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Title

Binaural hearing ability with mastoid applied bilateral bone conduction stimulation in normal hearing subjects

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Short running headline

Binaural hearing with bone conduction stimulation

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ABSTRACT

The ability to use binaural cues when stimulation was by bilaterally applied bone conduction (BC) transducers was investigated in twenty normal hearing participants. The results with BC stimulation were compared with normal air conduction (AC) stimulation through earphones. The binaural hearing ability was tested by spatial release from masking, binaural intelligibility level difference (BILD), binaural masking level difference (BMLD) using chirp stimulation, and test of the precedence effect. In all tests, the participants revealed a benefit of bilateral BC stimulation indicating use of binaural cues. In the speech based tests, the binaural benefit for BC stimulation was approximately half that with AC stimulation. For the BC BMLD test with chirp stimulation, there were indications of superposition of the ipsilateral and contralateral pathways at the cochlear level affecting the results. The precedence effect test indicated significantly worse results for BC stimulation than for AC stimulation with low-frequency stimulation while they were close for high-frequency stimulation; broad-band stimulation gave results that were slightly worse than the high-frequency results.

PACs numbers

43.66.Pn, 43.64.Bt, 43.71.An

I. INTRODUCTION

Binaural hearing relies on separation of the input to the two ears and the corresponding cochleae. For normal air conduction (AC) transmission of sound, whether by a sound field or from earphones, the ear canal entrances on the skull sides enable this separation where time of arrival to the two ears and/or level differences facilitates binaural processing of the sound. These differences are often referred to as interaural time differences (ITD) and interaural level differences (ILD) (Feddersen *et al.*, 1957). When the sound is transmitted by bone conduction (BC), it is not equally clear that the two cochleae are separated as BC sound from one position on the skull reaches both cochleae (Stenfelt, 2005; Stenfelt, 2012). A BC stimulation on the skull excites both cochleae with only a small level difference (Stenfelt, 2012). As a consequence, since both cochleae are excited from one stimulation position, it is unclear if binaural cues are available during BC stimulation. So, even if two BC stimulation positions on the skull are used, for example at the two mastoids, the possible binaural benefit is unknown.

Binaural hearing with BC sound has primarily been investigated in three groups of subjects: (1) subjects with conductive hearing impairment where BC transmission becomes important for hearing (Häusler *et al.*, 1983; Zurek, 1986), (2) subjects using bilaterally fitted BC hearing aids (BCHAs) where BC transmission dominates the perception of sound (Bosman *et al.*, 2001; Priwin *et al.*, 2004; Stenfelt, 2005; Colquitt *et al.*, 2011), and (3) normal-hearing subjects using BC headsets for communication (MacDonald *et al.*, 2006).

In a group of subjects with conductive impairment, the AC stimulated ITDs were elevated while ILDs were similar to normal; a similar pattern was seen in normal-hearing subjects when bilateral BC stimulation was applied at the mastoids (Häusler *et al.*, 1983). This result suggests that, for bilateral BC stimulation, ILDs are primarily used for binaural hearing by normal-hearing subjects. Also, the results in normal-hearing subjects with bilateral BC

stimulation are in level with that of conductive impaired patients with AC stimulation. In a recent study, patients with severe acquired unilateral conductive hearing loss showed improved horizontal localization ability when rehabilitated with BCHA (Agterberg *et al.*, 2011). We note that such results do not prove the use of binaural information, as monaural information can be used to some extent for localization tasks (Oldfield and Parker, 1986). The Agterberg *et al.* study did not include any additional binaural test as, for example, spatial release from masking.

A BCHA has proven to be an effective rehabilitation when fitted to patients needing amplification but where a conventional AC hearing aid is contraindicated (e.g. eczema in the ear canal or draining ears) or in patients with maximum conductive hearing loss (e.g. patients with atresia) (Snik *et al.*, 2005). The low cross-skull attenuation of BC sound means that both cochleae are excited from one stimulation position, and it has often been argued that one BCHA is sufficient for patients with bilateral conductive hearing loss. Another argument for only providing one BCHA in patients with bilateral conductive hearing loss has been that BC binaural hearing is inefficient due to the great cross transmission of BC sound in the skull. Therefore, most patients with bilateral conductive hearing loss only receive one BCHA. In a few studies where bilateral BCHAs were investigated, there were indications of binaural benefit (Bosman *et al.*, 2001; Priwin *et al.*, 2004). However, as the groups in these studies were small and heterogeneous with respect to their cochlear status, and the studies lacked control groups, it was difficult to draw firm conclusions about the binaural benefit from bilateral application of BC sound.

The third group listed above is normal-hearing subjects using BC headsets for communication. In such communication systems, one aim is to preserve the spatial information of the source, i.e. to preserve the binaural cues. In one study, MacDonald *et al.* (2006) showed that, when preserving the individuals' head related transfer functions (HRTFs)

(Wightman and Kistler, 2005), the localization results were almost the same when the stimulus was presented through earphones (AC) as through a BC headset. However, as stated above, localization does not only involve binaural hearing but can to some extent be accomplished by monaural cues. It is therefore not certain to what extent binaural information was processed when the sound was delivered by BC.

One general problem with bilateral BC stimulation is that, due to the low inter-aural attenuation, the stimuli from the two sides interact at the cochleae. It has been shown that a stationary narrowband signal, for example a pure tone, adds constructively or destructively as a function of the relative phase of the two contributors (Rowan and Gray, 2008; Deas *et al.*, 2010; Eeg-Olofsson *et al.*, 2011). Consequently, the result from a test with bilateral BC stimulation may rather be due to interaction of the stationary signals at the cochlea than results from binaural processes.

The aim of the study is to explore the ability to use binaural information in normal-hearing subjects with bilateral BC stimulation applied at the mastoids. The ability to use the binaural information with BC stimulation is compared to the same individuals when the stimulation is by AC.

The study was approved by the local ethical committee.

II. MATERIALS AND METHODS

A. Participants

Twenty normal-hearing participants with hearing thresholds equal or better than 20 dB HL for both AC and BC stimulation in the frequency range 125 to 8000 Hz (500 to 4000 Hz for BC) volunteered to participate in the study. They all had a maximum inter-aural difference of 10 dB at any frequency and their mean age was 30.6 years (range 18 to 42 years); twelve were male and eight were female. They all had otologically normal ears and none had history of ear surgery.

B. Test setup

All tests were computerized and programmed in MatLab®. The output of the computer soundcard was fed to a 4-channel power amplifier (Rotel RA-04 SE) where two channels were used for AC stimulation and two channels for BC stimulation. The AC stimulation was provided by a pair of Sennheiser HDA200 earphones coupled to the amplifier while the BC stimulation was provided by a pair of custom made BC transducers. The BC transducers, termed BEST (Balanced Electromagnetic Separation Transducer) used a balanced technology to minimize the distortion (Håkansson, 2003); the transducers were capsuled in a plastic housing with a flat elliptic surface of 25x18 mm and had a height of 10 mm. The BC transducers were bilaterally applied to the mastoid just behind the pinnae using an elastic band providing equal static force to both transducers. The exact static force depended on the size of the skull and the range for the participants was 3 to 5 Newtons.

C. Tests

1. Transcranial attenuation

After baseline audiometry (AC and BC) for the verification of the inclusion criteria, the transcranial attenuation was estimated at 15 frequencies between 160 and 8000 Hz. These data were used to show the inter-aural separation when the stimulation was by BC. The

transcranial attenuation was estimated from masked BC thresholds with stimulation at the ipsilateral and contralateral mastoids. First the masking level was set sequentially for each test frequency. The masking sound was a third-octave band-pass filtered noise with the center frequency equal to the test frequency. The masking noise was provided through modified ER-2 insert earphones where the foam insert was cut to small foam wings thus avoiding an occlusion effect (Stenfelt and Reinfeldt, 2007). The subject was instructed to adjust the volume of the masking noise to a clearly audible but comfortable level. This gave masking levels of 40 to 60 dB SPL. These levels were stored and used for both the ipsilateral and contralateral BC threshold testing. The use of masking in the non-test ear ensured the target tone to be detected in the test ear. Also, the same masking level was used for ipsilateral and contralateral threshold testing.

The target tone to be detected was a frequency modulated tone with a frequency deviation of 8%. The use of frequency modulated tones for BC threshold testing avoids extreme responses that can occur with pure tones due to anti-resonances in the skull (Stenfelt and Goode, 2005b). The modulation was chosen to be wide enough to overcome problems with sharp anti-resonance dips, while limited not to exceed the spectrum of the masker. The threshold estimation was done according to the modified Hughson-Westlake algorithm with a 2 dB stepsize, according to the standard ISO:8253-1 (2010). According to this standard, the threshold at each frequency was determined as three responses at the same level out of a maximum of five trials. That threshold level was stored and the threshold at the next frequency was tested. All threshold levels were based on a single estimation. The difference between the ipsilateral stimulated thresholds and the contralateral stimulated thresholds served as an estimate of the transcranial attenuation for the BC sound.

2. Spatial release from masking

The spatial release from masking test was done with a matrix sentence test (the Swedish Hagerman sentences) (Hagerman, 1982). This is an adaptive test that aims to estimate the level at which the listener will correctly hear 50% of the sentence words in stationary speech-weighted noise. The outcome is a signal to noise ratio (SNR) where lower result indicates better performance. The stimulation was provided through the headphones for the AC stimulation and through the BC transducers for the BC stimulation. Three different conditions were tested: 1) speech and noise co-located from the front (S_0N_0), 2) speech from the front and the noise from 45 degrees (S_0N_{45}), and 3) speech from the front and the noise from 90 degrees (S_0N_{90}). All sources were in the horizontal plane with no effects of elevation. The sound source in the front (0 degrees) meant that the same sound was provided to the two ears (via headphones or BC transducers). The other two locations (45 and 90 degrees) meant that the sound to the two ears differed according to the head-related transfer function (HRTF) (Wightman and Kistler, 2005). In this study, no individualized HRTFs were used but a general model presented by Brown and Duda (1998) was used to synthesize the binaural signal according to the source location.

First, a training list was presented to familiarize the participant with the test. Then the test started. In total, two presentation modes (AC, BC) and three conditions (S_0N_0 , S_0N_{45} , and S_0N_{90}) were tested resulting in six speech-in-noise tests. The test orders and test lists used were counter balanced among the participants as far as possible to minimize order effects. For each speech-in-noise test, two lists of ten Hagerman sentences were used, and the average result from the last list (ten SNRs) gave the SNR for that particular test condition. For the earphone based test, the speech level was set at 60 dB SPL which corresponds to approximately 40 dB HL_{AC} for the Hagerman corpus. The sensitivity function for AC sound in dB SPL when delivered by earphones differs from the BC sensitivity function in dB μN (micro-Newtons) when delivered by the BC transducers (cf ISO:389-1 (1998) and ISO:389-3

(1994)). For the testing to be comparable between AC and BC conditions, the speech level for the BC stimulation was set at 40 dB HL_{BC} as measured with the current BC transducers and the Hagerman corpus. This meant that even if the spectral contents of the stimulation by AC and BC were unequal, the overall loudness of the sentences was similar. Also, the 40 dB HL speech level for both stimulation modalities meant that audibility was not a problem. The noise level was varied according to the adaptive routine with the aim to find the level at which the listener correctly hear 50% of the sentence words (Hagerman and Kinnefors, 1995) (SNRs among the participants and tests varied between -5.5 and -20.4 dB).

3. Binaural intelligibility difference and binaural masking level difference

A binaural masking level difference (BMLD) test was administered with two types of stimulus material, speech and tones. The speech stimulus was the same matrix sentences as in the spatial release from masking test described above. Speech-based binaural masking level difference has also been termed binaural intelligibility level difference (BILD) (George *et al.*, 2012). To distinguish between the speech-based and tonal-based tests, the speech-based test is termed BILD while the tonal-based test is termed BMLD.

The tonal stimulus material consisted of a 1 second chirp tone oscillating between 400 and 600 Hz at a rate of 10 Hz. A problem with bilateral BC stimulation of stationary signals (as a pure tone) is that, due to the cross-transmission, the ipsilateral and contralateral transmitted signals are similar in level at the cochlea. This means that the vibrations from the two sides add at the cochlea resulting in a greater or reduced vibration magnitude as a function of the relative phase of the two signals. Consequently, the stimulation level of the cochlea in such case is not known and the outcome of the test can be severely affected by such summation of the two sounds at the cochlea. To minimize that type of summation, a non-stationary oscillating chirp was used.

The aim of the test was to estimate the level where the listener detected the chirp tone in noise. The noise was a band-limited white noise with a frequency range of 100 to 2000 Hz set to 60 dB SPL for earphone stimulation and a corresponding perception level for BC stimulation. The target tone (the oscillating chirp) threshold was estimated by the Hughson-Westlake algorithm with a 2 dB stepsize, similar to that described in Sec II.C1.

Both the BMLD and the BILD tests were conducted with the sound presented by AC and BC, and three conditions were used for each presentation: 1) S_0N_0 , 2) S_0N_{180} , and 3) $S_{180}N_0$. Here, the subscript 0 indicates identical phase of the stimulation and the subscript 180 indicate inverted phase of the stimulation at one side. The S_0N_0 condition in the BILD is identical to that tested for the spatial release from masking and it was not retested. Consequently, four speech-in-noise tests with the matrix sentences were conducted in addition to the six mentioned previously resulting in a total of 10 speech-in-noise tests for each participant. The BMLD test using the chirp stimuli was conducted for both presentation modalities and three conditions of signal and noise phase relations, resulting in 6 threshold tests.

4. Precedence effect

The precedence effect refers to the ability of the auditory system to fuse the sound image from two approximately equally loud sounds at the two ears with a short inter-aural time delay (Litovsky *et al.*, 1999). The fused sound image moves toward the leading sound source as the time delay increases, and, for delays of more than approximately 1 ms (depending on the stimulus), the sound is perceived at the location of the leading source, still fused. The sound image remains at this perceived position until the inter-aural time delay is large enough and the sound image breaks into two separate sound images, often referred to as the echo threshold. This perceptual phenomenon was tested with increasing inter-aural time delays to investigate if the cross transmission with BC sound can be considered as an “early reflection”

in the opposite ear. If so, the sound image as a function of inter-aural time delay should be similar irrespective of stimulation modality (AC, BC).

To test this, the perceived location of a sound source was tested when the signal was presented binaurally with a short inter-aural time delay. The stimulus was a 1 second noise-burst with a low-frequency content (LF noise, 400-600 Hz), high-frequency content (HF noise, 3000-5000 Hz), or broadband content (BB noise, 200-6000 Hz). The stimulus had a 1 ms sine² rise and fall. The apparent source location was judged between -90 to 90 degrees for 13 presentations with inter-aural time delays between 0 and 20 ms (delays: 0, 0.1, 0.2, 0.3, 0.5, 0.8, 1.2, 1.5, 2, 3.5, 5, 10, 20 ms). Each delay was tested once for each condition. After the stimulus was presented, the participant had to judge the apparent location of the sound source using a slide-control on the computer with a scale between -90 degrees (left ear of the participant) and +90 degrees (right ear of the participant). Zero degrees meant that the perception was directly in front of or in the midline of the participant, and if the sound was clearly heard in both ears this was reported as an echo by pressing a button labeled echo on the computer. The same two presentation modalities were used and three stimulus types resulted in six precedence tests for each participant. The presentation order of the time delays was randomized for each test and general test order was counter-balanced among the participants.

D. Calibration

The audiometer output for the baseline hearing test was calibrated according to the standard ISO:389-1 (1998) [AC thresholds] and ISO:389-3 (1994) [BC thresholds with B71 transducer]. For the other tests, the absolute values of the tones, noises, and speech were estimated. For AC, the stimulation was provided by a pair of Sennheiser HDA200 earphones attached to an ear simulator (IEC:60318-1, 2009) and the output measured by a Brüel and Kjær Pulse analyzer. For BC, the transducer (BEST) was attached to the artificial mastoid

Brüel and Kjær type 4930 and the output measured by a Brüel and Kjær Pulse analyzer. 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) was used to compute a dB HL estimate of the AC stimuli. A similar calculation of the BC stimuli was done with the hearing thresholds in 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, since 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 Hz to 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 degrees 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 Hz to 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 degrees 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 data specified in the standard (e.g. a circular interface of 175 mm²) and the absolute values from the calibration cannot be used. However, we feel that the

comparison between left and right transducers in this way gives a good estimate of the maximum difference.

E. Statistics

Repeated measures analyses of variance were conducted on the outcome scores of the spatial release of masking, BILD, BMLD, and precedence effect tests. Bonferroni adjustment for multiple comparisons was applied as appropriate. To further investigate the importance of the factors, if main effects were significant, multiple Student's two-tailed paired t-tests were administered to reveal significant differences between conditions for a specific presentation mode or differences between the different presentation modes for a specific condition. For the t-tests, the level of statistical significance was set at $p < 0.01$ and no adjustments for multiple comparisons were made.

III. RESULTS

A. Transcranial attenuation

The transcranial attenuation (TA) estimates are shown in Figure 1. The individual results of the 20 participants are shown in thin lines and their median result is shown with a thick line. The data are plotted at the 15 measured frequencies between 160 Hz and 8000Hz. There is a general tendency in the data indicated by the thick (median) line of around 5 dB attenuation at the lower frequencies, close to 0 dB at the mid-frequencies (1-2 kHz), and around 10 dB at the higher frequencies. However, the data of the participants differ; the average range (highest minus lowest) of the TA at each frequency is 21 dB and the standard error of the mean (SEM) ranges between 0.7 and 1.6 dB.

B. Spatial release from masking

The spatial release from masking results for the matrix sentence test are shown in Figure 2. The absolute results are displayed in Figure 2a where three groups of two bars are presented. In the S_0N_0 condition (left part of the graph), both presentation modes (AC, BC) gave similar results of -8.0 to -8.1 dB. In the S_0N_{45} (middle part of Figure 2a) and S_0N_{90} (right part of Figure 2a) the results differ, relative to the S_0N_0 condition but also between the presentation modalities. The best (lowest) SNRs were obtained in the S_0N_{45} condition where the average SNR with the AC stimulation was -16.7 dB and the average SNR with the BC stimulation was -12.6 dB. These SNRs were on average 0.5 to 1.0 dB better (lower) than the SNRs for the S_0N_{90} condition. This is made clearer in Figure 2b where the spatial benefit, i.e. the SNRs for the conditions S_0N_{45} and S_0N_{90} related to the SNRs for the S_0N_0 condition, are shown. The spatial benefit of changing the noise source 45 degrees and 90 degrees were 8.6 dB and 7.6 dB for AC stimulation, while the same for BC stimulation was 4.5 dB and 4.0 dB.

The above results were analyzed with repeated measures ANOVA with two within group factors, presentation mode (AC, BC) and condition (S_0N_0 , S_0N_{45} , S_0N_{90}) showing main effects of both [presentation: $F(1,18) = 177.20$, $p < 0.001$; condition: $F(2,36) = 601.76$, $p < 0.001$]. The interaction between presentation mode and condition was also significant [$F(2,36) = 64.85$, $p < 0.001$]. The subsequent t-tests showed no statistically significant difference between the AC and BC presentation modes for the S_0N_0 condition and between conditions S_0N_{45} and S_0N_{90} for BC stimulation, all other differences between conditions and presentation modes were significant at $p < 0.01$. These results indicate that, even if significant release from masking was obtained for both the AC and BC presentation modes, there were differences in the amount of spatial release from masking when the stimulation was by AC and BC. More specifically, the spatial release from masking in dB with AC stimulation was approximately twice the spatial release from masking in dB with BC stimulation.

C. Binaural intelligibility level difference, sentences

The same presentation modes were used for the binaural intelligibility level difference test (BILD) with the matrix sentence test. Three conditions were used, S_0N_0 , S_0N_{180} and $S_{180}N_0$. The results from the test are shown in Figure 3 in a way similar to Figure 2. It should be noted that the S_0N_0 results are the same in Figures 2 and 3. The absolute results as SNR level at 50% correct are shown in Figure 3a while the benefits of inverting the phase of either the noise or the target signal on one side are shown in Figure 3b. As discussed above, the SNR levels for the S_0N_0 were similar irrespective of presentation mode. Also, similar benefits were found for inverting the phase of the noise or inverting the phase of the speech. However, the results differed between the presentation modes. Shown in Figure 3b, the average benefits for AC stimulation were 6.8 dB and 7.6 dB while the benefits for BC stimulation were 3.7 dB and 3.8 dB, for noise and signal phase inversion, respectively.

The significance of the above results was tested with repeated measures ANOVA with two within group factors, presentation mode (AC, BC) and condition (S_0N_0 , S_0N_{180} , $S_{180}N_0$). That analysis showed main effects of both presentation mode and condition [presentation: $F(1,18) = 24.83$, $p < 0.001$; condition: $F(2,36) = 86.14$, $p < 0.001$]. The interaction between presentation mode and condition was also significant [$F(2,36) = 13.82$, $p < 0.001$]. The following t-tests indicated significant differences between S_0N_0 and phase inversion for both presentation modes, but no significant difference between S_0N_{180} and $S_{180}N_0$ in any of the presentation modes. Also, when investigating the significance of presentation mode for each condition, there were no significant differences in the S_0N_0 condition while the other two conditions showed significant difference between presentation by BC and presentation by AC. The BILD results were statistically significantly greater with AC stimulation than with BC stimulation.

D. Binaural masking level difference, chirps

The BMLD test was administered with an oscillating chirp tone as target. The average detection levels for the chirp tone are shown in Figure 4a for the three conditions S_0N_0 , S_0N_{180} and $S_{180}N_0$ while the benefits of phase inversion at one ear of either the target signal or the noise are shown in Figure 4b. As previously, two presentation modes are used, AC and BC. For the S_0N_0 condition, the results are similar independent of presentation mode with averages varying between 38.3 dB and 39.2 dB. These values changed when the phase of either the noise or target signal was inverted at one side. With phase inversion of the noise, the benefits were on average between 8.8 dB (AC) and 10.5 dB (BC) while the same benefits for signal inversion were between 4.9 dB (BC) and 11.7 dB (AC). In contrast to the BILD test using sentences (Figure 3), the BMLD test using chirp stimulation gave different results for the two phase inversions. The AC BMLD improved when the signal was phase-inverted ($S_{180}N_0$) compared to noise phase-inversion (S_0N_{180}): an average improvement of 2.9 dB.

However, the same comparison gave -5.6 dB for BC stimulation, i.e. the ability to detect the chirp in noise was better with noise phase-inversion (S_0N_{180}) than with signal phase-inversion ($S_{180}N_0$).

This finding was supported by the statistics where the repeated measures ANOVA with two within group factors as above showed main effects of presentation mode [$F(1,19) = 50.85$, $p < 0.001$] and condition [$F(2,38) = 76.55$, $p < 0.001$]. The interaction between presentation mode and condition was also significant [$F(2,38) = 13.94$, $p < 0.001$]. When investigating the differences further with t-tests, all conditions were found to differ significantly for both presentation modes except between S_0N_{180} and $S_{180}N_0$ with BC stimulation. When investigating the differences between presentation modes for each condition it was only the $S_{180}N_0$ condition that gave significant differences between the AC and BC presentation modalities.

E. Precedence effect test

The results of the precedence effect test are shown in Figure 5a for the low-frequency stimulation, in Figure 5b for the high frequency stimulation, and in Figure 5c for the broadband stimulation. The graphs show the median results of all 20 participants for each presentation mode (AC, BC) and at all measured inter-aural time delays (0 to 20 ms). The greater inter-aural time delays were expected to result in an apparent position of close to 90 degrees. The lower panels in Figure 5 show the percentage that reported the perception of an echo at the specified time delay. For all modes and stimulus (LF, HF, BB noise), the echo-perception increased with time-delay and reached nearly 100 percent at 20 ms inter-aural time delay with AC stimulation while BC stimulation gave echo-perception between 50 and 80 percent at 20 ms inter-aural time delay.

Figure 5 reveals similar trends for all three types of stimulus, i.e. LF, HF, and BB noise. With no inter-aural time delay, the apparent position was at the midline for both AC and BC sound. The AC presentation follows the expected course with increased lateralization of the sound image toward 90 degrees with increased inter-aural time delay; at delays of 0.5 to 0.8 ms and above, the apparent position was fully lateralized to the leading side. As visible in the lower panels, at greater inter-aural time delays, typically at and above 10 ms, most subjects perceived a non-fused sound where the sound was clearly perceived in both ears (echo). When the presentation was through BC, a similar but not equally pronounced trend was visible. For the HF noise (Figure 5b), the lateralization of the BC stimulation as a function of delay was different than for the AC presentation and an apparent position of 45 degrees was reached at 0.8 ms while full lateralization to the leading side was not reached until 3.5 ms. For the LF noise (Figure 5a), the sound image with BC stimulation was at the midline (0 degrees) for delays up to 0.8 ms; at delays of and above 1.2 ms the LF noise was perceived at 45 degrees and it was not until the highest delay tested (20 ms) that the sound became fully lateralized to the leading ear, but also clearly heard at both ears as a non-fused sound. The result with the BC BB noise (Figure 5c) fell in-between the BC responses with LF and HF noises. The spread in the data were greater with BC than with AC stimulation. For the BC data, the standard deviation was typically between 25 and 50 degrees while it was less than 25 degrees for the AC data.

The differences visible in Figure 5 between the presentation modes were analyzed for the three stimuli with repeated measures ANOVA with two within group factors, one was the presentation mode (AC, BC) and the other was the time delay (13 delays between 0 and 20 ms). For the LF noise, main effects were found for presentation mode, delay, and the interaction between presentation mode and delay [presentation: $F(1,19) = 4.79$, $p = 0.003$; delay: $F(12,228) = 14.55$, $p < 0.001$; interaction of presentation and delay: $F(12,228) = 2.21$, p

= 0.012]. For the HF noise, main effects were found for presentation mode and delay, but the interaction between presentation mode and delay was not significant [presentation: $F(1,19) = 8.22$, $p = 0.01$; delay: $F(12,228) = 22.69$, $p < 0.001$]. For the BB noise, main effects were found for presentation mode, delay, and the interaction between presentation mode and delay [presentation: $F(1,19) = 4.65$, $p = 0.044$; delay: $F(12,228) = 34.11$, $p < 0.001$; interaction of presentation and delay: $F(12,228) = 2.28$, $p = 0.009$]. These results support the notion that the outcome from the precedence effect test differed in general between AC and BC presentation. Also, as indicated by the interaction between presentation and delay, the perceived positions as a function of the delay were different between AC and BC sound when the stimulation was LF noise and BB noise. This interaction was not significant for the HF noise indicating that for this stimulation, there were similarities in the perceived position as a function of delay for AC and BC stimulation.

V. DISCUSSION

This study investigated the ability of binaural hearing when the stimulation was provided bilaterally by BC transducers on the mastoid of healthy participants with normal cochlear function. The participants were tested with spatial release from masking using sentences in noise, BILD using speech, BMLD using chirp stimulus, and tests of the precedence effect for three types of sounds: LF noise, HF noise and BB noise. Beside BC stimulation, AC stimulation through earphones was used as a reference for the BC results.

A. Superposition at the cochlea with bilateral bone conduction stimulation

As mentioned previously, due to the low attenuation between cochleae when stimulation is by BC (cross transmission between 0 and -10 dB) (Stenfelt, 2012), the stimulation at the contralateral mastoid is transmitted cross the skull and influences the perception at the ipsilateral cochlea. When the stimulation is by AC and the earphone is carefully positioned, the inter-aural separation is 60 to 80 dB (cross transmission is -60 to -80 dB) (Zwislocki, 1953). Therefore, cross transmission for AC is considered negligible for the current measurements.

When the stimulation is bilateral by BC, the contralateral transmitted BC sound adds to the ipsilateral transmitted BC sound and the resulting perception is a function of the two transmission pathways. However, how to add the two pathways are not obvious. Here, to estimate the monaural effect of bilateral BC stimulation, a simple model is used that uses the estimated transcranial attenuation (Figure 1) and a constant delay for the contralateral BC transmission similar to other models for BC cross transmission (Zurek, 1986; Stenfelt, 2005). The two BC transducers are positioned on the mastoids with the vibration direction towards each other (the vibrations are 180 degrees out of phase). Therefore, the contralateral BC signal is subtracted from the ipsilateral signal.

To evaluate the effect of contralateral BC transmission on the monaural response, the individually measured transcranial attenuation was implemented as an ARMA-filter with 20 filter coefficients using a least-squares fit to the frequency response. The sought after phase function of the filter, which corresponds to the time delay for the contralateral transmission, is unknown. Estimates in the literature from vibration measurements indicate a time delay of approximately 0.5 ms (Stenfelt and Goode, 2005b; Eeg-Olofsson *et al.*, 2011) which is in line with psychoacoustic based measures which has indicated an inter-aural time delay of 0.6 ms (Tonndorf and Jahn, 1981). For the computations here, a time delay of 0.5 ms was used. In Figure 6, an average of the filter magnitude function from the 20 participants is shown by the dashed line.

To visualize the effect of superposition at the cochlea by bilateral BC, two functions were computed for all the participants: the ipsilateral BC transmission plus the contralateral BC transmission and the ipsilateral BC transmission minus the contralateral BC transmission. For simplicity, the ipsilateral transmission is defined as unity and the contralateral transmission is that of the estimated filter just described. Accordingly, the average of the ipsilateral plus the contralateral BC transmission is shown in a solid line in Figure 6 while the average of the ipsilateral minus the contralateral BC transmission is shown in a dotted line in Figure 6. The interpretation of these two curves is that the ipsilateral minus contralateral transmission curve shows the effect at the ipsilateral cochlea of adding a contralateral BC transducer in-phase with the ipsilateral BC transducer (both transducers directed towards each other). Similarly, the ipsilateral plus contralateral transmission shows the effect at the ipsilateral cochlea of adding a contralateral BC transducer out of phase with the ipsilateral BC transducer.

Apparent from the two curves in Figure 6 showing the effect of adding a contralateral transducer, due to the addition of the same signal time delayed, the results are that of a comb-filter. The two curves show inverted characteristics, at a frequency where there is a peak in

one of the curves, there is a dip in the other curve, and vice versa. The frequencies of the peaks and dips are determined by the time delay used, and a time delay of 0.5 ms as used here gives intra-peak distances of 2 kHz. These curves indicate that, for a certain frequency range it is beneficial to stimulate the bilateral BC sound in-phase, while in other ranges, an out-of-phase stimulation is beneficial. Also, Figure 6 suggests that bilateral applied BC stimulation causes monaural changes, as suggested by others (Rowan and Gray, 2008), and these changes can affect the measurements in this study. It should be remembered that the data in Figure 6 are based on the transcranial attenuation measurements that are associated with some uncertainty. Moreover, the model used is a simplification and the time delay is only a frequency independent estimation. There is more than one pathway for BC sound and it is plausible that different mechanisms dominate in different frequency ranges (Stenfelt and Goode, 2005a; Stenfelt, 2011), causing a complex delay function. Consequently, the result in Figure 6 serve as an indication of how the data in this study may be affected by the superposition of the bilateral BC sound at one cochlea.

B. Binaural hearing by bone conduction

Several previous studies have indicated that subjects can benefit from binaural hearing when the stimulation was bilaterally by BC. However, the binaural benefit that is achieved with bilateral BC stimulation compared to bilateral AC stimulation has been difficult to determine. MacDonald *et al.* (2006) used individualized HRTFs and measured how well normal-hearing listeners could determine the source location for a pulse train of noise bursts. Their participants had similar results with both AC and BC stimulation. The caveat was that localizing sound sources did not necessarily exclude the use of monaural cues and the extent of binaural hearing through BC was difficult to estimate from such study. Lindeman *et al.* (2008) also compared the ability of young normal hearing subjects to localize sound sources in the frontal horizontal plane when the stimulation was bilaterally by AC and BC. They

reported the localization accuracy using bilaterally BC stimulation to be slightly worse than when the stimulation was through earphones (AC). Once again, it was not clear to what extent the results were based on pure binaural processing and what were based on other processes used for source location identification.

In a review of studies addressing the use of BCHAs with bilateral hearing impairment, it was concluded that several studies demonstrated some benefits of bilateral BCHAs compared with unilateral BCHA (Colquitt *et al.*, 2011). Improved sound source localization was found with bilateral BCHAs compared with unilateral BCHA in both adults and children (Bosman *et al.*, 2001; Priwin *et al.*, 2004; Priwin *et al.*, 2007). It was also shown that bilateral BCHAs gave on average 2.8 dB better speech-in-noise result compared to monaural BCHA when multi-source noise was used (the noise was from 11 speakers surrounding the subject) (Priwin *et al.*, 2004). Dutt *et al.* (2002) showed a slight benefit in speech perception in noise for bilateral BCHAs compared with monaural BCHA.

1. Spatial release from masking

The results in Figures 2-5 are indicative of binaural processing when the sound is delivered bilaterally by BC, but the binaural effect is less than when the sound is bilaterally presented through earphones (AC). The spatial release from masking test using sentence material (Figure 3) was the most ecologically relevant test used. In this test, the benefits of changing the location of the noise source 45 degrees and 90 degrees were 4.5 dB and 4.0 dB for BC stimulation while it was almost twice that, 8.6 dB and 7.6 dB, for AC stimulation. The AC benefit was in line with other studies that have measured spatial release from masking with sentence material. Bronkhorst and Plomp (1992) found an improvement of 8 dB between the noise position co-located at 0 degrees and a position at 90 degrees when a fluctuating masker was used. Dubno *et al.* (2002) reported the benefit between the positions of a speech-shaped

stationary noise source at 0 degrees and 90 degrees to be 6.1 dB in young normal hearing listeners when the speech signal was HINT sentences at 0 degrees. The slight difference in SNR threshold with the noise source at 45 and 90 degrees can be understood by the increase of the noise level at the ipsilateral ear when the noise source is at 90 degrees.

One difference between the AC and BC stimulation is the difference of the spectral content between the two presentation modes. In this study, the BC signal was provided by pressing the BC transducer onto the skin-covered mastoid. This means that skin and subcutaneous tissues were in the vibration transmission pathway, and the stiffness of the compressed skin and subcutaneous tissues act as a low-pass filter for the BC transmission. According to Stenfelt and Håkansson (1999), the damping of BC transmission due to the skin was 10 to 20 dB for frequencies above 2 kHz. Dubno *et al.* (2002) showed that limiting the spectral content affect the binaural benefit. In their study, a reduction of stimulation spectral content from 8.9 kHz to 2.0 kHz reduced the binaural benefit by 1.2 dB when the noise source location was changed from 0 degrees to 90 degrees. The reduction of binaural benefit for BC sound in the current study, due to the low-pass filtering of the BC stimulation by the skin, was estimated to be in the order of 1 dB. Consequently, this reduction of the binaural benefit when the stimulation was by BC was not the sole source for the difference between the BC and the AC results in the spatial release from masking test.

2. Binaural intelligibility level difference

The BILD results with Hagerman sentences (Figure 3) confirmed the finding from the spatial release from masking test: inverting the phase for either the source or noise gave an SNR improvement that was almost twice that for AC than for BC stimulation (6.8 dB and 7.6 dB vs 3.7 dB and 3.8 dB). The BILD benefit depends on the speech material for the test, but the results here were similar to those of others that have tested young normal-hearing subjects

with speech material using earphones. Here, the phase-inversion of the speech signal gave a benefit of 7.6 dB, while for the same condition using a material of everyday sentences, George *et al.* (2012) reported an improvement of 5.5 dB. In another study where spondaic words were used as targets, an improvement of 8.8 dB was found in young normal-hearing subjects when the phase of the speech was inverted (Grose *et al.*, 1994). Once again, the difference in speech material could explain the slight difference between that study and the results here. One study that investigated the benefit of inverting the phase of the speech with Swedish spondaic words gave a BILD of 5.8 to 6.7 dB (Johansson and Arlinger, 2002). As the BILD results were material dependent, there was a spread in the benefit among the studies in the literature, but the results here with headphones resembled those reported in the literature.

The binaural benefit with BC stimulation was similar for inverting the phase of the signal (sentences) or noise, 3.7 dB and 3.8 dB respectively. When investigating the monaural effect of inverting the signal or noise, as estimated in Figure 6, the monaural improvement for signal inversion in terms of RMS was 3.1 dB. This means that, according to the assumptions for Figure 6, the signal level at the cochlea increased by 3.1 dB when the BC signal was inverted at one side. This could be interpreted as the improvement seen in the $S_{180}N_0$ condition was mainly caused by the monaural level increase. However, due to the spectral filtering according to Figure 6, the change in RMS level cannot be directly related to a change in speech intelligibility. The noise used for the BILD test has the same long-term spectrum as the speech signal. Therefore, when the same analysis was done for the noise as for the speech signal, a phase inversion of the noise also gave a monaural RMS increase of 3.1 dB.

Consequently, during S_0N_{180} the overall noise level was 3.1 dB greater than at S_0N_0 . Even so, the binaural benefit with BC S_0N_{180} was 3.8 dB. This suggests that for the BILD results, the effect from monaural changes with bilateral BC application was limited.

3. Binaural masking level difference

Results from the BMLD test using low-frequency AC tonal stimuli have been reported extensively in the literature for various conditions (Hirsh, 1948; Colburn and Durlach, 1965; Zwicker and Zwicker, 1984; Grose *et al.*, 1994). However, we could not find any reports of using oscillating chirps as were used here. The bandwidth of the masker also affects the result of a BMLD test. A narrowband masker gives greater BMLD than wideband masker's do (Hall and Harvey, 1985). The masking noise for the BMLD testing here was between 0.1 and 2 kHz, which can be considered more as a wideband than narrowband masker.

Hirsh (1948) investigated the influence of using monaural and binaural stimulation as well as inverting the phase of both the target tone and the noise. For a pure tone of 500 Hz in wideband noise, that study showed a BMLD of 11.0 dB when inverting the target tone and 9.3 dB when inverting the noise with a noise level of close to 60 dB SPL. (Hall and Harvey, 1985) reported the BMLD to be 14.2 dB for a 500 Hz tone in noise with a density of 50 dB SPL/Hz while Colburn and Durlach (1965) found a 12.7 dB benefit of inverting a 500 Hz tone in wideband noise at 90 dB SPL.

It has been reported that the method of determining the threshold and the stimulation level influence the obtained BMLD. A forced-choice algorithm gave greater BMLD than a subjective threshold detection criterion (as used in this study) (Colburn and Durlach, 1965). Moreover, a greater stimulation level also result in greater BMLD (Hirsh, 1948; Zwicker and Zwicker, 1984). Therefore, it was ensured that the stimulation levels for the two conditions in the current study (AC, BC) were similar in terms of hearing level. As all participants had normal hearing, it was unlikely that the stimulation levels for the two presentation modalities affected the results.

For the S_0N_{180} the benefit was similar for both presentation modes (10.5 dB for BC stimulation and 8.8 dB for AC stimulation). When the signal phase was inverted, the $S_{180}N_0$

condition, the benefit improved for AC stimulation with 2.9 dB but worsened by 5.6 dB for BC stimulation (compared with the S_0N_{180} condition). Part of the difference between the AC and BC results were believed to originate in superposition of the sound at the cochleae due to the cross transmission. In the $S_{180}N_0$ condition with BC stimulation, the signal level at the cochlea decreased by 3.5 dB according to the analysis presented in Figure 6. If this effect is compensated for, the BMLD for the chirp with BC stimulation for the $S_{180}N_0$ condition should be 8.4 dB instead of the 4.9 dB obtained. The noise is also affected by the phase inversion, this effect is however merely 0.5 dB. Consequently, if the BC BMLD results are compensated for the monaural effects of inverting the signal, the BC BMLD is for $S_{180}N_0$ 8.4 dB and for S_0N_{180} 10.0 dB.

Others have shown that the resulting amplitude at the cochlea of bilaterally applied BC tones depends on the phase difference between the ipsilaterally and contralaterally transmitted signals (Rowan and Gray, 2008; Deas *et al.*, 2010; Eeg-Olofsson *et al.*, 2011). Although the frequency of the chirp used was constantly changing avoiding stationary build-up, the results of the BMLD test and the data in Figure 6 indicate that superposition affected the results with BC stimulation. Contrary to the results in this study, Deas *et al.* (2010) showed that inverting the signal phase (similar to S_{180}) improved the BC threshold by 3 to 5 dB at frequencies between 250 and 750 Hz. However, the data in Eeg-Olofsson *et al.* (2011) do not indicate that a phase inversion would result in improved BC thresholds at the 400 to 600 Hz frequency range. The results here agree with the data of Priwin *et al.* (2004) where BMLD was measured with a 500 Hz BC tone and the $S_{180}N_0$ gave 6 dB worse thresholds than the S_0N_{180} did. The opposite was reported by Bosman *et al.* (2001) where about 2.2 dB lower (better) results were obtained in the $S_{180}N_0$ condition compared with the S_0N_{180} condition when the stimulation was a 500 Hz tone. Consequently, there is no consensus in the literature on the effect of superposition of BC signals.

4. Precedence effect

The precedence effect, also known as the law of the first wavefront, has been thoroughly investigated and an excellent review can be found in Litovsky *et al.* (1999). The results depend on the specifics of the stimulation and setup, for example the stimulus length and the use of earphones or speakers. However, when the delay is zero and the earphones at the two ears are stimulated equally, the sound is a single image perceived at the center of the head (Blauert, 1997; Litovsky *et al.*, 1999). This sound image moves towards the ear of the leading sound and is fully lateralized at delays of about 1 ms. For greater delays, the sound image is still fused and perceived at the leading earphone until the echo threshold, where the sound breaks into two clearly perceived sound images, one at each ear. For the AC stimulation with earphones in this study, the expected echo threshold is at 8 to 10 ms (Blodgett *et al.*, 1956). This was approximately what was seen for the AC data in Figure 5.

To our knowledge, precedence effect measurement with bilateral BC stimulation has not been reported. However, Jahn and Tonndorf (1982) investigated the lateralization of the sound image when stimulation was bilaterally applied by BC transducers. Even if that was not exactly the same as the precedence test here, the results from that study can be compared with the current results. In their study, when the stimulation was by 0.1 ms clicks, the perception of a 45 degree shift appeared at 0.1 to 0.15 ms inter-aural delay, full lateralization at 0.2 to 0.25 ms, and an echo appeared at 3.0 to 5.0 ms delay. Those results were overall shorter than those presented in the current study, but the use of short clicks with sharp onset and offset may facilitate the lateralization compared to the 1 second noises with 1 ms rise and fall times used in the current study (Litovsky *et al.*, 1999).

The precedence effect functions with AC and BC were most similar when high-frequency stimulation was used. The broadband stimulation gave BC results with similar trends as the

AC results. The low-frequency stimulation resulted in the least correspondence between the AC and BC stimulated precedence effect functions. For the low-frequency BC stimulation, the average apparent position did not exceed 45 degrees until delays of 10 ms. These data indicated that the binaural hearing with bilateral BC stimulation was most effective at the higher frequencies. This may be explained by the greater inter-aural separation at higher frequencies seen in the transcranial attenuation data in Figure 1 as well as reported in the literature (Stenfelt and Goode, 2005b; Stenfelt, 2012). At lower frequencies, the ITD is the prominent binaural cue while at higher frequencies, the ILD is believed to be the useful cue for binaural hearing. Consequently, the ITDs and ILDs at low frequencies may not be significant enough to provide the binaural system unique information at the two cochleae when the stimulation was by BC. However, in the localization experiments presented by Bosman *et al.* (2001) and Priwin *et al.* (2004), there were no significant differences in the result for a 500 Hz and a 2000 Hz stimulation indicating that, at least for localization, low-frequency sounds were as effective as high-frequency sounds.

C. Transcranial attenuation

The transcranial attenuation was measured using a high-level masking procedure where the masking was higher than in the widely accepted plateau technique (Studebaker, 1964). The reason for this high-level masking was to ensure that the BC tone was only heard in the target ear independent if the stimulation was at the ipsilateral or contralateral mastoid. Moreover, the same masking level was used for both ipsilateral and contralateral BC stimulation resulting in the same tone detection condition.

The average transcranial attenuation was between 0 and 7 dB at frequencies up to 3 kHz, with the least attenuation at the lowest frequencies and at frequencies between 1.0 and 1.5 kHz. At the higher frequencies, above 3 kHz, the average transcranial attenuation was between 7 and 13 dB. This indicates that at frequencies below 3 kHz, the inter-aural difference for BC sound

was on average less than 7 dB. This low inter-aural separation was probably one reason for the worse results on the binaural tests with BC stimulation compared with the results with AC stimulation. The low inter-aural separation at 1.0 to 1.5 kHz indicates that this range may be the worst frequency range in terms of using binaural cues for BC hearing. However, none of the tests in the current study targeted that specific frequency range and it needs to be investigated thoroughly in the future for clarification.

The results presented in Figure 1 were similar to a recent study investigating the BC transcranial attenuation in unilateral deaf subjects (Stenfelt, 2012). The inter-individual spread in the data was relatively large with an average range of 21 dB between the highest and lowest attenuation. This spread can in part be explained by the estimation technique: the transcranial attenuation was the difference between two hearing thresholds. The spread may decrease if the threshold estimation was done by averaging several hearing thresholds. However, that would significantly increase the measurement time and may add to the uncertainty due to fatigue. Moreover, the individual spread of the transcranial attenuation data was similar to other studies that have measured the transcranial attenuation of BC sound in humans (Nolan and Lyon, 1981; Stenfelt, 2012).

D. Clinical implications

It has been suggested that early sound deprivation in children leads to abnormal binaural processing which can result in inferior use of binaural cues (Moore, 1986; Pillsbury *et al.*, 1991). Consequently, the results in this study obtained in normal hearing subjects may not be representative for the BCHA users with deprived binaural auditory stimulation during childhood. Such BCHA users can be, but are not limited to, users with bilateral atresia or other conductive hearing problem. However, when such patients are bilaterally fitted with BCHAs, they may learn to utilize the specific bilateral BC cues better than the acutely BC tested normal-hearing subjects in the current study. In a study of ITD and ILD for a low-

frequency noise signal applied bilaterally by BC, a group of children with atresia performed worse than the normal hearing controls (Schmerber *et al.*, 2005). Even so, that study indicated that subjects deprived of normal binaural stimulation do possess the ability, although somewhat worse than normal hearing subjects, to use binaural cues. Häusler *et al.* (1983) showed that normal hearing subjects had similar detectability for ILD with earphones and bone vibrators on the mastoids, but the ability to detect ITD were significantly worse with BC than with AC.

The data here suggest that subjects with good cochlear function can utilize bilateral BC input and extract binaural information. Even if the results with BC stimulation were generally worse than with AC stimulation, the speech based tests indicated about half of the benefit in terms of decibels in signal-to-noise ratio with BC applied sound than with AC sound. It should be noted that the current data were for subjects with normal hearing function and with the BC stimulation at the mastoid just behind the pinna. This is different from a typical BCHA user where additional sensorineural hearing loss is common and the BC stimulation position is about 2.5 centimeters further back (Snik *et al.*, 2005). Moreover, the HRTFs used for the BC stimulation were the same as for the AC stimulation and computed for a position corresponding to the opening of the ear canal. For a BCHA user, the microphone is positioned further back and it has been shown that the HRTFs for the BCHAs were less distinct than the normal AC HRTFs (Stenfelt, 2005); this was a result of less separation between the sides at the BCHA position compared with the ear canal entrance. Although the result here for binaural BC hearing was encouraging, the data from this study cannot be directly implemented in the clinically BCHA patients. However, the study corroborates the positive findings about bilateral BCHA use in the literature, see Colquitt *et al.* (2011) for an review.

VI. CONCLUSIONS

This study investigated the ability to use binaural cues when stimulation was bilaterally by BC sound in normal-hearing participants. The binaural hearing ability was investigated by tests of spatial release from masking, BILD using speech, BMLD using chirp stimulation, and tests of the precedence effect. The results with bilateral BC stimulation were compared with ordinary AC stimulation through earphones.

In all tests, the participants revealed a benefit of bilateral BC stimulation indicating use of binaural cues. The binaural benefit seen in the speech based tests for BC stimulation was approximately half that of the benefit with AC stimulation. For the BMLD test with chirp stimulation there were indications of superposition of the ipsilateral and contralateral pathways at the cochlear level affecting the results when stimulation was by BC. The precedence effect test indicated significantly different results for AC and BC low-frequency stimulation while they were close for high-frequency stimulation; broad-band stimulation gave BC results that were slightly different from the high-frequency results. The present results are consistent with the hypothesis that BC stimulation supports binaural processing, a benefit which may be obtained in bilateral BCHA patients.

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FIGURE CAPTIONS

Figure 1: The transcranial attenuation for BC stimulation at the mastoid. The individual subject's results are shown with thin lines while the median result is shown by a thick line. The frequency resolution is 2 frequencies per octave below 1 kHz and 3 frequencies per octave above 1 kHz.

Figure 2: Results from the spatial release from masking test. (a) The SNR threshold at 50% intelligibility for the three conditions (S_0N_0 , S_0N_{45} , S_0N_{90}) and the two presentation modes (AC, BC). The bar properties are given in the graph. The thin bar on top of the large bar indicates 1 SD. (b) The spatial benefit shown as thresholds at S_0N_0 - S_0N_{45} (S_0N_{45}) and S_0N_0 - S_0N_{90} (S_0N_{90}).

Figure 3: Results from the BILD test with speech material. (a) The SNR threshold at 50% intelligibility for the three conditions (S_0N_0 , S_0N_{180} , $S_{180}N_0$) and the two presentation modes (AC, BC). The bar properties are given in the graph. The thin bar on top of the large bar indicates 1 SD. (b) The spatial benefit shown as thresholds at S_0N_0 - S_0N_{180} (S_0N_{180}) and S_0N_0 - $S_{180}N_0$ ($S_{180}N_0$).

Figure 4: Results from the BMLD test with chirp stimulation. (a) The signal detection threshold for the three conditions (S_0N_0 , S_0N_{180} , $S_{180}N_0$) and the two presentation modes (AC, BC). The bar properties are given in the graph. The thin bar on top of the large bar indicates 1 SD. (b) The spatial benefit shown as thresholds at S_0N_0 - S_0N_{180} (S_0N_{180}) and S_0N_0 - $S_{180}N_0$ ($S_{180}N_0$).

Figure 5: The results from the precedence effect test. The lines in the upper panel show the perceived position for inter-aural delays between 0 and 20 ms. A solid line indicates results with BC stimulation and a dashed line with AC stimulation. The lower panel shows the percentage of the participants that perceived an echo for the given inter-aural delay. Results with low-frequency stimulation are shown in (a), with high-frequency stimulation in (b), and with broad-band stimulation in (c).

Figure 6: Estimations of the effect from superposition at the cochleae when stimulation is by BC. The solid line shows the average effect of adding the contralateral BC sound to the ipsilateral BC sound, while the dotted line shows the average effect of subtracting the contralateral BC sound from the ipsilateral BC sound. The dashed line shows the average contralateral BC transmission according to the transcranial attenuation given in Figure 1.