

# **Binaural Hearing Ability With Bilateral Bone Conduction Stimulation in Subjects With Normal Hearing: Implications for Bone Conduction Hearing Aids.**

Mehrnaz Zeitoni, Elina Mäki-Torkko and Stefan Stenfelt

**Journal Article**



N.B.: When citing this work, cite the original article.

Original Publication:

Mehrnaz Zeitoni, Elina Mäki-Torkko and Stefan Stenfelt, Binaural Hearing Ability With Bilateral Bone Conduction Stimulation in Subjects With Normal Hearing: Implications for Bone Conduction Hearing Aids., *Ear and Hearing*, 2016. 37(6), pp.690-702.

<http://dx.doi.org/10.1097/AUD.0000000000000336>

Copyright: Lippincott, Williams & Wilkins

<http://www.lww.com/>

Postprint available at: Linköping University Electronic Press

<http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-135367>

## **ABSTRACT**

### **Objectives**

The purpose of this study is to evaluate binaural hearing ability in adults with normal hearing when bone conduction (BC) stimulation is bilaterally applied at the bone conduction hearing aid (BCHA) implant position as well as at the audiometric position on the mastoid. The results with BC stimulation are compared with bilateral air conduction (AC) stimulation through earphones.

### **Design**

Binaural hearing ability is investigated with tests of spatial release from masking (SRM) and binaural intelligibility level difference (BILD) using sentence material, binaural masking level difference (BMLD) with tonal chirp stimulation, and precedence effect using noise stimulus.

### **Results**

In all tests, results with bilateral BC stimulation at the BCHA position illustrate an ability to extract binaural cues similar to BC stimulation at the mastoid position. The binaural benefit is overall greater with AC stimulation than BC stimulation at both positions. The binaural benefit for BC stimulation at the mastoid and BCHA position is approximately half in terms of decibels compared to AC stimulation in the speech based tests (SRM and BILD). For BMLD the binaural benefit for the two BC positions with chirp signal phase inversion is approximately twice the benefit with inverted phase of the noise. The precedence effects results with BC stimulation at the mastoid and BCHA position are similar for low frequency noise stimulation but differ with high frequency noise stimulation.

## **Conclusions**

The results confirm that binaural hearing processing with bilateral BC stimulation at the mastoid position is also present at the BCHA implant position. This indicates the ability for binaural hearing in patients with good cochlear function when using bilateral BCHAs.

## **INTRODUCTION**

The benefits of binaural hearing in the human auditory system include improved ability to locate sound sources, spatial perception, and spatial release from masking. The mechanism of binaural hearing relies on interaural time differences (ITDs) and interaural level differences (ILDs) that arise from separation of the signal received at the two ears (Bronkhorst & Plomp 1988). These differences can be large in normal air conduction (AC) stimulation where sound is transmitted to each cochlea with a different transmission path via the ear canal, the eardrum and the middle ear ossicles. Spatial separation of the ears, and interaction with the skull between them, produce interaural differences in time and level of the AC sound that facilitates the binaural hearing process. In hearing with bone conduction (BC) stimulation, vibrations are transmitted from the skull surface and the cranial bones to both the ipsilateral and contralateral cochlea with only a small level difference and a short time delay from one stimulation position on the skull (Stenfelt 2005; Stenfelt & Goode 2005a). The level difference between the cochleae is termed transcranial attenuation and is 0-5 dB at lower frequencies, increases to almost 10 dB at 3-5 kHz, and decreases to 4 dB at the highest frequencies (Stenfelt 2012; Stenfelt & Zeitouni 2013). The time delay between the cochleae for mastoid placement of the BC stimulation is estimated to be 0.3 to 0.5 ms at frequencies above 1 kHz (Stenfelt & Goode 2005b; Eeg-Olofsson et al. 2011), while there are no reliable

estimates at lower frequencies. Consequently, contralateral BC stimulation is transmitted across the skull and influences perception at the ipsilateral cochlea. This cross stimulation reduces the interaural separation leading to a decreased ability to extract binaural cues when stimulation is by BC in comparison to ordinary AC stimulation.

Binaural BC hearing is important for patients implanted with bone conduction hearing aids (BCHAs). The BCHA is an option for hearing rehabilitation in patients with conductive hearing loss, chronic middle ear diseases and congenital malformations, or in patients where an ordinary AC hearing aid is contraindicated but there is a need for amplification (Snik et al. 2005). The percutaneous BCHA is coupled to a titanium implant in the parietal bone positioned 55 mm behind the ear canal opening in line with the upper part of the pinna (Tjellström et al. 2001). Since BC sound from one BCHA reaches both cochleae, it has been argued that one BCHA is adequate in hearing rehabilitation of patients with bilateral hearing loss. In addition, the limited transcranial attenuation introduces an uncertainty towards the benefit of binaural hearing with BC stimulation due to decreased sound separation between the cochleae.

There are studies in patients implanted with bilateral BCHAs that have indicated binaural benefit in terms of improved sound localization ability and, to some extent, speech understanding in both quiet and noise (Bosman et al. 2001; Priwin et al. 2004). However, the small groups in these studies and their heterogeneous hearing status complicate the interpretation of the origin of the improvements as the results are influenced by both the use of bilateral BC stimulation and the participants' hearing loss. Furthermore, the tests used in those studies also add to the uncertainties. In the more basal binaural test, binaural masking level difference (BMLD), pure tones were used as BC stimulus. It has been shown that using narrowband stationary stimuli for bilateral BC stimulation, such as a pure tone, add

constructively or destructively depending on their relative phase (Rowan & Gray 2008; Stenfelt & Zeitoni 2013). It is therefore not possible to determine if the results reflect true binaural hearing effects or are summations of the stationary vibrations at the cochleae.

In a recent study, binaural hearing ability with bilateral BC stimulation at the mastoid position was evaluated in normal hearing subjects (Stenfelt & Zeitoni 2013). The results indicated several benefits of binaural hearing when stimulation was by bilateral BC, even if the binaural benefit was less through BC sound than AC sound. For the speech based tests, the data showed approximately half the benefit in terms of decibels in speech in noise ratio (SNR) for BC stimulation in comparison to AC stimulation. In the BMLD test, it was found that the results were influenced by superposition of the ipsilateral and contralateral pathways at the cochlear level when stimulation was by BC. The precedence effect test showed different results for BC and AC sound when assessed with low frequency stimulation, while they were similar with high frequency stimulation. A caveat is that the results in that study were obtained when BC stimulation was applied to the mastoid. As mentioned in the preceding text, the placement of a BCHA is some 35 mm back compared with the mastoid stimulation position. Furthermore, it has been shown that BC stimulation at the BCHA position gives less transcranial attenuation than when BC stimulation is at the mastoid position (Eeg-Olofsson et al. 2011; Stenfelt 2012). Therefore, it is not known how the binaural hearing results at the mastoid position relate to the BCHA position, but as the interaural separation is less at the BCHA position, it is likely worse in terms of binaural benefit. Moreover, it is uncertain how the data from Stenfelt and Zeitoni (2013) can be interpreted in patients using bilateral BCHAs.

The encouraging observations in the study of Stenfelt and Zeitooni (2013) led us to further explore binaural hearing with BC stimulation with the aim to extend the results in that study to persons using BCHAs. For that reason, the aim of the present study was to investigate binaural hearing when BC stimulation is applied at the BCHA position, and to compare those results with stimulation at the audiometric BC position on the mastoid as well as with ordinary AC stimulation. Moreover, the tests used for assessing binaural hearing ability were administered to a group of unilateral deaf participants to explore the validity of those tests when the stimulation was bilaterally by BC.

The study was approved by the Regional Ethical Review Board in Linköping, Sweden.

## **MATERIALS AND METHODS**

### **Participants**

Twenty-seven participants with normal hearing and otologically normal ears with no history of ear surgery performed the tests. They had AC and BC thresholds equal or better than 20 dB HL in the audiometric frequency range 125-8000 Hz (500-4000 Hz for BC) with air-bone gap  $\leq 10$  dB at any frequency. Their mean age was 29.4 years (ranging from 22-44 years), 17 were male and 10 were female. A few of the subjects also participated in the Stenfelt & Zeitooni (2013) study, but no data from that study were used and all subjects were tested according to the current protocol. An additional group of 6 patients with acquired unilateral deafness was included to evaluate the validity of the tests used since monaural contribution from bilateral application of BC sound can affect the outcomes from the tests. Their right ear was the hearing ear for 4 patients, while the other 2 patients used their left ear. They were all

considered unilaterally deaf: 4 of them were diagnosed with sudden deafness, and the other 2 had undergone surgery for vestibular schwannoma. They all had pure tone average (PTA4; 0.5, 1, 2 and 4 kHz) equal to or better than 20 dB HL in their hearing ear. For the deaf ear, 2 patients had measurable hearing thresholds but with an interaural difference of at least 50 dB in the lower frequencies (125-500Hz) and at least 80 dB at the higher frequencies (1000-4000 Hz). The other 4 patients had no measurable hearing thresholds in the deaf ear. Their mean age was 61.7 years (ranging from 50-68 years), 4 were male and 2 were female. All participants were given adequate written and oral information about the nature and benefit of the study. An informed consent was signed at the first visit and the participants had the possibility to terminate participation at any time throughout the study. All participants volunteered to take part in the study and were not compensated for their participation.

### **Test Setup**

All measurements were carried out in a double-walled sound insulated test booth with background noise levels consistent with ISO 8253-1 (2010). Baseline audiometry was obtained with an Interacoustics AC40 audiometer using TDH-39 earphones for AC measurements and Radioear B-71 transducer for BC hearing thresholds. All 4 binaural hearing tests were computer based and programmed in MATLAB<sup>®</sup> using 24-bit amplitude resolution and a sampling rate of 44.1 kHz. The computer soundcard (M-Audio Transit) was connected to a four-channel power amplifier (Rotel RA-04 SE) where two channels were coupled to a pair of Sennheiser HDA200 earphones for AC stimulation, and two channels were coupled to a pair of custom made BC transducers for BC stimulation. The BC transducers used in the binaural experiments, named balanced electromagnetic separation transducers (BEST) (Håkansson 2003), were encapsulated in a plastic housing with a flat elliptic surface of 25 x 18 mm, and had a height of 10 mm. The transducers were bilaterally

applied and held in place using an elastic band to provide equal static force to both transducers at the two BC positions compared: (1) the normal audiometric position at the most prominent point on the mastoid where the skin and subcutaneous tissue appeared thinnest, and (2) the standard BCHA implant position, 55 mm behind the ear canal opening in line with the of the upper part of the pinna. The static force exerted by the transducer on the skull was measured using a dynamometer. The exact static force depended on the size of the skull and the range of the static force for the participants was 3-5 N. There was no contact between the BC transducers or the elastic band and the pinna of the external ear.

### **Spatial Release From Masking**

Spatial release from masking (SRM) was tested with speech stimuli using the Swedish Hagerman sentences (Hagerman 1982). The Hagerman sentences are five-word structured and semantically correct sentences but have low predictability. The speech material was presented with a female voice in slightly modulated speech-weighted noise with the aim to determine the signal to noise ratio (SNR) where 50% of the sentence words were heard correctly. The test was done according to an adaptive routine (Hagerman & Kinnefors 1995) and lower SNR corresponds to better performance. The participants were instructed to repeat the words in the sentences as accurately as possible and were first familiarized with the test by a training sentence list before the test started. Each list consisted of 10 sentences and two lists were used for one test where the average result from the sentences in the last list gave the SNR for that specific presentation mode and test condition. The stimulation was bilaterally provided with three presentation modes: (1) AC stimulation through earphones (2) BC stimulation with BC transducers at the mastoid position, and (3) BC stimulation with BC transducers at the BCHA position. In all tests, the earphones were removed during BC testing. The speech in noise test was conducted for two conditions: (1) co-located with speech

and noise from front at  $0^\circ$  (S0N0), and (2) spatially separated with speech from front at  $0^\circ$  and noise from  $45^\circ$  (S0N45). In the S0N0 condition, the same signal was presented to the two ears. In the S0N45 condition, the sound sources differed by  $45^\circ$  according to the head related transfer function (HRTF) (Wightman & Kistler 2005). When filtering the speech and noise with HRTFs, they are perceived to originate from a certain angulation when presented through earphones or BC transducers. Since no individualized HRTFs were obtained in this study, a general model by Brown and Duda (1998) was used to provide the spatial conditions.

For the test with AC stimulation provided through earphones, the speech level was set at 60 dB SPL, which corresponds to approximately 40 dB HL<sub>AC</sub> for the Hagerman corpus. The sensitivity function for AC sound in dB SPL when sound is delivered by earphones differs from the BC sensitivity function in dB  $\mu$ N when delivered by BC transducers [cf ISO:389-1 (1998) and ISO:389-3 (1994)]. For the testing to be comparable between AC and BC stimulation, the speech level for BC stimulation was set at 40 dB HL<sub>BC</sub> as measured with the current BC transducers and the Hagerman corpus. This means that even if the spectral contents of the stimulation by AC and BC differed, the overall loudness of the sentences were similar. Also, the 40 dB HL speech level for both stimulation modalities meant that they were clearly audible. The order of stimulation mode, test condition and list sequence were randomized as far as possible across the participants and within each session. Altogether, three presentation modes and two test conditions resulted in six speech in noise tests for each participant in the SRM test.

### **Binaural Intelligibility Level Difference**

The binaural intelligibility level difference (BILD) test was performed using the same speech material (Hagerman sentences) as in the SRM test described above. Measurements comprised

two test conditions: (1) equal phase for the speech at the two ears and an interaural difference for the noise of  $180^\circ$  (S0N180), and (2) interaural phase difference for the speech of  $180^\circ$  while the phase was equal for the noise at the ears (S180N0). Since the condition with speech and noise with equal phases at the two ears (S0N0) is identical to the condition tested in the SRM test it was not retested. Stimuli were provided with (1) AC stimulation through earphones, (2) BC stimulation at the mastoid position with BC transducers, and (3) BC stimulation at the BCHA position with BC transducers. The three presentation modes and two test conditions resulted in six speech in noise tests for each participant in the BILD test. Presentation mode, test condition and list sequence were counterbalanced among the participants to minimize order effects.

### **Binaural Masking Level Difference**

The BMLD test was conducted with tonal stimuli using a chirp tone oscillating between 400 and 600 Hz at a rate of 20 Hz with 1s duration. The chirp tone was presented in band-limited white noise with a frequency range of 100-2000 Hz at 60 dB SPL. The oscillating chirp tone was used with the intention of avoiding summation effects that can occur with bilateral BC stimulation of stationary narrowband signals (Rowan & Gray 2008). Detection thresholds were estimated by the Hughson-Westlake algorithm with 2 dB steps according to ISO:8253-1 (2010) where the threshold is determined as the three lowest responses at the same level. The participant was seated in front of a computer screen and was instructed to give a response whenever the chirp tone was heard in the noise by clicking on a button labeled “hear”. The test was done with (1) AC stimulation through earphones (2) BC stimulation at the mastoid position with BC transducers, and (3) BC stimulation at the BCHA position with BC transducers. The chirp tone thresholds were obtained for three interaural phase conditions: (1) chirp tone and noise with no interaural phase difference (S0N0), (2) chirp tone with no

interaural phase difference and the noise  $180^\circ$  out of phase at the two ears (S0N180), and (3) chirp tone  $180^\circ$  out of phase at the two ears while the noise had equal phase at the two ears (S180N0). A training test was first presented with both AC stimulation and BC stimulation to familiarize the participant with the procedure and the stimuli. The order of stimulation mode and test condition was randomized across the participants. In total, three presentation modes and three test conditions resulted in nine BMLD tests for each participant.

### **Precedence Effect**

The precedence effect test in this study was done by using two types of stimuli, one low-frequency noise (400-600 Hz) and one high-frequency noise (3000-5000 Hz). The stimulus was presented as 1 s noise bursts that had a  $1 \text{ ms sine}^2$  rise and fall. The perceived sound location was tested for 12 stimulation presentations with interaural time delays between 0 and 50 ms (delays: 0, 0.2, 0.5, 0.8, 1.2, 2, 5, 10, 20, 30, 40, and 50 ms). The participant faced a computer screen and was instructed to give a response of the perceived location by using a slide control with a scale between  $-90^\circ$  (left ear of the participant),  $0^\circ$  (directly in front) and  $+90^\circ$  (right ear of the participant). If the stimulus was perceived as two separate sounds in both ears, the response was given by clicking on a button labeled “echo”. A response of the perceived location was always given before the next stimulation was provided. The stimuli were bilaterally presented with (1) AC stimulation through earphones (2) BC stimulation at the mastoid position with BC transducers, and (3) BC stimulation at the BCHA position with BC transducers. A training test was first presented with both AC stimulation and BC stimulation to familiarize the participant with the procedure and the stimuli. The precedence effect test was conducted with three presentation modes and two stimulus types that resulted in six tests for each participant. The order of presentation mode, type of stimuli and time delay were randomized across the participants.

## **Calibration**

The audiometer output for the baseline audiometry was calibrated according to ISO:389-1 (1998) for AC thresholds through TDH-39 earphones, and ISO: 389-3 (1994) for BC thresholds through a B-71 transducer. For the other computer generated tests in MATLAB®, the absolute values of the tones, noises and speech were estimated. The Sennheiser HDA200 earphones for AC stimulation were calibrated by attaching the earphone to an ear simulator, IEC:60318-1 (2009), and measuring the output level with a Brüel and Kjær pulse 12.0 analyzer. The BEST BC transducers were attached to the artificial mastoid Brüel and Kjær type 4930 and a Brüel and Kjær pulse 12.0 analyzer measured the output. The measurements were exported to MATLAB® for computation of the calibrations. First, the stimulation level in dB SPL was calculated for the AC stimulations and used as the reference for the AC stimulated tests. Next, the hearing thresholds from ISO:389-8 (2004) were used to compute a dB HL estimate of the AC stimuli by computing the audible 3<sup>rd</sup>-octave band signal levels above thresholds and integrating over the entire frequency range. A similar calculation of the BC stimuli was done with the hearing thresholds in ISO:389-3 (1994). The estimates of the dB HL for the stimuli were equated for AC and BC presentation, and the two modes of presentation had approximately the same overall stimulation level. However, because the outcomes are relative results, this calibration was only used to set an overall level for the tests.

The left and right earphones as well as right and left BC transducers were controlled for symmetry. The Sennheiser HDA200 earphones were tested by attaching the earphone to an ear simulator IEC:60318-1 (2009) and measuring the frequency response function for a chirp stimulus in the frequency region 200–8000 Hz with a frequency resolution of six points per octave. According to this measure, the maximum level deviation

was 1.0 dB and phase deviation was 7° between the left and right earphones at any of the measured frequencies. The left and right BC transducers were also controlled for their symmetry. In this case, the BC transducer (BEST) was attached to the artificial mastoid Brüel and Kjær type 4930. A chirp signal was fed to the BC transducer, and the output from the artificial mastoid was analyzed for its frequency response. In the frequency range 200-8000 Hz and with a frequency resolution of six points per octave, the maximum level deviation was 1.5 dB and phase deviation was 10° between the left and right BC transducers at any of the measured frequencies. It should be noted that the BEST BC transducer used for the binaural BC testing does not conform to the specifications in the ISO:389-3 (1994) standard (e.g., a circular interface of 175 mm<sup>2</sup>), and the absolute thresholds differ slightly between the BEST BC transducer here and an ordinary Radioear B71 transducer. However, we feel that the comparison between left and right transducers in this way gives a good estimate of the maximum difference.

### **Data and Statistical Analyses**

Data analysis was carried out using IBM SPSS 21.0 Statistics. Repeated measures analyses of variance (ANOVA) were used to evaluate the outcome scores for all examinations. The level of statistical significance was set at  $p < 0.05$  and Bonferroni adjustment was applied as appropriate. Multiple Student's two-tailed paired t-tests were conducted to further investigate significant differences between conditions for a specific presentation mode, or differences between presentation modes for a specific condition. The level of statistical significance for the t-test was set at  $p < 0.01$  and no adjustments for multiple comparisons were made.

## RESULTS

### **Spatial Release From Masking**

The results from the SRM test are presented in Figure 1(A) with comparison of the mean SNR obtained from the three presentation modes and the two test conditions. In the condition when speech and noise were co-located from front (S0N0), the results were similar across all presentation modes; AC stimulation exhibited an average SNR of -8.0 dB, BC stimulation at the mastoid position -8.6 dB, and BC stimulation at the BCHA position -8.5 dB. When speech and noise were spatially separated in the test condition S0N45, the best mean results were found with AC stimulation at -16.4 dB, and the SNR with BC stimulation at the mastoid was -13.3 dB giving a slightly better result than -12.5 dB with BC stimulation at the BCHA position. As seen in Figure 1(B), the average spatial benefit between the condition S0N0 and S0N45 was 8.4 dB for AC stimulation, 4.7 dB for BC stimulation at the mastoid, and 4.0 dB for BC stimulation at the BCHA position. A repeated measures ANOVA showed main effects of both presentation mode and test condition: [presentation:  $F(2,52) = 28.09$ ,  $p < 0.001$ ; condition:  $F(1,26) = 599.72$ ,  $p < 0.001$ ]. The interaction between presentation and condition was also significant [ $F(2,52) = 86.37$ ,  $p < 0.001$ ]. A more detailed analysis was then carried out to investigate the data further using the paired t-test to compare each presentation mode with each test condition. All differences between conditions and presentation modes were found to be significant at  $p < 0.01$  except for test condition S0N0 for the two BC stimulation positions.

### **Binaural Intelligibility Level Difference**

The BILD results are shown in Figure 2(A) with average SNR for the three presentation modes and the three test conditions. The results for test condition S0N0 are the same as in the

SRM test (Figure 1). For AC stimulation (black bars), inverting the phase of the noise (S0N180) gave a SNR threshold of -14.6 dB, and inverting the phase of the speech (S180N0) gave a SNR threshold of -14.9 dB. The SNR thresholds for BC stimulation at the mastoid position were -13.5 dB at both S0N180 and S180N0. Similar results were found with BC stimulation at the BCHA position where the SNR threshold was -13.2 dB for S0N180 and -13.3 dB for S180N0. Figure 2(B) illustrates the average benefits when inverting the phase of either the noise or the speech that for AC stimulation were 6.6 dB (S0N0-S0N180) and 6.8 dB (S0N0-180N0). Bone conduction stimulation at the mastoid position gave an average benefit of 4.9 dB at both test conditions, while the benefit for BC stimulation at the BCHA position was 4.7 dB (S0N0-S0N180) and 4.8 dB (S0N0-S180N0). This calculation indicates an approximately 2 dB greater binaural benefit for AC stimulation when inverting the phase of the noise or the speech in comparison to BC stimulation at the mastoid position and BCHA position. Furthermore, the SNR results for test condition S0N180 and S180N0 were similar within each presentation mode.

The statistical analysis done with repeated measures ANOVA showed main effects of both presentation mode and test condition [presentation:  $F(2,52) = 4.85$ ,  $p < 0.01$ ; condition:  $F(2,52) = 164.34$ ,  $p < 0.001$ ]. The interaction between presentation and condition was also significant [ $F(4,104) = 8.206$ ,  $p < 0.001$ ]. The paired t-tests showed significant differences between S0N0 and the two test conditions with inverted phase (S0N180 and S180N0) in all three presentation modes. The analysis showed no significant difference between S0N180 and S180N0 within any of the presentation modes. A significant difference was found between AC stimulation and the two BC positions for test conditions S0N180 and S180N0, but no significant difference between the BC stimulations.

### **Binaural Masking Level Difference**

The data from the BMLD test are illustrated with average detection levels in dB for the three presentation modes and the three test conditions in Figure 3(A). The best results were found with AC stimulation (left part of the figure) with detection levels at 36.7 dB SPL for the S0N0 condition, 29.2 dB SPL for S0N180, and 27.3 dB SPL for S180N0. The S0N0 test condition for BC stimulation at the mastoid position resulted in 40.1 dB, while the detection levels improved to 38.0 dB at S0N180 and 35.9 dB at S180N0. BC stimulation at the BCHA position gave similar results with 40.2 dB at S0N0, 37.7 dB at S0N180, and 35.6 dB at S180N0. As shown in Figure 3(B), phase inversion of the noise for AC stimulation (S0N180) gave an average benefit of 7.5 dB, and 9.4 dB for phase inversion of the chirp signal (S180N0). The binaural benefit for BC stimulation at the mastoid position was 2.1 dB (S0N180) and 4.2 dB (S180N0). The results were similar with BC stimulation at the BCHA position: the benefit was 2.5 dB (S0N180) and 4.6 dB (S180N0). The BMLD improved when the phase was inverted for all conditions in comparison with S0N0 in all three presentation modes. Furthermore, the results were also better for S180N0 than for S0N180 across all presentation modalities. The binaural benefit of detection levels for the two BC positions with chirp signal phase inversion was approximately twice the benefit in noise phase inversion. These results were analyzed with repeated measures ANOVA that showed main effects of both presentation mode and test condition [presentation:  $F(2,52) = 166.63$ ,  $p < 0.001$ ; condition:  $F(2,52) = 31.85$ ,  $p < 0.001$ ]. The interaction between presentation and condition was also significant [ $F(4,104) = 6.11$ ,  $p < 0.001$ ]. The paired t-test showed significant differences between all test conditions with AC stimulation,  $p < 0.01$ . When analyzing the results with BC stimulation at the mastoid position and BCHA position, only the differences between S0N0 and S180N0 were significant, all other test conditions did not reach statistical significance.

## **Precedence Effect**

The precedence effect test results are presented in Figure 4(A) for low frequency (LF) stimulation and in Figure 4(B) for high frequency (HF) stimulation. The graph in the upper panel illustrates the median results for each presentation mode as a function of interaural time delay. The lower panel in the figure shows the percentage of participants that perceived an echo at the tested interaural delay. With AC stimulation, lateralization of the sound towards 90° increases with time delay for both LF and HF noise. The sound image is prominently lateralized to the leading side at 0.5 ms and above for both LF and HF noise. The echo perception also increased with time delay and was between 70-85% at 20 ms and above for LF noise, and slightly higher for HF noise with 75-90% at 20 ms and above. With BC stimulation at the mastoid position, full lateralization to the leading side is shown at 10 ms and above for LF noise, and at 5 ms and above with HF noise. The echo perception for BC stimulation at the mastoid was nearly 50% for LF noise at and above 20 ms, and approximately 70% at and above 20 ms for HF noise. The median results with BC stimulation at the BCHA position showed similar results as BC stimulation at the mastoid position when tested with LF noise. For the test with HF noise, the results were similar to LF noise and full lateralization to the leading side was not reached until 40 ms interaural time delay with BC stimulation at the BCHA position, while it was reached at 10 ms with BC stimulation at the mastoid position. The echo perception for BC stimulation at the BCHA position was almost 50% at 50 ms for both LF noise and HF noise.

The inter-individual variability of the perceived sound image was greater with BC than with AC excitation, but the standard deviations (SDs) of the data in Figure 4 were relatively similar for the different time delays and between low and high frequency stimulation. For the AC LF noise the SDs were between 20 and 45 degrees with an average of 33 degrees while

they were between 21 and 46 degrees with an average of 35 degrees for AC HF noise. At the mastoid, the BC LF noise had SDs between 49 and 66 degrees with an average of 59 degrees while the HF data with BC at the mastoid were between 38 and 61 degrees with an average of 51 degrees. The same data for the BCHA position gave LF BC SDs between 54 and 68 degrees (mean 58 degrees) and HF BC SDs between 41 and 56 degrees (mean 50 degrees).

All results were analyzed with repeated measures ANOVA that showed main effects for presentation mode, delay, and the interaction between presentation mode and delay for the test with LF noise [presentation:  $F(2,52) = 17.39$ ,  $p < 0.001$ ; delay:  $F(11,286) = 29.87$ ,  $p < 0.001$ ; interaction of presentation mode and delay:  $F(22,572) = 2.72$ ,  $p < 0.001$ ]. Furthermore, the results with AC stimulation were significantly better than BC stimulation at the mastoid position and the BCHA position with LF noise, while there was no significant difference between the two BC positions. For the test with HF noise, main effects were found for presentation mode, delay, and the interaction between presentation mode and delay [presentation:  $F(2,52) = 13.56$ ,  $p < 0.001$ ; delay:  $F(11,286) = 39.06$ ,  $p < 0.001$ ; interaction of presentation mode and delay:  $F(22,572) = 2.00$ ,  $p < 0.004$ ]. The difference between the results with AC stimulation and BC stimulation at the mastoid position was approaching significance ( $p = 0.051$ ), whereas the difference between AC stimulation and BC stimulation at the BCHA position was significant,  $p < 0.001$ . The difference between BC stimulation at the mastoid position and BCHA position was also significant,  $p = 0.022$ .

### **Unilateral Deafness**

The 6 patients with acquired unilateral deafness with contralateral normal hearing ear were evaluated with the BILD and BMLD tests. The purpose was to investigate if these tests gave monaural contribution due to the phase inversion when the stimulation was bilaterally applied

BC sound. This was only tested with bilateral BC transducers on the mastoid position. For the BILD test, the average SNR was -5.4 dB for S0N0, -8.2 dB for S0N180, and -7.8 dB for S180N0. This gives a binaural benefit of 2.8 dB (S0N180) and 2.4 dB (S180N0). A repeated measures ANOVA showed main effects for test condition  $F(2,10) = 6.21$ ,  $p = 0.018$ . The paired t-tests between S0N0 and the two test conditions with inverted phase did not reach significance;  $p = 0.037$  (S0N180) and  $p = 0.075$  (S180N0).

For the BMLD test, one outlier was detected in the results from the 6 patients with unilateral deafness (results more than the mean + 2 SDs), and therefore data from 5 patients were analyzed. The BMLD test with chirp tones gave tone detection thresholds at 42.0 dB at S0N0, 44.8 dB at S0N180 and 38.8 dB at S180N0. The binaural benefit was -2.8 dB (S0N180) and 3.2 dB (S180N0). These results showed no significant effect when analyzed with repeated measures ANOVA,  $F(2,8) = 2.41$ ,  $p = 0.152$ .

## **DISCUSSION**

The current study explored binaural hearing in 27 normal hearing subjects when BC stimulation was bilaterally applied at the BCHA implant position, and compared the results to bilateral BC stimulation at the mastoid position and bilateral AC stimulation through earphones. All participants showed binaural processing when tested with SRM and BILD test using sentences, BMLD test using chirp tones, and the precedence effect test with noise stimulus. In addition, 6 patients with acquired unilateral deafness were tested with BILD and BMLD with the same test procedure as for the normal hearing participants in order to evaluate if monaural contribution due to phase inversion from bilateral BC application affected the results in these tests.

## **Previous studies**

Binaural hearing ability with BC stimulation is limited due to cross-skull transmission where BC vibrations from one stimulation position on the skull reach both cochleae (Stenfelt & Goode 2005a; Stenfelt 2012). However, the transcranial transmission has been reported in the literature to be inter-individually large, and varies with frequency where there are frequency regions with more than 10 dB transcranial attenuation (Eeg-Olofsson et al. 2011; Stenfelt 2012; Stenfelt & Zeitoni 2013). These measurable transcranial attenuations may, to some extent, explain the data from Stenfelt and Zeitoni (2013) where normal hearing subjects revealed binaural hearing ability with bilateral mastoid applied BC stimulation in all tests, indicating the use of binaural cues. In that study, as in this one, the results from the speech based tests through SRM and BILD with BC stimulation showed almost half the benefit in terms of decibels in SNR when compared to AC stimulation. The subjects also demonstrated similar precedence effect functions with BC and AC stimulation with high frequency noise, while the results differed with low frequency noise. Once again, these results were based on mastoid stimulation and do not describe the benefits to the BCHA patients as the BCHA implant position is placed further back than the mastoid position. Some of the tests in Stenfelt and Zeitoni (2013) were replicated in the current study and they are discussed below.

Previous studies have presented positive findings of bilateral BCHA compared to unilateral BCHA, and a review by Colquitt et al. (2011) conclude that several studies in the literature indicate benefit from bilateral BCHA in patients with bilateral hearing loss. Bosman et al. (2001) demonstrated improved sound source localization ability and better speech in noise results when comparing bilateral BCHA to unilateral. The evaluations in that study were later replicated by Priwin et al. (2004) where they also showed bilateral BC hearing benefit when testing directional hearing and speech understanding in noise.

## **Spatial Release from Masking**

Spatial cues are fundamental in improving speech understanding in noise. The improvement arises when a condition in which the signal and noise are at the same source location is compared to a condition in which they are spatially separated (Hawley et al. 1999). In this study, SRM was tested with sentence material presented as speech and noise co-located from 0° (SON0), and spatially separated with speech from 0° and noise from 45° (SON45). As expected, and seen in Figure 1, the best results were obtained with AC stimulation and the spatial benefit with 8.4 dB was approximately twice the benefit given with BC stimulation at the mastoid position (4.7 dB) and BCHA position (4.0 dB). The results with AC stimulation and BC stimulation at the mastoid are very close to earlier results in the Stenfelt and Zeitooni (2013) study where the spatial benefit at 45° was 8.6 dB for AC stimulation and 4.5 dB for BC stimulation at the mastoid position. The SNRs for the BCHA implant position only differ by 0.1 dB at SON0 and 0.8 dB at SON45 compared to the SNRs with BC stimulation at the mastoid position (-8.5 dB at SON0 and -13.3 at SON45).

The binaural benefit depends on both the sentence material and the specifics of the test situation (e.g. room reverberation and the source separation). With that in mind, the results for AC stimulation are similar to other studies that have investigated the binaural benefit in a way similar to the current study (Bronkhorst & Plomp 1992; Dubno et al. 2002). We did not find any study that had investigated the SRM with bilateral BCHAs as in the current study, but Bosman et al. (2001) showed 3.3 dB better speech in noise results and Priwin et al. (2004) showed 2.8 dB better SNR with bilateral BCHAs compared to unilateral. Even if they are not measured in the exactly same way as the current study, they show binaural benefits that are reasonable compared to the findings in the current study. Moreover, the difference between a

BC position close to the cochlea (mastoid position) and further away (BCHA position) reduced the binaural benefit by 0.7 dB indicating that the detrimental effect of less interaural separation between these positions is minor. To summarize, according to the current study there is a clear and significant binaural benefit with bilateral BC stimulation at the BCHA position.

When the noise source is changed from 0 degrees (N0) to 45 degrees (N45), the spectrum of the noise signal changes at the two ears. This means that the ipsilateral ear SNR is different from the contralateral ear and also different from the N0 condition. As a consequence, there is a better ear advantage that provides monaural better SNR that could contribute to the results obtained; this is not part of the binaural effect. Its contribution was estimated by computing the speech intelligibility index (SII) ANSI S3.5 (1997) for S0N0 and S0N45 by changing the overall SNR for the two conditions to obtain the same SII. This indicated that, for BC stimulation at the mastoid, the contralateral ear had 1.7 dB better SNR due to the head shadow and the ipsilateral ear had 2.7 dB worse SNR with S0N45 compared with S0N0. The same computation for the AC testing indicated 2.1 dB improvement in SNR for the contralateral ear and 3.4 dB worse SNR for the ipsilateral ear. No estimations were done for the BCHA position as lack of exact threshold data prevented the computations, but the results are expected to be similar to the BC mastoid position. These estimations based on the SII indicate that the changed spectral levels of the noise at the two ears contributed to the better performance at S0N45 compared with S0N0 but the greatest part of the improvement were due to binaural processing of the signals.

### **Binaural Intelligibility Level Difference**

Binaural intelligibility level difference is a measure of the improvement in speech intelligibility that is facilitated by interaural phase differences under binaural listening conditions (Licklider 1948). Here, the BILD test was conducted with the same sentence material as in the SRM test. The SNR improvement in the inverted test conditions was approximately 2 dB greater with AC stimulation than the two BC stimulation positions, and there was no difference between inverting the noise or the signal in any of the presentation modes. The binaural benefit was 6.6 dB (SON180) and 6.8 dB (S180N0) for AC stimulation, while 4.9 dB at both inverted test conditions for BC stimulation at the mastoid position, and 4.7 dB (SON180) and 4.8 (S180N0) for BC stimulation at the BCHA position. The results with BC stimulation are 1 dB better than those obtained in the Stenfelt and Zeitoni (2013) study where the binaural benefit was 3.7 dB (SON180) and 3.8 dB (S180N0). The reason for this difference is unknown and unexpected as the test was conducted the same way and the two groups tested were similar in age and hearing status. The similar binaural benefit shown between BC stimulation at the BCHA position and BC stimulation at the mastoid position in the SRM test is confirmed in the BILD test where the maximum difference is 0.2 dB. This similarity indicates that interaural phase information is not severely distorted by changing from the mastoid to the BCHA position with BC stimulation. The similarity between S180N0 and SON180 can be explained by the fact that both signals are broadband and non-stationary. Therefore, the binaural improvement with phase inversion of either is expected to be similar.

### **Binaural Masking Level Differences**

The BMLD test differs from the BILD test described above by the use of tonal stimuli instead of speech. The BMLD is affected by the type of stimuli, the bandwidth of the masker, the stimulation level and the method of determining the thresholds (Hirsch 1948). The BMLD test in this study used an oscillating chirp tone in band-limited white noise. For AC

stimulation, the detection thresholds improved with 7.5 dB (S0N180) and 9.4 dB (S180N0), while the same were 2.1 dB and 4.2 dB for BC stimulation at the mastoid, and 2.5 dB and 4.6 dB for BC stimulation at the BCHA position. Even if the binaural benefit is slightly better at the BCHA position than the mastoid position, the differences were not statistically significant. In comparison with the data from Stenfelt and Zeitooni (2013) study, the BMLD results differ. The results in that study gave BMLD of 8.8 dB (S0N180) and 11.7 dB (S180N0) for AC stimulation, and 10.5 dB benefit for BC stimulation at the mastoid in phase inversion of the noise, and 4.9 dB for phase inversion of the signal. That study used a different chirp-tone for the test, oscillating between 400 and 600 Hz at a rate of 10 Hz while the same chirp tone in this study had a rate of 20 Hz. The different results are ascribed to this difference. One origin of the difference is the less tonal stimulation in the current study due to the faster oscillation, seen for example in the reduced BMLD for AC stimulation. Another factor influencing the result is the superposition at the cochleae from the BC stimulation at the two sides. Estimations in the Stenfelt and Zeitooni (2013) study showed that this alone could be responsible for a 15 dB difference between in-phase and out-of-phase stimulation. Due to the higher oscillation rate in the current study, the superposition of the ipsilateral and contralateral signals are less as the frequency changes faster, which thereby reduces the amplitude buildup at the cochlea. Consequently, the influence from cross-transmission superposition is less than in the previous study.

### **Precedence Effect**

The precedence effect test examines ability of the auditory system to fuse two similar sounds with a short interaural time difference (Wallach et al. 1949). The leading and the lagging sound are perceived as one single fused sound image at very short delays (0-1 ms), and as the delay increases (1-5 ms), the leading sound dominates the perceived location (Litovsky et al.

1999; Brown et al. 2015). When the time delay is long enough, the two sounds are heard as separate sound images, also termed as the echo threshold (Blauert 1997). The precedence effect in this study was tested with both LF content (noise 400-600 Hz) and HF content (noise 3000-5000 Hz) for 12 interaural time delays between 0-50 ms. The results for the 3 presentation modalities show similar trends in increased lateralization with increased time delay. AC stimulation gives more pronounced lateralization to the leading side at short interaural time delays (at 0.5 ms), and gives a higher percentage of echo perception (70-90%) than the two BC stimulations for both LF and HF noise. BC stimulation at the mastoid position showed better results when tested with HF noise, and the results were more similar to AC stimulation than when tested with LF noise. The results with BC stimulation at the BCHA position were close to those obtained with BC stimulation at the mastoid position for LF noise, but differed with HF noise where BC stimulation at the mastoid showed better results.

With LF BC stimulation, the lateralization of the sound does not begin until the delay is 5 ms. This is unexpected since most studies show that the interaural time delays are most efficient at this frequency range and sounds are usually fully lateralized at 1 ms delays (Brown et al, 2015). This suggests that the interaural time cues used for binaural processing are distorted for BC stimulation. Measures have shown interaural level differences to be small at low frequencies for BC sound (Stenfelt, 2012, Stenfelt & Zeitooni, 2013), but there are no measures of the time delay for mastoid applied BC sound at low frequencies. Stenfelt & Goode (2005b) showed that the human head behaved nearly as a rigid body at low frequencies. If this is so, the speed of sound is very high and the interaural time difference is close to zero. Such behavior leads to very small interaural differences as the ipsilateral BC sound is transmitted to the contralateral ear with nearly identical amplitude and very little time difference. So even if the interaural stimulation delay increases, the BC excitation of the

ears occurs almost simultaneously, or at very small temporal differences, and the binaural cues are distorted. For higher frequencies, the interaural level and time difference increases and the auditory system is able to separate the excitation at the two sides leading to a better result on the precedence effect test.

The precedence effect test in Stenfelt and Zeitooni (2013) used the same method as in this study, however, they tested 13 presentations with interaural time delays between 0 and 20 ms while the same was tested with 12 presentations between 0 and 50 ms in the current study. Their data showed similar results to those obtained here, where lateralization with LF noise through AC stimulation increased at 0.5 ms, while it increased at and above 10 ms for BC stimulation at the mastoid. The results with BC stimulation in that study were also better when tested with HF noise than LF noise, and the BC results were more close to the AC results compared with the current study. Altogether, the precedence effect results here resembled those reported in the previous study by Stenfelt and Zeitooni (2013) and the BC stimulation at the BCHA position indicate similar binaural hearing effects.

### **Monaural effects in the tests with BC stimulation**

Altogether, 6 patients with acquired unilateral deafness with contralateral normal hearing ear were included in the study in order to estimate how much monaural contribution the phase-inversion test gave when the stimulation was bilateral by BC. They were tested with the same test procedure and method in the BILD test with sentences and BMLD test with chirp tones as the normal hearing group. The tests were only performed with BC transducers on the mastoid position for the 3 test conditions S0N0, S0N180 and S180N0. In the BILD test, the binaural benefit was 2.8 dB (S0N180) and 2.4 dB (S180N0). In comparison to the normal hearing group, the binaural benefit is approximately half where BC stimulation at the mastoid position gave a benefit of 4.9 dB at both S0N180 and S180N0. The BMLD result at S0N180

showed 2.8 dB worse threshold for the unilateral deafness group, whereas it was 2.1 dB in the normal hearing group. For phase inversion of signal, the binaural benefit was shown to be 3.8 dB in the unilateral deaf subjects which is similar to the normal hearing subjects (4.2 dB).

According to these results, there is a positive monaural contribution to the BILD results with phase inversion of either the signal or the noise. This monaural benefit may be explained by the vibration superposition of the two BC inputs at the cochlea. According to Fig 6 in Stenfelt and Zeitoni (2013), where the effect of adding the two BC stimuli in-phase or out-of-phase were simulated, the result was a spectral comb-filter. Consequently, there are spectral regions that are enhanced with in-phase summation while other spectral regions get a reduced level, and the opposite when the summation is out-of-phase. Since both the noise and the signal have a broad bandwidth in the BILD test, there will be spectral areas with enhanced SNR for both the S180N0 and the S0N180 condition, compared to the S0N0 condition. These regions of enhanced SNR could be used by the participants to achieve better speech in noise performance, thereby the results are enhanced in both S180N0 and S0N180 conditions. Even if there are indications that monaural cues enhance the speech in noise results, the normal hearing group had BILD scores that were 4.9 dB compared to 2.4 and 2.8 dB for the unilateral deaf group. This indicates that the improved performance with phase inversion cannot be ascribed to the monaural summation alone but binaural processing provides additional benefit. Even if this benefit is less with bilateral BC stimulation than with AC stimulation, it gives users with bilateral BC stimulation the ability to benefit from binaural cues.

In the estimation of monaural contribution from bilateral BC stimulation at the mastoid (Fig 6, Stenfelt & Zeitoni 2013), the monaural level increases at frequencies between 400 Hz and 1400 Hz for inverted phases compared to in-phase stimulation. It is therefore expected that for the unilateral deaf subjects, in the BMLD test, the S180N0

(stronger signal) condition would be beneficial while the S0N180 condition would be detrimental (stronger noise). This is found where the S0N180 gave almost 3 dB worse thresholds than S0N0 while S180N0 gave nearly 4 dB improved thresholds. The chirp stimuli was chosen as it was hypothesized that the monotonic change in frequency would avoid the stationary build up at the cochlea. However, the data indicates that the results with the tonal chirp stimulation is largely affected by this monaural summation and only a part of the BMLD data for BC stimulation is caused by true binaural processing. We therefore conclude that the BMLD test is unsuitable to test binaural hearing ability when stimulation is bilateral by BC.

### **Stimulation differences**

There is a significant difference in the binaural benefit between AC and BC stimulation throughout the tests in this study. The major reason for this difference is ascribed to the cross-head transmission of BC sound (Stenfelt 2005, 2012). The level separation at low frequencies is nearly non-existent (close to zero dB) and the results here indicate worse binaural benefit at low-frequency BC stimulation than at high-frequency BC stimulation. The interaural time delay for BC sound applied at the mastoid or the BCHA position is unknown but estimates have been given between 0.4 and 0.6 ms (Tonndorf & Jahn 1981; Stenfelt & Goode 2005b; Eeg-Olofsson et al. 2011). This is actually similar to the interaural time delay for a laterally incoming airborne sound field, which is approximately 0.65 ms. Consequently, the estimated interaural time delay for BC sound would be large enough to provide binaural temporal cues at low frequencies. The caveat is that the above cited measures of interaural time delay for BC sound have been unable to provide low-frequency data, and the estimates are primarily for high-frequency sounds, above 1 kHz. It is therefore not known if the temporal separation at low frequencies is similar to that at high frequencies for BC sound. However, the inability

to use low-frequency temporal cues with BC stimulation indicates that the separation at low frequencies is probably less than at high-frequencies.

Binaural processing is based on both interaural time delays and interaural level differences. The current study did not investigate the specific usage of these cues, but as indicated above, interaural time delay with BC stimulation is questionable at lower frequencies. The relatively good results in the BC stimulated SRM test may be attributed to the usage of interaural level differences and the poorer BC stimulation precedence effect results at low frequencies can be caused by the inability to use interaural delays. However, the BILD test showed similar binaural benefit as the SRM test with BC stimulation. This test is based on interaural phase information that is driven by the interaural delays. Even so, the BILD test is spectrally broadband and the transcranial attenuation at higher frequencies can be used to separate the signals at the two sides where the ipsilateral signal is significantly stronger than the contralateral signal. As a result, the current study cannot conclude whether interaural delays or level differences are driving the ability to process BC sound binaurally. However, the results indicate that high-frequency level differences may be most important for the test used here.

Another difference between AC and BC stimulation in the current study is the bandwidth of the signals. It has been shown that a skin interface for BC stimulation limits the high frequency content of the signal (Håkansson et al. 1985; Stenfelt & Håkansson 1999; Stenfelt & Goode 2005b). We therefore investigated the spectral content of the AC and BC signals. This was done by first measuring the output from the transducer with a constant voltage drive. The earphones were coupled to an artificial ear (Brüel & Kjær type 4153) and the corresponding sound pressure level measured, while the BC transducers were coupled to an artificial mastoid (Brüel & Kjær type 4930) and the corresponding force levels were obtained. The measurements were done with Brüel & Kjær Pulse 12.0 and the results are

presented in Figure 5A. The output of the earphones for a constant voltage is fairly flat (dashed line) and the output levels are primarily within 15 dB for the frequency range 0.1 to 10 kHz. The BC transducer on the artificial mastoid shows greater variance of the output level with frequency. Between 0.25 and 3.5 kHz, the force output is approximately within 20 dB, but the output level range is about 80 dB for the measured frequencies (0.1 to 10 kHz). These two curves are not directly comparable as the hearing sensitivity is different at the ear (in dB SPL) and at the skin covered mastoid (in dB re 1 $\mu$ N). These two sensitivity curves also are included in Figure 5A, the hearing thresholds for the HDA 200 as a thin dashed line and the sensitivity for a BC transducer (Radioear B71) at the mastoid as a thin solid line. The morphology of these two sensitivity curves differ significantly and the hearing level, i.e. the difference between the output (thick line) and the hearing sensitivity (thin line), is shown in Figure 5B. In Figure 5B the data are only given for frequencies between 0.125 and 8 kHz. These two curves illustrate the spectral difference between AC and BC stimulation in the current study. The AC stimulation (dashed line) is again relatively flat throughout the whole frequency range but it is apparent that very little stimulation is provided through BC at frequencies below 250 Hz and above 3.5 kHz. Such limitation of high frequencies affects perception of speech. It was estimated that the reduced binaural benefit for SRM (Figure 1B) with BC stimulation is about 1 dB due to the limited high frequency content (Dubno et al. 2002; Stenfelt & Zeitooni 2013). A similar effect is expected for the BILD test which uses the same speech material. As a result, the binaural benefits for SRM and BILD with BC stimulation are expected to be about 1 dB better if the low-frequency filter-effect caused by the skin and subcutaneous tissues is removed (Håkansson et al. 1985; Stenfelt & Håkansson 1999). Consequently, in BC hearing with direct access of the stimulation to the skull bone, as is used in BCHAs with titanium implants, the binaural benefit for broad-band signals is about 1 dB better than the results presented in the current study.

## **Clinical Implications**

The novelty of the current study was to explore binaural hearing ability at the more clinically valid BCHA implant position. Altogether, the results at the BCHA position resembled those obtained at the mastoid position, corroborating that the ability to use binaural cues is almost equivalent at the BCHA position as at the mastoid position. Even so, hearing ability in this study was evaluated in normal hearing subjects, and it should be noted that the efficiency of binaural hearing is reduced in a person with hearing loss, regardless of impairment origin (Häusler et al. 1983). Consequently, the data in this study may not be fully representative for the typical BCHA patient where a sensorineural hearing loss is common. It was, for example, found in the study by Priwin et al. (2004) that the BCHA users with good cochlear function showed more benefit of bilateral BC stimulation than those with worse cochlear function. Altogether, the results from this study confirm that for a person with good cochlear function, bilateral BC stimulation is beneficial and should be considered when rehabilitating persons with BCHAs.

The aim of the current study was to explore binaural processing when the sound was by BC. This was done by comparing results with AC and BC stimulation. In the SRM test, the sound source was changed 45 degrees by using a HRTF function. The target for this HRTF function was the ear canal opening. This means that the filtering effect of the pinna was excluded and also that the difference in position between the ear canal and a BCHA was ignored. Since a BCHA is placed at the BCHA position, the microphone placement is posterior of the ear. This difference in sound recording position would influence the result for a BCHA patient as the HRTF function is different (Stenfelt, 2005). Therefore, in a patient using BCHAs, the different HRTFs compared to those used in the current study will slightly alter the results.

## **Conclusions**

This study explored binaural hearing ability in normal hearing subjects when stimulation was by BC at the BCHA implant position and compared those results with bilateral AC stimulation as well as BC stimulation at the audiometric mastoid position. In all tests used - SRM, BILD, BMLD, and the precedence effect - results with bilateral BC stimulation at the BCHA position illustrated an ability to extract binaural cues similar to BC stimulation at the mastoid position. The binaural benefit was overall better with AC stimulation than BC stimulation at both positions. The results presented in the current investigation confirm that previous findings of binaural hearing processing with bilateral BC stimulation at the mastoid position can also be extrapolated to the BCHA implant position. This indicates that binaural hearing is present in patients with good cochlear function using bilateral BCHAs. It was also found that part of the results of the tests can be ascribed to BC bilateral stimulation leading to monaural cues. Even so, binaural processing is present when stimulation is bilaterally applied by BC.

## **REFERENCES**

- Agterberg, M. J., Snik, A. F., Hol, M. K., et al. (2011). Improved horizontal directional hearing in bone conduction device users with acquired unilateral conductive hearing loss. *J Assoc Res Otolaryngol*, *12*, 1-11.
- American National Standards Institute (1997). ANSI S3.5, *American National Standard Methods for Calculation of the Speech Intelligibility Index* (American National Standards Institute, New York).
- Blauert, J. (1997). Spatial hearing: The psychophysics of human sound localization, Revised edition. *The MIT Press, Cambridge, MA*.
- Bosman, A. J., Snik, A. F., van der Pouw, C. T., et al. (2001). Audiometric evaluation of bilaterally fitted bone-anchored hearing aids. *Audiology*, *40*, 158-167.
- Bronkhorst, A. W., & Plomp, R. (1988). The effect of head-induced interaural time and level differences on speech intelligibility in noise. *J Acoust Soc Am*, *83*, 1508-1516.
- Bronkhorst, A. W., & Plomp, R. (1992). Effect of multiple speechlike maskers on binaural speech recognition in normal and impaired hearing. *J Acoust Soc Am*, *92*, 3132-3139.
- Brown, C., & Duda, R. (1998). A structural model for binaural sound synthesis. *IEEE Trans Speech Audio Process*, *6*, 476-488.
- Brown, A. D., Stecker, G. C., & Tollin, D. J. (2015). The precedence effect in sound localization. *J Assoc Res Otolaryngol*, *16*, 1-28.
- Colquitt, J., Loveman, E., Baguley, D., et al. (2011). Bone-anchored hearing aids for people with bilateral hearing impairment: a systematic review. *Clin Otolaryngol*, *36*, 419-441.
- Dubno, J. R., Ahlstrom, J. B., & Horwitz, A. R. (2002). Spectral contributions to the benefit from spatial separation of speech and noise. *J Speech Lang Hear Res*, *45*, 1297-1310.

- Eeg-Olofsson, M., Stenfelt, S., & Granström, G. (2011). Implications for contralateral bone-conducted transmission as measured by cochlear vibrations. *Otol Neurotol*, *32*, 192-198.
- Hagerman, B. (1982). Sentences for testing speech intelligibility in noise. *Scand Audiol*, *11*, 79-87.
- Hagerman, B., & Kinnefors, C. (1995). Efficient adaptive methods for measuring speech reception thresholds in quiet and in noise. *Scand Audiol*, *24*, 71-77.
- Hawley, M. L., Litovsky, R. Y., & Colburn, H. S. (1999). Speech intelligibility and localization in a multi-source environment. *J Acoust Soc Am*, *105*, 3436-3448.
- Håkansson, B., Tjellström, A., & Rosenhall, U. (1985). Acceleration levels at hearing threshold with direct bone conduction versus conventional bone conduction. *Acta Otolaryngol*, *100*, 240-252.
- Håkansson, B. E. (2003). The balanced electromagnetic separation transducer: A new bone conduction transducer. *J Acoust Soc Am*, *113*, 818-825.
- Häusler, R., Colburn, S., & Marr, E. (1983). Sound localization in subjects with impaired hearing. Spatial-discrimination and interaural-discrimination tests. *Acta Otolaryngol Suppl*, *400*, 1-62.
- Hirsch, I. (1948). The influence of interaural phase on summation and inhibition. *J Acoust Soc Am*, *20*, 536-544.
- International Organization for Standardization (1994). ISO:389-3, *Reference Zero for the Calibration of Audiometric Equipment. Part 3: Reference Equivalent Threshold Force Levels for Pure Tones and Bone Vibrators* (International Organization for Standardization, Geneva).
- International Organization for Standardization (1998). ISO:389-1, *Reference Zero for the Calibration of Audiometric Equipment. Part 1: Reference Equivalent Threshold Sound*

- Pressure Levels for Pure Tones and Supra-Aural Earphones* (International Organization for Standardization, Geneva).
- International Organization for Standardization, (2004). ISO:389-8, *Reference Zero for the Calibration of Audiometric Equipment. Part 8: Reference Equivalent Threshold Sound Pressure Levels for Pure Tones and Circumaural Earphones* (International Organization for Standardization, Geneva).
- International Electrotechnical Commission (2009). IEC:60318-1, *Simulators of Human Head and Ear. Part 1: Ear Simulator for the Measurement of Supra-Aural and Circumaural Earphones* (International Electrotechnical Commission, Geneva).
- International Organization for Standardization, (2010). ISO 8253-1, *Acoustics-Audiometric Test Methods - Part 1: Pure-Tone Air and Bone Conduction Audiometry* (International Organization for Standardization, Geneva).
- Licklider, J. (1948). The influence of interaural phase relations upon the masking of speech by white noise. *J Acoust Soc Am*, 20, 150-159.
- Litovsky, R. Y., Colburn, H. S., Yost, W. A., et al. (1999). The precedence effect. *J Acoust Soc Am*, 106, 1633-1654.
- Oldfield, S. R., & Parker, S. P. (1986). Acuity of sound localisation: A topography of auditory space. III. Monaural hearing conditions. *Perception*, 15, 67-81.
- Priwin, C., Stenfelt, S., Granstrom, G., et al. (2004). Bilateral bone-anchored hearing aids (BAHAs): An audiometric evaluation. *Laryngoscope*, 114, 77-84.
- Rowan, D., & Gray, M. (2008). Lateralization of high-frequency pure tones with interaural phase difference and bone conduction. *Int J Audiol*, 47, 404-411.
- Snik, A. F., Mylanus, E. A., Proops, D. W., et al. (2005). Consensus statements on the BAHA system: where do we stand at present? *Ann Otol Rhinol Laryngol Suppl*, 195, 2-12.

- Stenfelt, S. P., & Hakansson, B. E. (1999). Sensitivity to bone-conducted sound: excitation of the mastoid vs the teeth. *Scand Audiol*, 28, 190-198.
- Stenfelt, S. (2005). Bilateral fitting of BAHAs and BAHA fitted in unilateral deaf persons: acoustical aspects. *Int J Audiol*, 44, 178-189.
- Stenfelt, S., & Goode, R. L. (2005a). Bone-conducted sound: Physiological and clinical aspects. *Otol Neurotol*, 26, 1245-1261.
- Stenfelt, S., & Goode, R. L. (2005b). Transmission properties of bone conducted sound: Measurements in cadaver heads, *J. Acoust. Soc. Am*, 118, 2373–2391.
- Stenfelt, S. (2012). Transcranial attenuation of bone-conducted sound when stimulation is at the mastoid and at the bone conduction hearing aid position. *Otol Neurotol*, 33, 105-114.
- Stenfelt, S., & Zeitoni, M. (2013). Binaural hearing ability with mastoid applied bilateral bone conduction stimulation in normal hearing subjects. *J Acoust Soc Am*, 134, 481-493.
- Tjellström, A., Håkansson, B., & Granström, G. (2001). Bone-anchored hearing aids: current status in adults and children. *Otolaryngol Clin North Am*, 34, 337-364.
- Tonndorf, J., & Jahn, A., F. (1981). Velocity of propagation of bone-conducted sound in human head. *J Acoust Soc Am* 70, 1294-1297
- Wallach, H., Newman, E. B., & Rosenzweig, M. R. (1949). The precedence effect in sound localization. *Am J Psychol*, 62, 315-336.
- Wightman, F., & Kistler, D. (2005). Measurement and validation of human HRTFs for use in hearing research. *Acta Acust. Acust*, 91, 429-439.

## FIGURE LEGENDS

Figure 1:

Results from the SRM test using speech material. The test was conducted for three presentation modes (AC Earphone, BC Mastoid, BC BCHA) and two conditions (S0N0, S0N45). (A) The mean SNR threshold at 50% intelligibility. (B) The average spatial benefit shown as thresholds at S0N0-S0N45. The thin black lines on top of the bars indicate 1 SD. Significant differences between the stimulation modalities within each test condition are marked with asterisks ( $p < 0.01$ ).

Figure 2:

Results from the BILD test using speech material. The test was conducted for three presentation modes (AC Earphone, BC Mastoid, BC BCHA) and three conditions (S0N0, S0N180, S180N0). (A) The mean SNR threshold at 50% intelligibility. (B) The average spatial benefit shown as thresholds at S0N0-S0N180 and S0N0-S180N0. The thin black lines on top of the bars indicate 1 SD. Significant differences between the stimulation modalities within each test condition are marked with asterisks ( $p < 0.01$ ).

Figure 3:

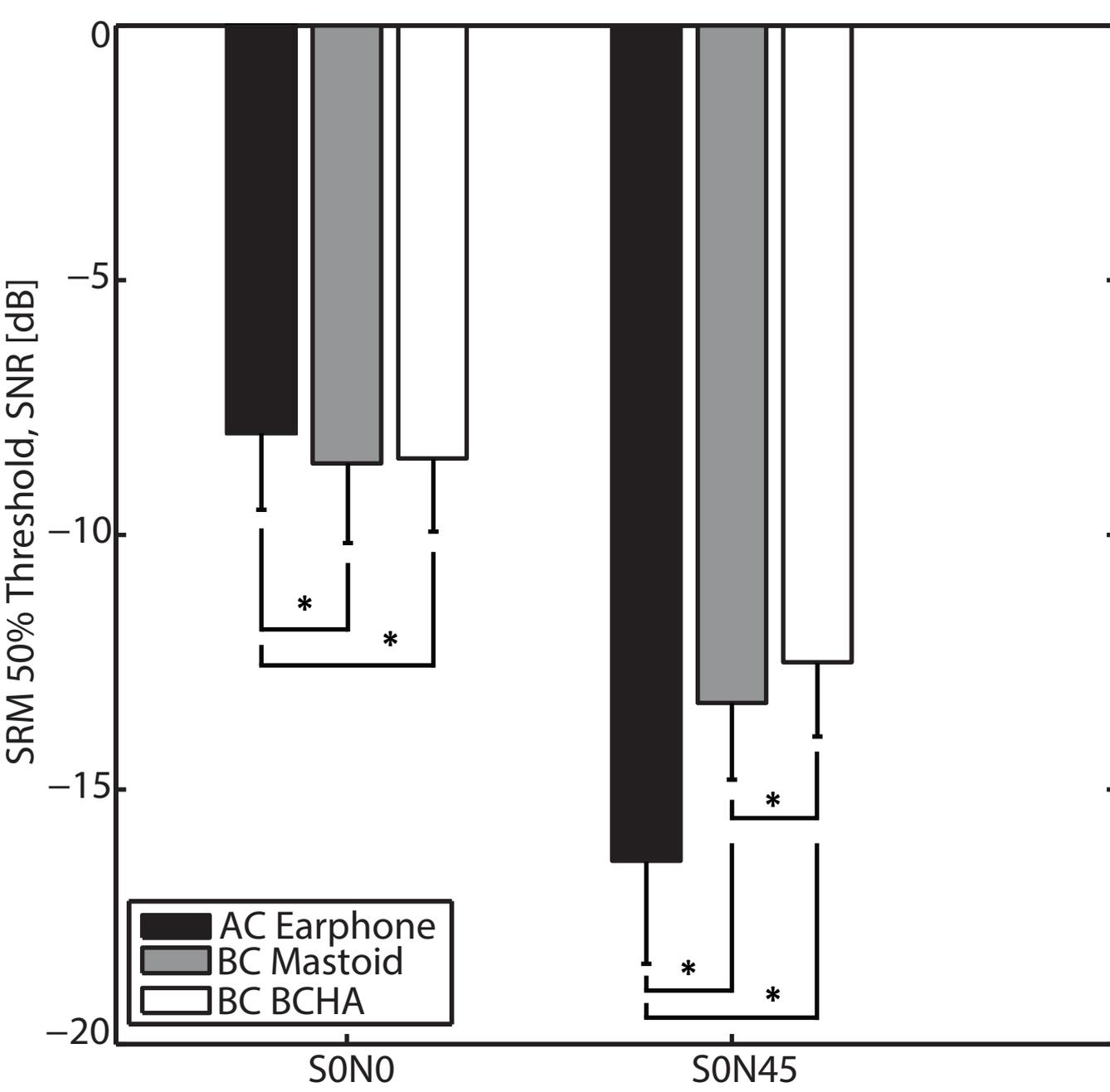
Results from the BMLD test using chirp tones. The test was conducted for three presentation modes (AC Earphone, BC Mastoid, BC BCHA) and three conditions (S0N0, S0N180, S180N0). (A) The average tone detection level. (B) The average spatial benefit shown as thresholds at S0N0-S0N180 and S0N0-S180N0. The thin black lines on top of the bars indicate 1 SD. Significant differences between the stimulation modalities within each test condition are marked with asterisks ( $p < 0.01$ ).

Figure 4:

The results from the precedence effect test using noise stimuli. Data with low frequency stimulation are shown in (A) and with high frequency stimulation in (B). The graph in the upper panel illustrates the median results of perceived location for interaural time delays between 0 and 50 ms. The lower panel in the figure shows the percentage of participants that perceived an echo at the tested interaural delay.

Figure 5:

(A) The output from the BC transducer is shown with a thick solid line when the stimulation is a constant voltage of  $0.1 V_{\text{RMS}}$  (levels on the left y-axis) and from the earphone with a thick dashed line when the stimulation is a constant voltage of  $0.01 V_{\text{RMS}}$  (levels on the right y-axis). The details of the measurements are given in the text. The thin solid line indicates the hearing thresholds for a BC transducer Radioear B71 applied at the mastoid and the thin dashed line the hearing thresholds for the earphone HDA200. (B) The curves from (A) shown as hearing levels, i.e the output (thick lines) relative to the hearing thresholds (thin lines). The hearing levels of the earphone are reduced by 20 dB to be at a similar level as for the BC transducer.



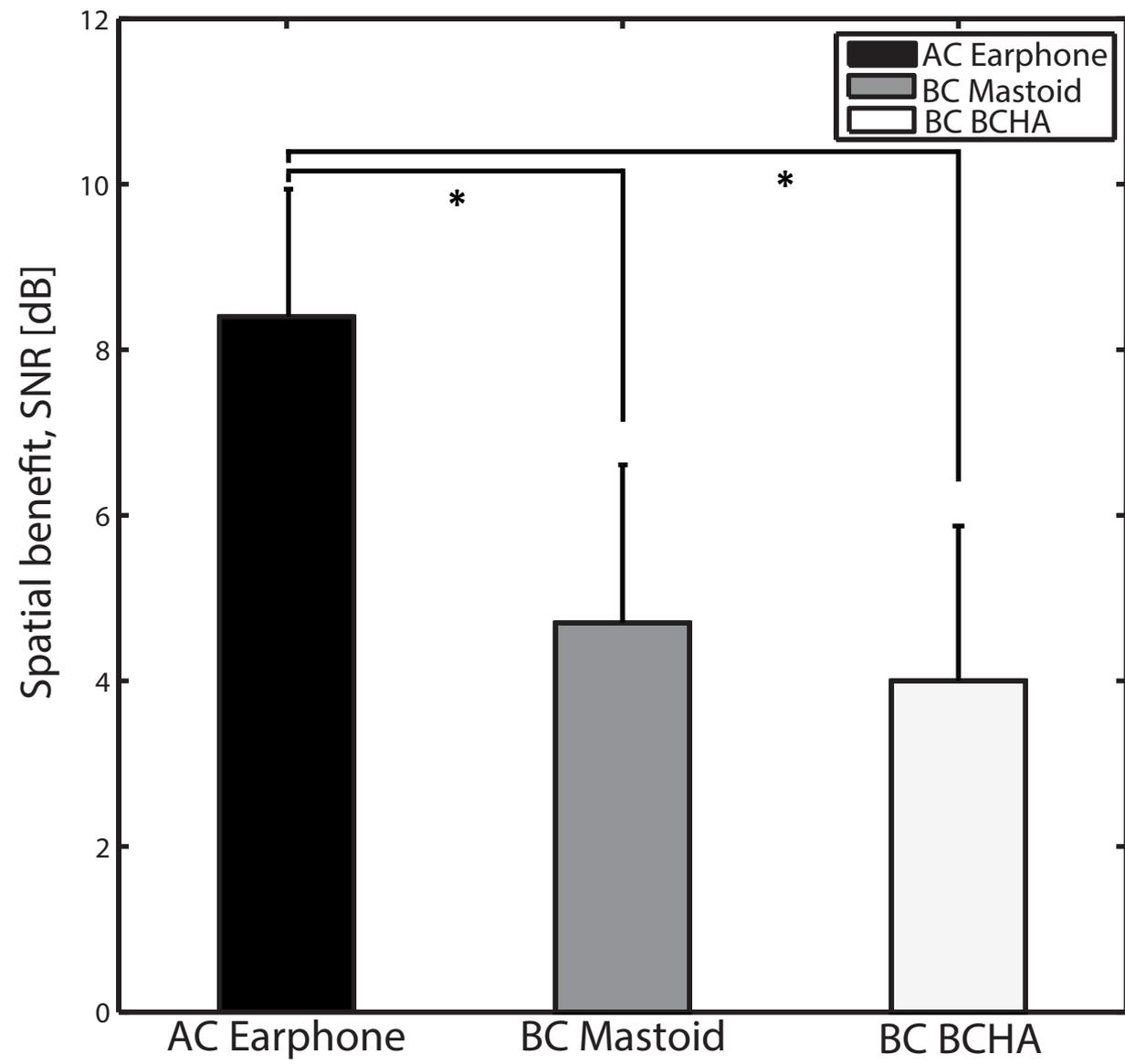
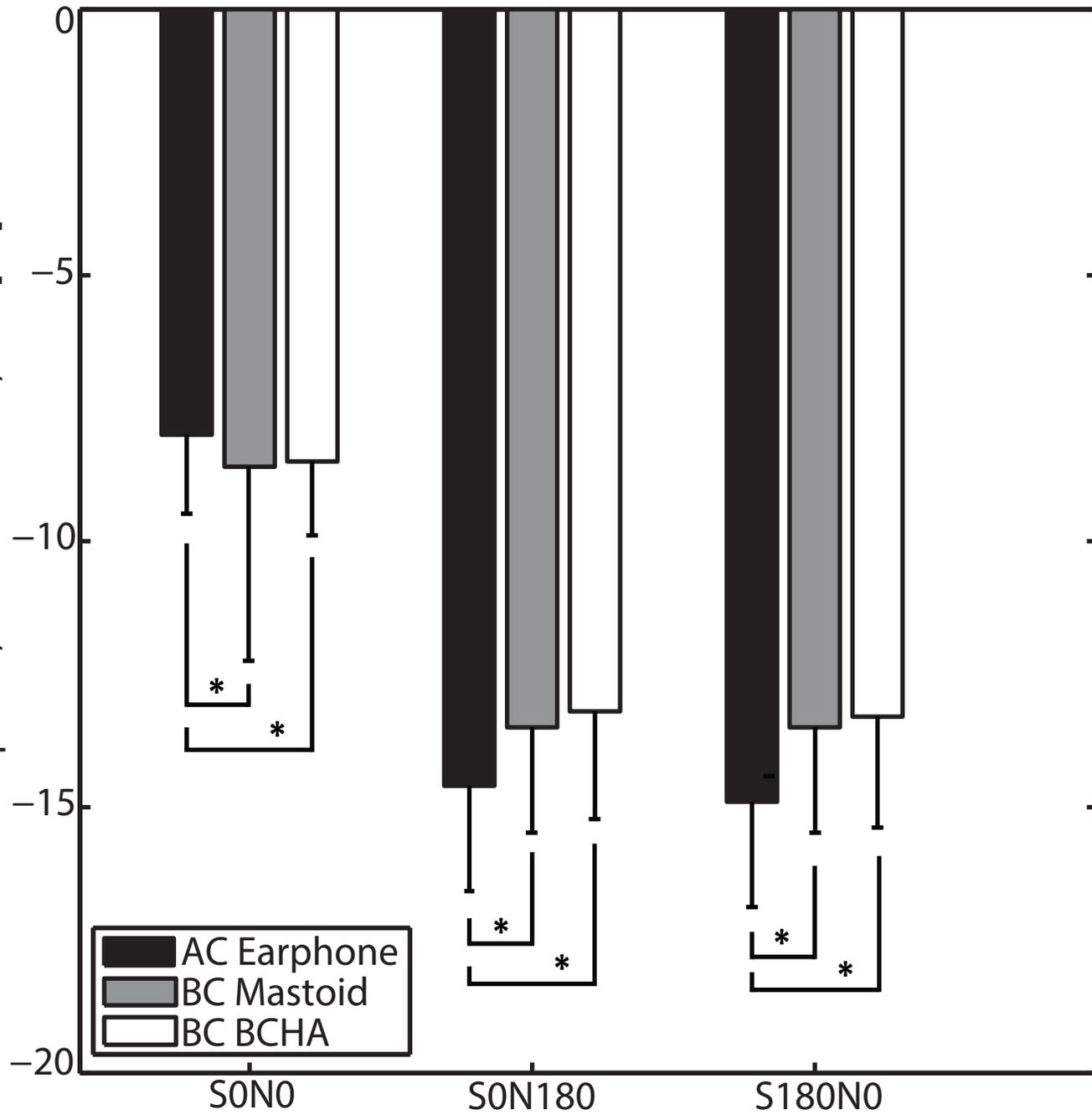


BILD Speech, 50% Threshold, SNR [dB]



- AC Earphone
- BC Mastoid
- BC BCHA

BILD Speech benefit, SNR [dB]

