenated without any pauses. The fundamental frequency of the speaker uttering these sentences was very similar to that of the target speaker (~110 Hz). The ISTS masker used here was identical to the original ISTS except that its fundamental frequency was

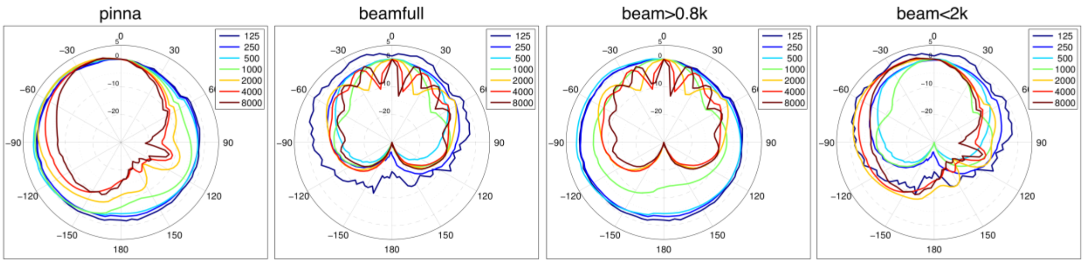

Fig. 1 (colour version online): Polar patterns of the pinna (left ear), beamfull (both ears), beam>0.8k (left ear), and beam<2k (left ear) settings calculated in octave bands with centre frequencies of 125, 250, 500, 1000, 2000, 4000 and 8000 Hz (see legend). The azimuth is in degrees and the gain in decibels.

lowered to match that of the target speaker. Thus, the main difference between the OLSA and ISTS maskers was that the latter was largely unintelligible. The OLSA and ISTS maskers were presented from ±60° azimuth. Below, we refer to the three stimulus conditions as the *olsa60*, *ists60* and *cafnois* scenarios.

For each combination of acoustic scenario and HA condition, we measured two SRTs (corresponding to 50%-correct speech intelligibility) per participant. A correlation analysis revealed that the test-retest reliability of these measurements was very good (all $r > 0.73$, all $p < 0.00001$).

RESULTS

Due to the bimodal distribution of the ΔPTALF data, we performed separate analyses of variance on the data from the symmetric and asymmetric groups. In each case, we included acoustic scenario and HA condition as within-subject factors and the BILD as a covariate. Furthermore, we initially also included age, PTA4, reading span and distractibility to control for potentially confounding effects due to these characteristics. Because age and distractibility did not contribute significantly to the models, we excluded them from all additional analyses.

For both groups, we found significant main effects of the BILD ($p < 0.001$) and acoustic scenario ($p < 0.00001$), a significant two-way interaction between HA condition and acoustic scenario ($p < 0.00001$) and a significant three-way interaction between the BILD, HA condition and acoustic scenario ($p < 0.016$). Follow-up analyses revealed (1) a strong negative association between the BILD and the SRT ($r < -0.76$), (2) better performance in the ists60 scenario than in the other two scenarios, (3) a very similar influence of the different HA conditions on performance in the olsa60 and ists60 scenarios but not in the cafnois scenario, (4) a differential influence of the BILD on performance with the different HA conditions in the osla60 and ists60 scenarios but not in the cafnois scenario, and (5) no performance benefits due to beambetter processing.

Symmetric group

Figure 2 shows scatter plots of the SRT and BILD data from the symmetric group for each acoustic scenario and HA condition together with regression lines. These plots indicate that, in situations with intelligible (olsa60) or unintelligible (ists60) speech maskers, participants with BILDs >2 dB profited from the preservation of low-frequency binaural cues (pinna and beam>0.8k). In contrast, for smaller BILDs and for spatially diffuse conditions (cafnois) in general, the maximal SNR improvement (beamfull) was beneficial. The plots also illustrate the negative association between the BILD and the SRT mentioned above.

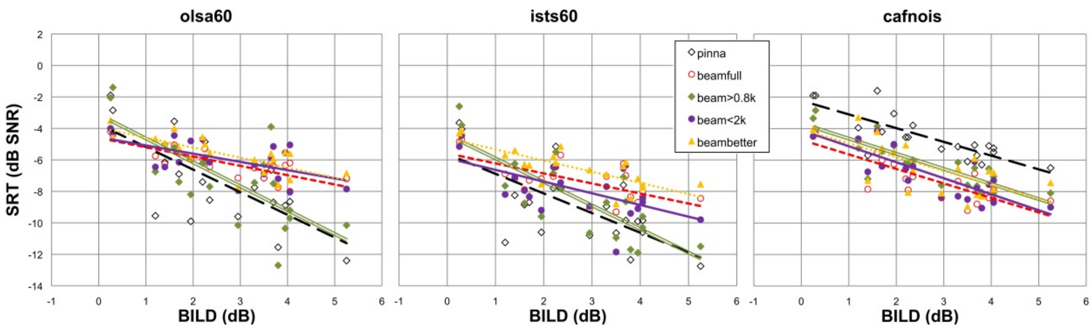

Fig. 2 (colour version online): Scatter plots of the BILD and SRT data for the *symmetric* group. Left: olsa60 scenario; Middle: ists60 scenario; Right: cafnois scenario. Least-squares regression lines corresponding to the pinna (long-dashed black line, unfilled black diamonds), beamfull (short-dashed red line, unfilled red circles), beam>0.8k (double green line, filled green diamonds), beam<2k (solid purple line, filled purple circles), and beambetter (dotted yellow line, filled yellow triangles) settings are also shown.

Asymmetric group

Figure 3 shows scatter plots of the SRT and BILD data from the asymmetric group for each acoustic scenario and HA condition together with least-squares regression lines. In general, these plots resemble those for the symmetric group (Fig. 2). For the asymmetric group, however, the benefit from low-frequency binaural cues (pinna and beam<0.8k) relative to more directionality (beamfull and beam<2k) occurred for participants with larger BILDs (>2.5 dB), leading to a reduction in the maximal benefit from binaural cue preservation (for a BILD of ~5 dB, ~2 dB for the asymmetric group vs. ~3 dB for the symmetric group).

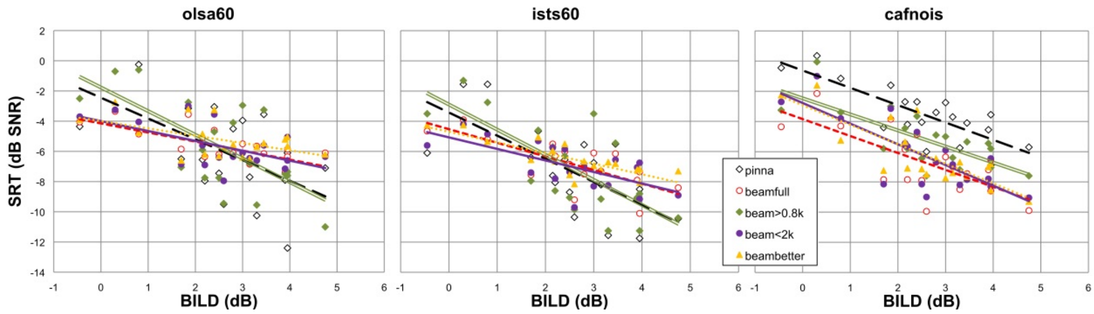

Fig. 3 (colour version online): Scatter plots of the BILD and SRT data for the *asymmetric* group. Left: olsa60 scenario; Middle: ists60 scenario; Right: cafnois scenario. Least-squares regression lines corresponding to the pinna (long-dashed black line, unfilled black diamonds), beamfull (short-dashed red line, unfilled red circles), beam>0.8k (double green line, filled green diamonds), beam<2k (solid purple line, filled purple circles), and beambetter (dotted yellow line, filled yellow triangles) settings are also shown.

Beambetter setting and abnormal BILDs

To test if HA users with clearly abnormal BILDs may benefit from the (rather extreme) beambetter setting, we analysed the data of a subset of participants with BILDs <1 dB (two 'symmetric' and three 'asymmetric' participants; mean BILD: 0.2 dB; range: –0.4 to 0.8 dB). Because some of the resultant datasets were not normally distributed, we used the Wilcoxon signed-rank test for this. Furthermore, we restricted our analysis to a comparison of the beambetter and beamfull settings. For none of the acoustic scenarios was there a significant difference between the two, nor was there one averaged across acoustic scenarios (all $p > 0.17$).

BILD vs. N_0S_π

As pointed out above, our participants had previously completed N_0S_π detection threshold measurements at 500 Hz, which were strongly correlated with the BILD data. To test if the BILD and N_0S_π measures can be used interchangeably to predict the effects of binaural hearing abilities on speech reception with bilateral directional processing, we repeated the analysis of the data from the symmetric group with the N_0S_π measure instead of the BILD included. There were significant effects of N_0S_π ($p < 0.001$), HA condition ($p < 0.021$), acoustic scenario ($p < 0.00001$), N_0S_π × HA condition ($p < 0.017$), HA condition × acoustic scenario ($p < 0.00001$) and N_0S_π × HA condition × acoustic scenario ($p < 0.009$). Thus, the results were very similar to those obtained with the BILD.

SUMMARY

In the current study, we investigated the influence of binaural hearing abilities, audiometric asymmetry <2 kHz and the acoustic scenario on aided speech reception with five directional processing schemes. The schemes, which were realized using virtual acoustics together with a computer simulation of a pair of completely occluding BTE devices, traded SNR improvement against binaural cue preservation below 800 Hz or above 2 kHz. In addition, they included a BICROS-like condition that combined maximal SNR improvement with better-ear stimulation. The participants were two groups of elderly individuals with symmetric or asymmetric hearing thresholds <2 kHz, large variation in the BILD, and no difference in age or PTA4. Our analyses revealed an influence of the BILD (or, alternatively, N_0S_π detection performance at 500 Hz) for intelligible (olsa60) and unintelligible (ists60) directional speech maskers from ±60° azimuth. Listeners with BILDs greater than 2-3 dB benefited more from low-frequency binaural cues than from greater directionality, whereas for smaller BILDs the opposite was true. Audiometric asymmetry reduced the influence of binaural hearing. Under spatially diffuse conditions (cafnois), performance was driven by SNR improvement, with the (maximally directional but diotic) beamfull setting giving the best results, irrespective of BILD and ΔPTALF status. The BICROS-like scheme did not result in any performance benefits, likely because only one of the participants tested here had a negative BILD (and thus a disbenefit from binaural interaction).

Together, these findings provide a valuable basis for adapting bilateral directional processing to the user and the acoustic scenario. Ongoing research is concerned with investigating their generalizability to clinical HA fittings.

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