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Title: Contribution of monaural and binaural cues to sound localization in listeners with acquired unilateral conductive hearing loss: improved directional hearing with a bone-conduction device

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Corresponding Author: Dr Martijn Agterberg, PhD

Corresponding Author's Institution: Donders Institute for Brain, Cognition and Behaviour

First Author: Martijn Agterberg, PhD

Order of Authors: Martijn Agterberg, PhD; Ad F Snik; Myrthe K Hol; Marc M Van Wanrooij; A J Van Opstal

Abstract: Sound localization in the horizontal (azimuth) plane relies mainly on interaural time differences (ITDs) and interaural level differences (ILDs). Both are distorted in listeners with acquired unilateral conductive hearing loss (UHL), reducing their ability to localize sound. Several studies demonstrated that UHL listeners had some ability to localize sound in azimuth. To test whether listeners with acquired UHL use strongly perturbed binaural difference cues, we measured localization while they listened with a sound-attenuating earmuff over their impaired ear. We also tested the potential use of monaural pinna-induced spectral-shape cues for localization in azimuth and elevation, by filling the cavities of the pinna of their better-hearing ear with a mould. These conditions were tested while a bone-conduction device (BCD), fitted to all UHL listeners in order to provide hearing from the impaired side, was turned off. We varied stimulus presentation levels to investigate whether UHL listeners were using sound level as an azimuth cue. Furthermore, we examined whether horizontal sound localization abilities improved when listeners used their BCD. Ten control listeners without hearing loss demonstrated a significant decrease in their localization abilities when they listened with a monaural plug and muff. In 4/13 UHL listeners we observed good horizontal localization of 65 dB SPL broadband noises with their BCD turned off. Localization was strongly impaired when the impaired ear was covered with the muff. The mould in the good ear of listeners with UHL deteriorated the localization of broadband sounds presented at 45 dB SPL. This demonstrates that they used pinna cues to localize sounds presented at low levels. Our data demonstrate that UHL listeners have learned to adapt their localization strategies under a wide variety of hearing conditions and that sound localization abilities improved with their BCD turned on.

Cover Letter

February 21st, 2012

Dear Editor, Associate Editor,

We would like to thank the associate editor for the efforts to improve the manuscript entitled **'Contribution of monaural and binaural cues to sound localization in patients with acquired unilateral conductive hearing loss: improved directional hearing with a bone-conduction device'**. We received a hard copy with suggestions and corrections. We modified the manuscript according to these comments. All suggestions and corrections are accepted. The title of the manuscript is changed in: **'Contribution of monaural and binaural cues to sound localization in listeners with acquired unilateral conductive hearing loss: improved directional hearing with a bone-conduction device'**.

A point-by-point response to the criticisms of the associate editor is uploaded together with the revised version of the manuscript.

We would be grateful if our work is now acceptable for publication in 'Hearing Research'.

Looking forward to hear from you,

Yours sincerely,

Martijn Agterberg

Department of Biophysics
Donders institute for Brain, Cognition and Behaviour
Radboud University Nijmegen
Geert Grooteplein 21
6525 EZ Nijmegen
The Netherlands

Telephone: +31-24-3614242

Telefax: +31-24-3541435

E-mail: m.agterberg@donders.ru.nl

Response to Associate Editor

We would like to thank the associate editor for the effort to improve our manuscript and for the efforts to improve the clarity and precision. We received a hard copy of the MS with remarks and comments. All remarks are accepted as suggested. Below find a list of our responses to the comments.

Response to the comments made by the Associate Editor:

Comments: *Italic*

Responses: Normal

Original text: **Bold**

The writing still sometimes lacks clarity and precision. The authors also tend to use more words than necessary. I have marked up a hard copy of the MS, which I will post to the corresponding author.

We modified the manuscript according to the hard copy of the MS.

The abstract is way above the permitted word limit. Also, it is unclear at many points. It is not clear what results go with which listening conditions.

- We reduced the number of words from 330 to 289.

- We now mention that: 'Ten control listeners without hearing loss demonstrated a significant decrease in their localization abilities when they listened with a monaural plug and muff.'

- We now mention that: 'The mould in the good ear of listeners with UCHL deteriorated the localization of broadband sounds presented at 45 dB SPL. This demonstrates that they used pinna cues to localize sounds presented at low levels.'

It is inappropriate to describe the subjects as "patients". They were not receiving treatment as part of this study. I suggest calling them listeners or participants throughout. The control listeners can be distinguished by referring to them as control listeners.

We changed '**subjects**' in 'listeners' and we changed '**patients**' in 'UCHL listeners' throughout. Therefore, also the title is changed.

Line 102. It is not clear in what way previous data are "incomplete".

Line 96: '**However, objective data on the improvement of horizontal sound localization with a BCD are incomplete**' is changed in 'However, it remains unclear which factors determine the success of the BCD.'

Line 124. Was the saccade in the appropriate direction? Was this a selection criterion?

The head-orienting saccade was not always toward acoustic stimuli and the response was not a selection criterion. Line 119: We changed '**All patients responded with a rapid head-orienting saccade toward acoustic stimuli presented at pseudo-randomized locations.**' in 'All patients responded with a rapid head-orienting saccade after stimulus presentation. Acoustic stimuli were presented at pseudo-randomized locations.'

There is no need to keep repeating "Unaided (BCD off)" and "Aided (BCD on)". Just chose one term (Unaided or BCD off) and stick to it.

Changed as suggested.

Line 161. Give a full reference for ISO4869-1.

Line 156: The reference (DIN ISO 4869-1, 1991) is now included in the reference list.

Line 185. How do you know there was no "discernable" reverberation?

We agree that we cannot be sure there was no discernable reverberation. Furthermore this statement is double. Line 182: We changed **'No discernable room reverberation occurred at the position of the listener's head which was in the center of the room at a minimum distance of 1.6 m from the walls.'** In 'The listener's head was in the center of the room at a minimum distance of 1.6 m from the walls.'

Page 9. Define ALL terms in the equations. I assume that both p and q represent partial correlations. If so, say so, and put both p and q in italics.

We modified this section. All terms in the equation are now defined. The associate editor is correct that both p and q represent partial correlation. Line 232: We changed **'proximal sound-level coefficient'** in partial correlation coefficient for the proximal sound level.

Line 254. Were different elevations used only for the BB noise?

No, different elevations were used for BB and HP noise and not for LP noise. This is no mentioned more clearly (Line 173).

Line 335. This is not a good description of what the figure shows. Please reword and be more precise.

'When the BCD was turned off (filled symbols in panels A and B), the effect of the proximal sound level was systematic for both BB (panel A) and HP (panel B) stimuli, indicating that responses of the UCHL listeners were indeed influenced by the sound level of the stimulus, despite stimulus amplitude roving.' is changed in Line 323: 'With the BCD turned off (filled symbols in panels A and B), the proximal sound level coefficient decreased with increasing azimuth coefficient, for both BB (panel A) and HP (panel B) stimuli. This result indicates that responses of UCHL listeners were indeed influenced by sound level, despite stimulus amplitude roving.'

Lines 439-445. Isn't the individual variability just as likely to be related to variability in the sound transmitted to the cochlea on the SAME side as the BCD? This is what would determine the ability to use binaural cues.

The variability in transcranial attenuation is considerably larger (around 40 dB) than the variability in the sound transmitted to the cochlea (17 dB in our study). Therefore it is not likely that the variability in the sound transmitted to the cochlea on the same side as the BCD determines the ability to use binaural cues. Line 431: We changed **'It has been shown that subjects demonstrate large variability in trancranial attenuation of bone-conducted sounds (Stenfelt, 2012)'** in 'It has been shown that the attenuation of bone-conducted sounds has a

large inter-subject variability of nearly 40 dB (Stenfelt, 2012), which could underlie the variability of localization performance with the BCD on.'

Lines 449-500. Even the range used here may not have been large enough to eliminate level as a cue.

The attenuation of sounds by the head is in the order of 10 dB for high-frequency (>3 kHz) stimuli (Van Wanrooij and Van Opstal 2004). Still we cannot totally exclude that the range used here may not have been large enough to eliminate level as a cue. Therefore we are cautious with our statement, and we say: Line 486 '**in principle, the sound level could not provide a valid cue to azimuth**'.

References should be double spaced. The references are not in the correct style for Hearing Research.

References are now double spaces and in the style for Hearing Research.

In most of the figures, there should be less empty space between panels. Font sizes should be similar for numbers, axis labels, figure legends, and text within figures.

All figures are modified and are now uniform in lettering and size. Only in figures where we indicate the listener with a number the numbers have a smaller size (8 instead of 14).

Figure 2 lacks numbers on the x axis.

Numbers on the x axis are inserted.

With kind regards,

Martijn Agterberg

Highlights

- Listeners with unilateral conductive hearing loss use remnant binaural cues to localize sounds in azimuth
- Spectral cues can provide location information for horizontal sound localization
- Sound localization abilities improve when the bone-conduction device is turned on
- Altering binaural hearing of control listeners immediately deteriorates sound localization
- Listeners with unilateral conductive hearing rely on the sound level for localization of high-pass noises

**Contribution of monaural and binaural cues to sound localization in listeners
with acquired unilateral conductive hearing loss: improved directional hearing
with a bone-conduction device**

Martijn J.H. Agterberg^{1,2}; Ad F.M. Snik²; Myrthe K.S. Hol²; Marc M. Van Wanrooij¹; A.
John Van Opstal¹

¹ Department of Biophysics, Donders Institute for Brain, Cognition and Behaviour, Radboud
University Nijmegen, P.O. Box 9101, 6500 HB, Nijmegen, The Netherlands

² Department of Otorhinolaryngology, Donders Institute for Brain, Cognition and Behaviour,
Radboud University Medical Centre Nijmegen, the Netherlands

Corresponding author:

Dr. Martijn J.H. Agterberg (address, Dept. of Biophysics, see above)

Telephone: +31-24-3614247

Telefax: +31-24-3541435

E-mail: m.agterberg@donders.ru.nl

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Number of words in Abstract: 289

Number of words in Introduction: 744

Number of words in Discussion: 1152

Abstract

Sound localization in the horizontal (azimuth) plane relies mainly on interaural time differences (ITDs) and interaural level differences (ILDs). Both are distorted in listeners with acquired unilateral conductive hearing loss (UHL), reducing their ability to localize sound. Several studies demonstrated that UHL listeners had some ability to localize sound in azimuth. To test whether listeners with acquired UHL use strongly perturbed binaural difference cues, we measured localization while they listened with a sound-attenuating earmuff over their impaired ear. We also tested the potential use of monaural pinna-induced spectral-shape cues for localization in azimuth and elevation, by filling the cavities of the pinna of their better-hearing ear with a mould. These conditions were tested while a bone-conduction device (BCD), fitted to all UHL listeners in order to provide hearing from the impaired side, was turned off. We varied stimulus presentation levels to investigate whether UHL listeners were using sound level as an azimuth cue. Furthermore, we examined whether horizontal sound localization abilities improved when listeners used their BCD. Ten control listeners without hearing loss demonstrated a significant decrease in their localization abilities when they listened with a monaural plug and muff. In 4/13 UHL listeners we observed good horizontal localization of 65 dB SPL broadband noises with their BCD turned off. Localization was strongly impaired when the impaired ear was covered with the muff. The mould in the good ear of listeners with UHL deteriorated the localization of broadband sounds presented at 45 dB SPL. This demonstrates that they used pinna cues to localize sounds presented at low levels. Our data demonstrate that UHL listeners have learned to adapt their localization strategies under a wide variety of hearing conditions and that sound localization abilities improved with their BCD turned on.

Keywords: azimuth, bone conduction, head-shadow effect, earmuff, spectral pinna cues

Abbreviations

BB, broadband; BCD, bone-conduction device; HP, high-pass; HSE, head-shadow effect; ILDs, interaural level differences; ITDs, interaural time differences; LP, low-pass; MAE, mean absolute error, UCHL, unilateral conductive hearing loss

1. Introduction

Sound localization in the horizontal plane (azimuth) relies mainly on the neural processing of binaural acoustic differences in sound level (interaural level differences, or ILDs) for frequencies above approximately 3 kHz, and phase (interaural time differences, or ITDs) for frequencies below about 1.5 kHz (Blauert, 1997). Localization in the vertical plane (elevation) is determined by spectral pinna cues (Batteau, 1967; Middlebrooks and Green, 1991). Although ITDs and ILDs are highly distorted in listeners with acquired unilateral conductive hearing loss (UCHL), several studies reported remarkably good horizontal localization performance in such listeners (Snik et al., 2002; Hol et al., 2005; Agterberg et al., 2011a). Similar abilities have been reported for listeners with congenital UCHL (Wilmington et al., 1994; Snik et al., 2002; Priwin et al., 2007), and for single-sided (totally) deaf patients (Slattery and Middlebrooks, 1994; Shub et al., 2008). Colburn (1982, review) concluded that unilaterally hearing-impaired patients are able to localize sounds when the sound spectrum includes energy at high frequencies. Such listeners may have learned to rely on the spectral-shape cues provided by their normal-hearing ear (Batteau, 1967; Häusler et al., 1983; Shub et al., 2008). Spectral cues were indeed shown to contribute to sound localization performance in single-sided deaf patients (Van Wanrooij and Van Opstal, 2004), and in normal-hearing control listeners with a plug in one ear (Van Wanrooij and Van Opstal, 2007; Kumpik et al., 2010). However, in familiar acoustic environments, other cues, like sound level of the

stimulus, may also be used for directional hearing (Van Wanrooij and Van Opstal, 2004), as sounds presented on the hearing side are typically perceived as louder and with a different timbre than sounds presented on the deaf side. It is therefore possible that horizontal localization performance of listeners with unilateral hearing loss, in studies that only applied a small range of sound levels (e.g., Humes et al., 1980; Newton and Hickson, 1981; Slattery and Middlebrooks, 1994; Snik et al., 2002; Hol et al., 2005; Priwin et al., 2007), was not based on spectral cues, but may instead have relied on sound level.

It is unclear whether sound-localization abilities in the horizontal plane develop differently in listeners with congenital and acquired UCHL (Agterberg et al., 2011b). It is conceivable that for adequate maturation of the neuronal mechanisms that underlie the processing of ITDs and ILDs, binaural input during a sensitive period is critical (Grothe et al., 2010). For example, animal studies have demonstrated that inducing UCHL at birth led to a reduction in the size of auditory brainstem neurons (Webster, 1983a). In contrast, hearing loss induced during adulthood did not affect neuronal size (Webster, 1983b). To avoid this potential confound, in this study we only included listeners with acquired UCHL, who had all experienced normal binaural hearing during childhood.

All listeners with UCHL included in this study had been fitted with a bone-conduction device (BCD) in order to provide hearing from the hearing impaired side. In a previous study we demonstrated that the ability of these listeners to localize narrow-band (1/3 octave) noises was better with their BCD turned on than in the unaided condition (Agterberg et al., 2011a); suggesting that improved sound localization was based on restored ITDs and ILDs. However, it remains unclear which factors determine the success of the BCD (Snik et al., 2002; Stenfelt, 2005; Priwin et al., 2007; Agterberg et al., 2011a).

In the present study we examined whether a BCD helps to restore horizontal localization of stimuli with different bandwidths. We compared the results with the

localization performance of normal-hearing control listeners who were tested in two conditions; a normal-hearing condition and a condition with a unilaterally plugged ear covered with an additional earmuff. To investigate the possibility that sound level is used as an azimuth cue, sound-presentation levels were roved over a broad range (45 – 65 dB SPL) in 10-dB steps.

We investigated whether UCHL listeners make use of the perceived sound level, remaining binaural difference cues, or monaural spectral cues. To assess whether listeners used remaining binaural cues, we tested them with a sound-attenuating muff over their impaired ear. To determine whether they used spectral pinna cues for horizontal localization we inserted a custom-made mould in the pinna of their better-hearing ear, while evaluating its effect on sound localization in the horizontal and vertical planes. We also determined the potential beneficial effect of the BCD device on horizontal sound-localization performance for broadband sounds of different frequency ranges that dissociated the use of different acoustic localization cues.

2. Methods

2.1. UCHL listeners and control listeners

We report on the localization results of thirteen listeners with acquired UCHL. Twelve listeners had participated in a previous study (Agterberg et al., 2011a). All listeners responded with a rapid head-orienting saccade after stimulus presentation. Acoustic stimuli were presented at pseudo-randomized locations. UCHL listeners, aged 27-68 (mean: 42 years) were randomly selected from a list of patients who received a BCD (type: bone-anchored hearing aid (BAHA), Cochlear®). The UCHL listeners had normal hearing in one ear and acquired conductive hearing loss (i.e. an air-bone gap) in the other ear. Near normal hearing ability in the functioning ear was confirmed for all UCHL listeners. They had thresholds below 20 dB

HL for all frequencies between 0.5 and 4 kHz and thresholds below 40 dB HL at 8 kHz. All UCHL listeners had a pure-tone (1, 2, 4 kHz) average above 43 dB HL for the impaired ear (Table 1). Four UCHL listeners (P2, P3, P7 and P12) had a threshold of 35 or 40 dB HL at 0.5 or 2 kHz. One UCHL listener (P12) had stopped using the BCD.

Audiometric characteristics of the UCHL listeners and the type of implanted BCD are presented in Table 1. The UCHL listeners used either the BAHA-Compact or BAHA-Divino. These devices make use of linear amplification. Only the BAHA-Divino has a microphone that can be switched between omnidirectional and directional. The five BAHA-Divino users were tested while the device was in the omnidirectional mode.

For comparative purposes, we recruited an age-matched control group of ten listeners (ages 22 – 66 years; mean: 42 years) without hearing loss. These listeners had thresholds of 20 dB HL, or better, between 0.5 and 4 kHz in both ears. Thresholds at 8 kHz were 40 dB HL or better.

- Table 1 about here -

2.2. Conditions

The UCHL listeners were tested in four conditions: (i) Unaided (BCD off); (ii) Aided (BCD on); (iii) Unaided with a custom-made mould inserted in the pinna of the better-hearing ear; (iv) Unaided while the impaired ear was covered with a sound-attenuating muff. Some UCHL listeners were first tested in the BCD on condition and then in the BCD off condition and other were tested in the reverse order. UCHL listener P12 stopped using the BCD and was therefore not tested in the BCD on condition. Four UCHL listeners (P1, P4, P5 and P6) were not tested in the ‘unaided + muff’ condition.

All control listeners were tested after altering their binaural hearing by ear-canal plugging either the left or right ear (chosen at random) and covering the same ear with a muff (plugged sound-localization), and in the normal binaural listening condition (unplugged, no muff). The plugs were fabricated by filling the ear canal and pinna with rubber casting material (Otoform Otoplastik –K/c; Dreve, Unna, Germany). The muff (E.A.R. Muff Model 4000) increased hearing thresholds by about 30 dB for low frequencies (<1 kHz) and about 50 dB for high frequencies (>3 kHz). This was measured according to ISO 4869-1 (DIN ISO 4869-1, 1991).

2.3. Stimuli

To dissociate the contributions from ILDs and ITDs to localization we employed low-pass noise (LP; 0.5-1.5 kHz) and high-pass noise (HP; 3-20 kHz) stimuli. Spectral cues are minimal for narrow-band noises, and for frequency bands below about 3 kHz (Middlebrooks, 1992; Blauert, 1997; Van Wanrooij and Van Opstal, 2004, 2007). Broadband noise (BB; 0.5-20 kHz) and HP stimuli were chosen to maximize the possibility of using spectral-shape cues provided by the pinna of the better-hearing ear for localization. BB and HP stimuli had randomly-selected sound levels in the range 45 - 65 dB SPL. The attenuation of sound level by the head is not very effective for low-frequency sounds, and to minimize measurement time we decided not to rove the levels of the LP stimuli. These stimuli were presented at a level of 55 dB SPL. All stimuli had 150-ms duration, 5-ms cosine-squared on- and offset ramps and a flat spectrum level within their passbands. Sounds were digitally generated in Matlab (The Mathworks 7.4) at a sampling rate of 50 kHz, and were delivered through a broadband loudspeaker, moved by a computer-controlled motorized system (Hofman and Van Opstal, 1998) at a distance of 0.85 m from the listener's head. Stimulus coordinates for BB

and HP stimuli ranged from -85° to $+85^{\circ}$ in azimuth and from -30° to $+30^{\circ}$ in elevation. LP stimuli were presented at 85° in elevation.

2.4. Setup

To ensure that listeners could only use acoustic information to localize sounds, directional hearing was tested in a completely dark, sound-attenuated room ($3.2 \times 3.2 \times 3.5$ m). Walls, ceiling, floor and every large object present were covered with sound-attenuating foam (50 mm thick with 30 mm pyramids, AX2250, Uxem b.v., Lelystad, The Netherlands). The listener's head was in the center of the room at a minimum distance of 1.6 m from the walls. Acoustic measurements (Brüel & Kjær BK2610 amplifier and Brüel & Kjær BK4144 microphone) at different positions in the room, showed slight reverberation only for low frequencies (around 500 Hz) near the walls of the room. We verified that the listener's ears were within the room's reverberation radius (critical distance) for the low-frequency stimuli (approximately 1.1 m at $T_{60} = 0.09$ s, given that the absorption coefficient of the walls for 500-Hz sounds was about 0.7; manufacturer's data sheet). From this, we conclude that the listeners were exposed to the loudspeaker's direct sound field only. The room had an ambient background noise level of 30 dBA. Horizontal and vertical head-movement components were recorded with the magnetic search-coil induction technique (Robinson, 1963; Bremen et al., 2010). To that end, each listener wore a lightweight spectacle frame to which a small coil was attached. Three orthogonal pairs of square coils (6 mm^2 wires, $3 \text{ m} \times 3 \text{ m}$) were attached to the rooms' edges to generate the horizontal (80 kHz), vertical (60 kHz), and frontal (48 kHz) magnetic fields, respectively. The head-coil signal was amplified and demodulated, low-pass filtered at 150 Hz, and digitized at 500 Hz (Hofman and Van Opstal, 1998).

A head-fixed laser pointer projected onto a small (1 cm^2) black plastic plate that was positioned in front (40 cm) of the listener's eyes (for details, see Van Wanrooij and Van

Opstal, 2004). UCHL listeners and control listeners were asked to point the laser dot as fast and as accurately as possible in the perceived sound direction after stimulus exposure. This procedure ensured that listeners pointed with their head, rather than with their eyes to the perceived location.

2.5. Paradigm

The experimental session started with a brief visual calibration experiment to establish the off-line mapping of the coil signals onto known target locations. After this, listeners performed a brief practice session containing 20 trials to become familiar with the sounds, hearing in the unaided condition, and the head-movement response procedure.

During the sound-localization experiments the listener first fixated on an LED that was located at 0° azimuth and 0° elevation and then triggered the start of the trial by pressing a button. Within 150 ms the LED disappeared and the sound stimulus was presented. After stimulus exposure the listener had to direct the head toward the apparent sound direction. Listeners were observed continuously by the experimenter with an infrared camera, but did not receive any feedback about their performance during the experiments.

2.6. Data analysis

We analyzed the azimuth responses separately for each stimulus condition (BB, HP and LP noise) and for each listener as described previously (Agterberg et al., 2011a). We determined the best linear fit (based on the mean-squared error) of the stimulus-response relationship (pooled across presentation levels):

$$\alpha_{RESP} = b + g \cdot \alpha_{STIM} \quad (1)$$

where α_{RESP} is the response azimuth (in degrees), α_{STIM} is the stimulus azimuth (in degrees), b is the response bias (in degrees) and g the response gain (dimensionless). We also computed the Pearson correlation coefficient between fit and data, as well as the coefficient of determination (r^2). To differentiate the potential contribution of the proximal sound level, L , from that of the actual stimulus location, we performed a partial correlation analysis:

$$\hat{\alpha}_{RESP} = p \cdot \hat{\alpha}_{STIM} + q \cdot \hat{L} \quad (2)$$

with p and q the partial correlation coefficients for stimulus azimuth and the proximal sound-level, respectively; each determines to what extent sound-source azimuth or proximal sound level explain the observed responses. Variables α_{RESP} , α_{STIM} and L were transformed into their (dimensionless) z-scores $\hat{x}$:

$$\hat{x} \equiv \frac{x - \mu_x}{\sigma_x} \quad (3)$$

with x the variable to be z-transformed, μ_x its mean, and σ_x its standard deviation (resulting in $\hat{\alpha}_{RESP}$, $\hat{\alpha}_{STIM}$ and $\hat{L}$). We determined proximal sound level L by correcting the free-field presentation levels of the stimuli with the frequency- and azimuth-dependent attenuation produced by the head-shadow effect (HSE). The HSE for BB and HP stimuli was derived from the best fit of free-field head-shadow effect measurements of four listeners (Van Wanrooij and Van Opstal, 2004), which correspond well to other data sets (verified with CIPIC database, Algazi et al., 2001; Kacelnik et al, 2006). Although the HSE is negligible for LP noise, for BB and HP noises the effect is appreciable (between -5 and +5 dB over the entire azimuth range). Note that we ignored any fine spectral details provided by the HSE. We determined the mean absolute error (MAE) for the BCD off and BCD on conditions.

We also determined the best linear fit of the stimulus-response relationship (Eq. 1) for the elevation responses.

3. Results

3.1. Benefit of the BCD

Figure 1 shows the stimulus-response relationships for azimuth for two UCHL listeners (P2 and P4), for BB, HP and LP stimuli. Responses for the different presentation levels (45, 55 and 65 dB SPL) were pooled (BB and HP stimuli) and the best-fit linear regression results (Eq. 1) are represented by the dashed lines. Stimulus-response relationships for the BCD off and BCD on conditions are plotted. Both UCHL listeners were hearing impaired on their right side, which is indicated with a cross in each panel. UCHL listener P2 demonstrated good unaided localization performance for BB and HP stimuli ($r^2 > 0.61$; $b < -18^\circ$). In the unaided condition UCHL listener P4 perceived the stimuli mainly on the better-hearing side, which resulted in a considerable leftward bias ($b = -39^\circ$ for BB stimuli), and low coefficients of determination ($r^2 < 0.15$) for all stimuli and conditions. The BCD was beneficial for all stimuli and conditions for both UCHL listeners, as r^2 values and response gains (g in Eq. 1) were closer to one in the aided conditions and the response bias for both UCHL listeners nearly disappeared ($b < 7.5^\circ$ for BB stimuli). These two examples were chosen to illustrate the localization abilities of a listener with good unaided localization abilities (P2) and of a listener who perceived all the BB stimuli on the better-hearing side (P4).

- Figure 1 about here -

The response gain, r^2 and bias of all UCHL listeners in the BCD off and BCD on conditions for BB stimuli are presented in Table 2. P1, P6 and P9 demonstrated a gain higher

than 1.0 in the aided condition. A Hartigan's Dip test revealed that, in contrast to the other UCHL listeners, the data for these three UCHL listeners showed a bimodal distribution for the BCD on condition. Therefore the best linear fit could only be reliably determined in the BCD off condition. Compared to the other UCHL listeners, these three UCHL listeners demonstrated a high bias, 91, 80 and 43°, in the unaided condition. Figure 2 shows a stimulus-response relationship for one of the three UCHL listeners (P1) with a gain higher than 1.0 for BB stimuli. The bimodal distribution of the data for this UCHL listener is illustrated with the bar histogram on the right-hand side of the figure. The data show that the UCHL listener had some ability to determine whether sounds were coming from the left or from the right when the BCD was turned on.

- Figure 2 about here –

Seven UCHL listeners (P2, P4, P5, P7, P8, P10 and P13) demonstrated an increased gain and r^2 when the BCD was turned on, indicating improved localization performance. There was an obvious decrease in the bias for most UCHL listeners.

- Table 2 about here -

Fig. 3 plots response gains for the unaided condition against those for the aided condition for nine UCHL listeners (filled circles; excluding P1, P6, P9 and P12, see above) and ten control listeners (open circles). Most UCHL listeners demonstrated clearly improved localization ability in the aided condition, as the majority of data points fall below the diagonal lines. Data points on the diagonal indicate no difference between the aided and unaided condition. Data points below the diagonal indicate improved sound localization in the

aided condition. However, separate binomial tests for the BB, HP and LP stimuli showed a significant improvement for the LP stimuli only (8/9 UCHL listeners below the diagonal: $p < 0.02$), whereas the improvement for HP (7/9: $p = 0.07$) and BB (7/9: $p = 0.07$) stimuli was not significant. For the pooled data the improvement (22/27) was highly significant ($p < 0.001$). The mean localization bias for the BB stimuli was $+32.5^\circ$ contralateral to the impaired side for the unaided condition. This decreased significantly to $+4.1^\circ$ for the BCD on condition (paired t -test, $p < 0.01$). The mean r^2 was 0.41 for the unaided condition, which increased to 0.73 when the BCD was turned on (paired t -test, $p < 0.01$). In summary, the data clearly demonstrate that horizontal localization improved when the BCD was turned on.

The control listeners demonstrated a significant decrease in their localization abilities in the plugged hearing condition for all stimulus conditions (open circles; Fig. 3A, binomial test, $p < 0.001$; Fig. 3B, binomial test, $p < 0.001$; Fig. 3C, binomial test, $p < 0.01$). Plugging one ear was less effective in attenuating the LP noise than the HP noise, as some data points lay close to the diagonal (Fig. 3A,C). Indeed, the HP stimuli were shielded most effectively (Fig. 3B). The mean bias for the BB stimuli was $+32.7^\circ$ contralateral to the plugged side for the plugged condition, decreasing significantly to $+0.4^\circ$ for the normal binaural listening condition (paired t -test, $p < 0.001$).

- Figure 3 about here -

3.2. Sound level of the stimulus

Figure 4 shows the partial correlation coefficients for azimuth (p in Eq. 2) and proximal sound level (q in Eq. 2) plotted against each other for BB (left) and HP (right) stimuli, and for UCHL listeners (Fig 4A,B) and control listeners (Fig 4C,D), respectively. The partial correlation coefficients reveal the relative contributions of stimulus azimuth and

proximal sound level to the azimuth localization responses. With the BCD turned off (filled symbols in panels A and B), the proximal sound level coefficient decreased with increasing azimuth coefficient, for both BB (panel A) and HP (panel B) stimuli. This result indicates that responses of UCHL listeners were indeed influenced by sound level, despite stimulus amplitude roving. This effect was strongest for HP stimuli (Fig. 4B). Moreover, on average, azimuth coefficients were larger (closer to the ideal value of one) for BB stimuli (Fig. 4A) than for HP stimuli (Fig. 4B). This suggests that some UCHL listeners might have had access to binaural cues for frequencies below 3 kHz in the BCD off hearing condition.

In the BCD on hearing condition (open symbols), the azimuth coefficients of UCHL listeners were closer to the ideal value of one, and the proximal sound level coefficients decreased for BB and HP stimuli. This finding further supports our observation that the BCD is beneficial for localization of BB and HP noises (see also Fig 3A,B). Furthermore, UCHL listeners exhibiting smaller azimuth coefficients demonstrated increased proximal sound level coefficients, which was especially clear for the HP stimuli (Fig. 4B). In other words, when localization abilities were poor, these UCHL listeners typically perceived more intense sounds on their better-hearing side.

The plugged control listeners (filled circles) demonstrated larger azimuth coefficients (closer to the ideal value of one) for BB stimuli (Fig. 4C) than for HP stimuli (Fig. 4D). This effect might be due to the less effective attenuation of low frequencies (30 dB) than of high frequencies (50 dB, see also Fig. 3B,C), suggesting that some control listeners might have had access to binaural ITD cues for frequencies below 3 kHz. Like the UCHL listeners with their BCD off (Fig. 4B), the plugged control listeners relied more on sound level for HP stimuli than for BB stimuli (Fig. 4D). For the normal (binaural) hearing condition the azimuth coefficients were always close to one, and proximal level coefficients close to zero, which indicates good localization performance.

- Figure 4 about here -

3.3. Unaided horizontal sound-localization of UCHL listeners

The data in Fig. 1, Fig. 3A and Table 2 show that several UCHL listeners demonstrated remarkably good horizontal sound localization performance in the unaided condition (high azimuth gain, high r^2 , low bias and low MAE). Sound levels were roved over a range of 20 dB to investigate whether UCHL listeners were using sound level as a cue. Nevertheless, UCHL listeners P2, P4, P7, P10, P12 and P13 still demonstrated good localization performance in the unaided condition. To assess the degree to which UCHL listeners relied on remaining binaural difference cues, we reduced the potential contribution of these cues by adding a muff over the impaired ear, while at the same time turning the BCD off. If binaural cues influence the unaided localization of UCHL listeners, the effect of the muff would be strongest for the most intense stimuli. Fig. 5A shows the gains and the stimulus-response relations for UCHL patient P3 (BCD off, no muff) when analyzed separately for BB noises of 45, 55 and 65 dB SPL. The gains for 55 and 65 dB SPL stimuli were much higher than for the 45 dB stimuli, indicating that good localization was only possible for the more intense stimuli. Consistent with this, the slopes of the stimulus-response relations for the more intense stimuli strongly decreased for the ‘unaided + muff’ condition (Fig. 5B). In addition, the responses shifted more toward the direction of the better-hearing side for the more intense stimuli (resulting in a large level-dependent bias). This result indicates that this UCHL listener may have learned to map the highly distorted binaural input for high-intensity broadband noises (65 dB SPL) to correct sound locations (Fig. 5A). In contrast, response accuracy for the weakest sounds (45 dB SPL) was poor and nearly

unaffected by the muff (gains: $g=0.42$ vs. 0.38 ; biases close to zero), suggesting that this UCHL listener may have relied on a different localization mechanism for low sound levels.

- Figure 5 about here -

Figure 6 plots the response gains (g in Eq. 1, panels A, B and C) and r^2 values (panels D, E and F) for the ‘unaided + muff’ hearing condition against those for the unaided condition for BB stimuli (for 45, 55 and 65 dB SPL) for eight UCHL listeners (P9 was excluded because the data for this UCHL listener showed a bimodal distribution). The figure clearly demonstrates that although the UCHL listeners already had a significant hearing loss without the muff (43 – 75 dB, see Table 1), adding the muff further degraded their horizontal localization ability for intense sounds, as the majority of data points lie below the diagonal (Fig. 6C, paired t -test, $p<0.001$). Low-intensity sound localization, however, was unaffected by the muff (Fig. 6A, paired t -test, $p=0.3$). For 4/8 UCHL listeners, gains (Fig. 6C) and r^2 (Fig. 6F) were near one for high-intensity (65 dB SPL) broadband noises. Panels D, E and F show that the linear stimulus-response relation shift was largest for the most intense stimuli, as the r^2 values were most affected for the loudest sounds (panel F). Placing the muff over the impaired ear also affected the bias (b in Eq. 1, data not shown). For BB noise at 55 dB SPL, the mean bias worsened from $+28^\circ$ in the unaided condition to $+36^\circ$ in the ‘unaided + muff’ condition (paired t -test, $p<0.05$). For stimuli at 65 dB SPL the mean bias worsened even more, from $+28^\circ$ to 49° (paired t -test, $p<0.01$).

- Figure 6 about here -

3.4. Use of spectral cues

Figure 7 plots the response gains (panels A, B and C) and r^2 values (panels D, E and F) with a mould in the good ear for the BCD off condition against those for unaided listening without a mould for BB stimuli (at 45, 55 and 65 dB SPL) for ten UCHL listeners (P1, P6 and P9 were excluded because the data for these listeners showed a bimodal distribution). Placing a mould in the pinna affected horizontal localization of BB stimuli predominantly at the lowest level (45 dB SPL, panels A and D). This result suggests that UCHL listeners used spectral information from their intact ear to localize soft sounds (45 dB SPL) in azimuth.

- Figure 7 about here -

The contribution of spectral cues to localization in azimuth is further supported by the observation that UCHL listeners with a high elevation gain also tended to demonstrate a high azimuth gain for the unaided condition. Figure 8 plots the response gains in elevation for BB stimuli (at the better-hearing side) against the response gains in azimuth for the unaided condition (response gains are pooled across sound levels). Not all UCHL listeners with a high azimuth gain demonstrated a high elevation gain. Nevertheless, elevation gains were correlated with azimuth gains ($r^2=0.32$, $p<0.05$). The r^2 value increased to 0.44 ($p<0.05$) for the lowest levels (45 dB SPL) (data not shown).

- Figure 8 about here -

4. Discussion

4.1. Directional hearing with a BCD

The data demonstrate that a BCD benefits the majority of listeners with acquired UCHL in the localization of sounds in the horizontal plane (Figs. 1, 2 and 3). These results

support subjective evaluations indicating that most listeners with UCHL are satisfied with a BCD (Wazen et al., 2001; Hol et al., 2005), and they support studies demonstrating improved sound localization by BCD users (Priwin et al., 2007; Agterberg et al., 2011a). In the present study we presented BB, HP and LP noise stimuli. Horizontal localization improved with the BCD turned on, but not for all UCHL listeners. Some UCHL listeners demonstrated a striking advantage of the BCD, for example UCHL listener P4 (Fig. 1), while other UCHL listeners hardly benefited from their BCD. We speculate that the considerable variability in localization performance might be related to differences in the effect of bone-conductive cross-stimulation of the cochlea contralateral to the BCD (Stenfelt and Goode, 2005; Agterberg et al., 2011b; Stenfelt, 2012). It has been shown that the attenuation of bone-conducted sounds has a large inter-subject variability of nearly 40 dB (Stenfelt, 2012), which could underlie the variability of localization performance with the BCD on.

The improved horizontal localization in most UCHL listeners suggests that in terms of neural processing, listeners with acquired UCHL could successfully use ILDs and ITDs to localize sounds in azimuth, despite the presumed asymmetry in hearing (normal air-borne acoustic hearing in one ear vs. hearing via bone conduction in the other ear, and additional cross-stimulation, through bone-conduction, of the cochlea contralateral to the BCD side).

4.2. Unaided horizontal sound localization

Several listeners with acquired UCHL may have learned to use the highly distorted remaining binaural cues to localize sound sources in the horizontal plane. The unaided localization ability of several UCHL listeners was good for a 65 dB SPL sound level (Figs. 5 and 6). Similar results have been reported previously. Slattery and Middlebrooks (1994) and Snik et al. (2002) reported that some UCHL listeners demonstrated a MAE of 12-20° and that these UCHL listeners showed significantly less lateral bias than plugged controls. Shub et al.

(2008) reported a high gain (slope) for listeners with congenital unilateral hearing loss. These results suggest that the unaided horizontal localization ability of listeners with UCHL (Wilmington et al., 1994; Snik et al., 2002; Hol et al., 2005; Priwin et al., 2007; Agterberg et al., 2011a) could be partly based on the use of remaining binaural hearing cues. The present result is remarkable since all UCHL listeners had severe conductive hearing loss (see Table 1). However, some UCHL listeners demonstrated pure-tone thresholds of 35 or 40 dB HL at 0.5 or 2 kHz and therefore the use of binaural cues by these UCHL listeners is plausible. Closer inspection of the anatomical status of the UCHL listeners revealed that all UCHL listeners with gain and r^2 values near one (Fig. 6 and 7) had a mobile footplate in combination with a radical cavity. UCHL listeners with a mobile footplate did not demonstrate better (lower) hearing thresholds than UCHL listeners with an immobile footplate (i.e. ossification of the annular ligament due to otosclerosis or tympanosclerosis). Further research is needed to reveal the actual mechanisms that enable the apparent binaural processing seen in these UCHL listeners.

Unaided horizontal localization of sounds may also depend on monaural spectral pinna cues. In a previous study we demonstrated that some listeners with UCHL were able to localize narrow-band noises, centered at either 0.5 or 3 kHz, when the BCD was turned off (Agterberg et al., 2011a). Narrow-band noises minimize the possibility of using spectral cues (Middlebrooks and Green, 1991; Middlebrooks, 1992; Blauert, 1997; Van Wanrooij and Van Opstal, 2004, 2007). However, in the present study, UCHL listeners were tested with broadband noise, allowing the possible use of spectral pinna cues. Placing a mould in the pinna, which effectively removed most of the spectral localization cues, degraded unaided sound localization of broadband stimuli at lower sound levels (Fig. 7A, D). This observation is in line with studies in which patients with single-sided deafness relied, to some extent, on

spectral cues at the intact ear to localize sound sources in azimuth (Slatery and Middlebrooks, 1994; Van Wanrooij and Van Opstal, 2004; Shub et al., 2008).

A third factor that could determine unaided horizontal localization responses of listeners with acquired UCHL is the HSE. Under familiar acoustic circumstances the HSE can serve as a valid cue to azimuth, because the learned sound will appear louder and with a different timbre when presented on the better-hearing side. In the study of Shub et al. (2008), sound levels were roved over a 10-dB range, which would not eliminate sound level as a localization cue because the attenuation produced by the head can be 15 dB for high frequencies. The data in Fig. 4 demonstrated that UCHL listeners indeed rely on proximal sound level in their localization response when the BCD is turned off. The contribution of sound level is largest for HP noise stimuli, for which the attenuating effect of the head is largest. In addition, also the plugged control listeners used the proximal sound-level cue to guide responses to HP stimuli (Fig. 4D). Apparently, single-sided deaf patients (Van Wanrooij and Van Opstal, 2004) as well as acute plugged control listeners use the proximal sound level to localize sounds in azimuth. However, it should be noted that in the present study, in principle, the sound level could not provide a valid cue to azimuth since the stimuli were roved over a substantial range of sound levels. Moreover, UCHL listeners and control listeners did not receive any feedback about localization performance. Nevertheless, sound level contributed significantly to the localization responses. The contribution of sound level was consistently smaller for the localization of BB sounds than for the HP sounds, both for the UCHL listeners and the plugged controls (Fig. 4). This suggests that the auditory system employs a weighted cue strategy, in which the (more reliable) ITD cue reduces the contribution of the (potentially ambiguous) sound level cue, or (poorly defined) spectral azimuth cues (Van Wanrooij and Van Opstal, 2007).

4.3. Conclusions

In conclusion, our results showed that spectral pinna cues can provide consistent information for the unaided localization of sounds in the horizontal plane for listeners with acquired UCHL, when the sounds are presented at low levels (45 dB SPL). In this case, no other localization cues remain. Moreover, listeners with acquired UCHL are able to use remaining binaural difference cues for unaided azimuthal localization of stimuli presented at high (65 dB SPL) presentation levels. Although this explanation may seem unlikely for UCHL listeners with a hearing loss exceeding 60 dB (for example P11), the present data hint that the unaided localization responses were not purely based on monaural processing. The data demonstrate that sound localization abilities of listeners with UCHL improve when they are using a BCD.

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518   **REFERENCES**

- 519   Agterberg MJH, Van Esch TEM, Hol MKS, Van Wanrooij, MM, Cremers CWRJ, Van
520   Opstal AJ, Snik AFM., 2011a. Improved horizontal directional hearing in bone conduction
521   device users with acquired unilateral conductive hearing loss. J. Assoc. Res. Otolaryngol. 12,
522   1-11.
- 523   Agterberg MJH, Hol MKS, Cremers CWRJ, Mylanus EAM, van Opstal AJ, Snik AFM.,
524   2011b. Conductive hearing loss and bone conduction devices: restored binaural hearing? Adv
525   Otorhinolaryngol. 71, 84-91.
- 526   Algazi VR, Duda RO, Thompson DM, Avendano C., 2001. The CIPIC HRTF database. New
527   Paltz. New York. 99-102.
- 528   Batteau DW., 1967. The role of the pinna in human localization. Proc. R. Soc. Lond. B Biol.
529   Sci. 168, 158-180.
- 530   Blauert J., 1997. Spatial hearing. The psychophysics of human sound localization. MIT,
531   Cambridge, MA.
- 532   Bremen P, van Wanrooij MM, van Opstal AJ., 2010. Pinna cues determine orienting response
533   modes to synchronous sounds in elevation. J Neurosci. 30, 194-204.
- 534   Colburn HS., 1982. Binaural interaction and localization with various hearing impairments.
535   Scand. Audiol. Suppl. 15, 27-45.
- 536   DIN ISO 4869-1., 1991. Acoustics; hearing protectors; subjective method for the
537   measurement of sound attenuation. Beuth Verlag, Berlin.

538 Hol MKS, Snik AFM, Mylanus EA, Cremers CW., 2005. Does the Bone-Anchored Hearing
 539 Aid Have a Complementary Effect on Audiological and Subjective Outcomes in Patients with
 540 Unilateral Conductive Hearing Loss? *Audiol. Neurotol.* 10, 159-168.

541 Humes LE, Allen SK, Bess FH., 1980. Horizontal sound localization skills of unilaterally
 542 hearing-impaired children. *Audiology.* 19, 508-518.

543 Kacelnik O, Nodal FR, Parsons CH, King AJ., 2006. Training-induced plasticity of auditory
 544 localization in adult mammals. *PLoS Biol.* 4, 627-638.

545 Kumpik DP, Kacelnik O, King AJ., 2010. Adaptive reweighting of auditory localization cues
 546 in response to chronic unilateral earplugging in humans. *J Neurosci.* 30, 4883-4894.

547 Middlebrooks JC, Green DM., 1991. Sound localization by human listeners. *Annu. Rev.*
 548 *Psychol.* 42, 135-159.

549 Middlebrooks JC., 1992. Narrow-band sound localization related to external ear acoustics. *J.*
 550 *Acoust. Soc. Am.* 92, 2607-2624.

551 Newton VE, Hickson FS., 1981. Sound localization. Part II: a clinical procedure. *J Laryngol*
 552 *Otol.* 95, 41-48.

553 Priwin C, Jonsson R, Hultcrantz M, Granström G., 2007. BCD in children and adolescents
 554 with unilateral or bilateral conductive hearing loss: a study of outcome. *Int. J. Pediatr.*
 555 *Otorhinolaryngol.* 71, 135-145.

556 Robinson DA., 1963. A method of measuring eye movements using a sclera search coil in a
 557 magnetic field. *IEEE Trans. Biomed. Eng.* 10, 137-145.

558 Shub DE, Carr SP, Kong Y, Colburn HS., 2008. Discrimination and identification of azimuth
 559 using spectral shape. *J. Acoust. Soc. Am.* 124, 3132-3141.

560 Slattery WH. III, Middlebrooks JC., 1994. Monaural sound localization: acute versus chronic
561 unilateral impairment. *Hear. Res.* 75, 38-46.

562 Snik AFM, Mylanus EAM, Cremers CW., 2002. The bone-anchored hearing aid in patients
563 with a unilateral air-bone gap. *Otol. Neurotol.* 23, 61-66.

564 Stenfelt S., 2005. Bilateral fitting of BCDs and BCD fitted in unilateral deaf persons.
565 Acoustical aspects. *Int. J. Audiol.* 44, 178-189.

566 Stenfelt S, Goode RL., 2005. Transmission properties of bone conducted sound:
567 measurements in cadaver heads. *J Acoust Soc Am.* 118, 2373-2391.

568 Stenfelt S., 2012. Transcranial attenuation of bone-conducted sound when stimulation is at the
569 mastoid and at the bone conduction hearing aid position. *Otol Neurotol.* 33, 105-114.

570 Van Wanrooij MM, Van Opstal, AJ., 2004. Contribution of head shadow and pinna cues to
571 chronic monaural sound localization. *J. Neurosci.* 24, 4163-4171.

572 Van Wanrooij MM, Van Opstal, AJ., 2007. Sound localization under perturbed binaural
573 hearing. *J. Neurophys.* 97, 715-726.

574 Wazen, JJ, Spitzer J, Ghossaini SN, Kacker A, Zschommler A., 2001. Results of the bone-
575 anchored hearing aid in unilateral hearing loss. *Laryngoscope.* 111, 955-958.

576 Wilmington D, Gray L, Jahrsdoerfer R., 1994. Binaural processing after corrected congenital
577 unilateral conductive hearing loss. *Hear. Res.* 74, 99-114.

578 Webster DB., 1983a. Auditory neuronal size after a unilateral conductive hearing loss. *Exp.*
579 *Neurol.* 79, 130-140.

580 Webster DB., 1983b. Late onset of auditory deprivation does not affect brain stem auditory
581 neuron soma size. *Hear. Res.* 12, 145-147.

Legends to the Figures

Fig. 1. Sound-localization responses for UCHL listeners P2 and P4. Responses are plotted for the BB, HP and LP stimuli in the BCD off and BCD on conditions. Both UCHL listeners localized better with the BCD on, for all three stimulus conditions. Note that UCHL listener P2 had fairly good localization of BB stimuli in the unaided condition. r^2 = coefficient of determination, g = response gain, b = bias.

Fig. 2. Sound-localization responses for UCHL listener P1. Responses are plotted for the BB stimuli in the BCD on condition. The BCD was fitted on the right side.

Fig. 3. Response gain for the BCD off condition plotted against that for the BCD on condition (UCHL listeners, filled circles), and that for the plugged condition against that for the binaural (normal hearing) condition (Control listeners, open circles), for three stimulus conditions: BB (A), HP (B), and LP noise bursts (C).

Fig. 4. Results of multiple linear regression analysis of unaided/plugged and binaural azimuth localization performance for BB (left) and HP (right) noises for UCHL listeners P1-P13 and control listeners. The coefficients for proximal sound level (q in Eq. 2) and azimuth (p in Eq. 2) are plotted against one another for each UCHL listener (A and B) and control listener (C and D). The azimuth coefficient shifts to a value close to one for the aided condition, indicating a clear benefit of the BCD (A and B). Effective plugging (control listeners) is indicated by azimuth coefficient shifts to a value smaller than one (C and D). Plugging is less effective for BB sounds since most azimuth coefficients in the plugged condition remain close to one (C).

607

608 Fig. 5. Unaided sound-localization responses for UCHL listener P3 for brief BB noises. The
609 UCHL listener localized in the BCD off condition (A), and in the BCD off condition with an
610 additional muff over the impaired ear (B). The gains of responses to stimuli with levels of 55
611 and 65 dB SPL decreased significantly when the impaired ear was covered with the muff. ○
612 45 dB SPL (gray dashed regression lines). ● 55 dB SPL (solid gray regression lines). ● 65 dB
613 SPL (solid black regression lines). X: indicates the hearing-impaired side. g = response gain.
614

615 Fig. 6. Response gains (panels A, B and C) and r^2 values (panels D, E and F) for the ‘BCD off
616 + muff’ condition plotted against those for the BCD off condition for BB stimuli for each
617 sound level. Data for nine UCHL listeners (P2, P3, P7-P13) are presented. The gains and r^2
618 values for stimuli with the highest sound level (panels C and F, 65 dB SPL) decreased
619 significantly (below the diagonal) in the ‘BCD off + muff’ condition.
620

621 Fig. 7. Response gains (panels A, B and C) and r^2 values (panels D, E and F) for the condition
622 with mould plotted against those for the BCD off condition for BB stimuli for each sound
623 level. Data from all UCHL listeners are presented. The gains and r^2 values for low-intensity
624 sounds (panels A and D, 45 dB SPL) decreased moderately in the condition with the mould.
625

626 Fig. 8. Response elevation gain for BB stimuli presented on the better-hearing side plotted
627 against the BCD off azimuth gain. Data from all UCHL listeners are presented. Data are
628 pooled across presentation levels.

Figure 1

Figure 2

Figure 2

Figure 3

Figure 3

Figure 4

Figure 4

Figure 5

Figure 5

Figure 6

Figure 6

Figure 7

Figure 7

Figure 8

Figure 8

Table 1

UCLH listener	Age (y)	PTA dB HL		Side HL	Years UCLH before BCD	Years BCD	Type BCD
		AC	BC				
P1	37	63	25	Right	19	9	Baha-Divino
P2	46	57	12	Right	14	7	Baha-Compact
P3	53	57	10	Left	10	8	Baha-Compact
P4	34	62	17	Right	14	8	Baha-Compact
P5	40	75	22	Right	25	6	Baha-Divino
P6	51	75	22	Left	7	5	Baha-Compact
P7	30	52	10	Right	14	5	Baha-Compact
P8	47	72	33	Right	24	5	Baha-Divino
P9	68	48	15	Right	35	5	Baha-Compact
P10	31	43	13	Right	17	2	Baha-Divino
P11	30	70	25	Left	19	5	Baha-Compact
P12	27	55	8	Right	8	10	Baha-Compact
P13	48	63	25	Left	37	1	Baha-Divino

Table 1. Audiometric characteristics of the UCLH listeners.

PTA = Pure-tone average (1, 2, 4 kHz). AC = Air conduction. BC = Bone conduction. BCD = Bone-conduction device. Baha = Bone-anchored hearing aid.

Table 2

UHL listener	BCD off				BCD on			
	Gain	r^2	Bias	MAE	Gain	r^2	Bias	MAE
P1	0.005	0.079	-91	87	1.2	<i>x</i>	<i>x</i>	62
P2	0.63	0.62	-18	26	0.94	0.87	-7.5	15
P3	0.79	0.6	-10	23	0.77	0.51	-13	23
P4	0.16	0.14	-39	42	0.95	0.93	4.2	10
P5	0.26	0.22	-25	35	0.58	0.76	-4.2	20
P6	0.089	0.017	-80	83	1.2	<i>x</i>	<i>x</i>	35
P7	0.81	0.77	-7	18	0.89	0.93	-8.6	12
P8	0.29	0.23	-41	43	0.6	0.57	-9.1	22
P9	0.69	0.51	-43	41	1.2	<i>x</i>	<i>x</i>	21
P10	0.75	0.56	-14	27	1	0.92	6	12
P11	0.82	0.74	-6	16	0.71	0.55	-8.3	19
P12	0.71	0.42	-16	27	NM	NM	NM	NM
P13	0.33	0.41	-33	36	1	0.87	-11	16

Table 2. The response gain, r^2 , and bias for all UHL listeners in the BCD off and BCD on conditions.

BCD = Bone-conduction device. MAE = Mean absolute error. NM = Not Measured.