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Research Paper

Crosstalk cancellation for users of bilateral bone-conduction hearing aids

Ryan D. Barnsley, John F. Culling *

School of Psychology, Cardiff University, Tower Building, Park Place, Cardiff, CF10 3AT, UK

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ABSTRACT

A bone-conduction hearing aid delivers sound to both cochleae by vibrating the skull. Consequently, bilateral fitting results in poor stereo separation. Here, we demonstrate improved stereo separation using crosstalk cancellation in unimpaired listeners using two bone vibrators and in two patients with bilateral bone-conduction hearing aids. The crosstalk filters were calibrated using a psychophysical sound-lateralisation method and the benefit of crosstalk cancellation was assessed using masked thresholds when noise was presented to one side and a tone to the other. Improvements in masked threshold of ~10 dB were demonstrated bilaterally in unimpaired listeners using digital filters typical of a clinical device. Improvements were also demonstrated bilaterally in one patient, albeit with a strong asymmetry, and unilaterally in another. Without recalibration of the filters, the patients' improvements decreased gradually over successive experimental sessions. We conclude that crosstalk cancellation can be successfully implemented for bilaterally implanted users of bone-conduction hearing aids but may require periodic recalibration.

1. Introduction

Bone-conduction hearing aids (BCHAs) transmit sound from the air to the cochleae by vibrating the skull. In many cases, the vibration is transmitted from the vibrating device into the skull by a percutaneous titanium abutment which is screwed into the skull at one end and has a snap connector at the exposed end for attachment of the hearing aid. However, some recently developed devices have an implanted bone vibrator (Reinfeldt et al., 2015). BCHAs are used to treat patients with severe conductive hearing loss, caused, for instance, by aural atresia or cholesteatoma (Maier et al., 2022). They are also used in cases where conventional hearing aids are contraindicated by skin irritation or excessive cerumen production.

In cases where patients are fitted bilaterally, some binaural function is restored but is limited by crosstalk between the two input signals (Stenfelt, 2009; Stenfelt and Zeitooni, 2013; Zeitooni et al. 2016). The crosstalk results in difficulty hearing a signal in noise (Priwin et al., 2007) and poor sound localisation (den Besten, 2020; Caspers et al., 2021). The crosstalk is caused by sound from each bone vibrator being conducted by the skull and other tissues to both cochleae, rather than exclusively to the ipsilateral cochlea (Stenfelt and Goode, 2005). The difference in sound level reaching each cochlea from a given transducer is known as the transcranial attenuation. Ideally, the transcranial attenuation should therefore be high in order to limit crosstalk and preserve stereo separation. However, in practice transcranial attenuation is often low (Snik et al., 1998).

Direct measurement of transcranial attenuation for a single bone transducer between the two cocheae is not straightforward. Consequently, estimates tend instead to measure the difference in detection threshold for tones presented by bone transducers on opposite sides of the head at the same cochlea (e.g., Nolan and Lyon, 1981; Agterberg et al., 2014). Assuming perfect symmetry the two measures would be the same. Thresholds can be measured at one cochlea in isolation by recruiting patients with single-sided deafness. These measurements show that transcranial attenuation is highly idiosyncratic, varying widely between individuals and across frequency (Stenfelt, 2012,). Transcranial attenuation can even become negative, especially at lower frequencies (Dobrev et al., 2019; Mattingly et al., 2020).

In theory, crosstalk can be eliminated using a signal processing technique called crosstalk cancellation (Liao, 2010). Crosstalk cancellation involves developing an estimate of the crosstalk signal at each of two receivers. On each side, a signal is added ipsilaterally that will be equal and opposite to (i.e., out of phase with) the crosstalk signal from the opposite side when they both arrive at the receiver. The crosstalk will thus be cancelled out, leaving only the intended signal on each side. In a patient, if one knew the transfer function from each transducer (bone vibrator) to each receiver (cochlea) then it would be possible to do this without any distortion to the signals at each cochlea. Unfortunately,

* Corresponding author.
E-mail address: cullingj@cardiff.ac.uk (J.F. Culling).

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like the transcranial attenuation, these transfer functions are extremely variable and idiosyncratic to each patient. Attempts have been made to measure full transfer functions in human cadaver heads using vibrometers placed close to the cochlea (Stenfelt and Goode, 2005), but due to their idiosyncrasy, these data cannot be readily applied to a different individual. Moreover, the vibrational motion differs across the three measured axes of vibration, and it is not clear what combination of these motion vectors would be relevant to perception, although a correspondence between auditory nerve activity (the compound action potential) and vibration along the interaural axis has been observed in guineapigs (Zhao et al. 2021).

While there is no known method of deriving the full transfer function for each transducer at each cochlea in a living person, Mcleod & Culling (2017, 2019) have shown that (1) one can measure the *interaural differences* in phase and level between the two cochleae psychophysically and (2) that this information is sufficient to achieve a cancellation effect (Mcleod and Culling, 2020). Moreover, these measurements can be made by using two bone vibrators together, as would be required for a clinical implementation. Mcleod and Culling (2020) showed that improvements in masked tone thresholds (tone on one bone vibrator, noise on the other) could be as large as 10 dB when the crosstalk from the noise was cancelled on the side of the tone. These benefits also transferred to speech signals that were filtered to match the cancellable noise band (1.5 −8 kHz).

The proposed scheme is illustrated in Fig. 1. In this scheme, each crosstalk signal is prevented from reaching the contralateral cochlea by a cancelation signal (dashed line of the same colour), which is a filtered copy of the same microphone output. The cancellation signal is shown as intercepting the crosstalk using a line terminating in a circle, rather than an arrow. Note that the signals that still reach each cochlea all originate from the same microphone (same colour), although they have each been delivered by both bone transducers. For simplicity, we will refer to this cancellation at the cochlea as applied to one 'ear' or the other, regardless of whether the signals passed through the listener's outer and middle ear during the particular procedure.

The present work extended that of Mcleod and Culling in several ways. First, Mcleod and Culling (2020) developed a cancellation signal at one ear only. The present work demonstrates that the same method will work for both ears simultaneously. Second, Mcleod and Culling directly adjusted the phase and amplitude of signals in the frequency domain, allowing very high frequency resolution, equivalent to using a finite-impulse response (FIR) filter that was as long as the duration of the signal. The present work used an FIR filter that was typical of those used in bone-conduction devices. It was a 256-point FIR filter, giving a frequency resolution of 62.5 Hz and a processing lag of 3.2 ms at a 16-kHz sampling frequency. Finally, Mcleod and Culling demonstrated improvements in masked thresholds only in unimpaired listeners using bone vibrators. For these listeners, the filter design needed to be recalibrated for every experimental session. The present study demonstrated some improvement for both ears in a bilaterally fitted patient via transducers from the Cochlear Baha 5 Superpower® hearing aid attached to their percutaneous abutments. This benefit could be maintained to some extent from session to session without recalibrating.

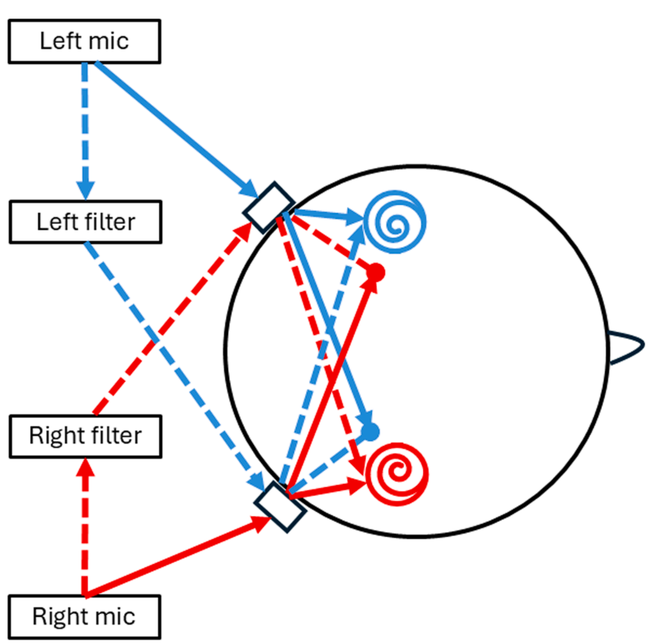

Fig. 1. Illustration of the proposed crosstalk cancellation scheme. Signals originating from the left microphone are in blue and those from the right microphone are in red. Due to the cancellation signals (dashed lines) each cochlea is exclusively excited by signals from the ipsilateral microphone.

2. Material and methods

2.1. Participants

Seventeen students and staff at Cardiff University with no self-reported hearing impairments ("unimpaired listeners") volunteered to participate. Ethical approval for these participants was granted by the School of Psychology Research Ethics Committee. They were initially tested with simulated crosstalk. The simulation first introduced only a phase difference to be corrected and later a phase and level correction. Three unimpaired listeners found the phase-only cancellation task difficult and did not move on to the phase and level cancellation task. Five participants found the phase and level cancellation task difficult and did not move on to the bone-conduction experiment. The remaining nine, plus the first author, provided data using bone vibrators. However, three of the listeners were unable to make the time commitment and two encountered greater difficulty when working with the bone vibrators. The remaining five participants (including the first author) completed all stages of the study. Only results from these five listeners (22–43 years old; 3 males, 2 females) are reported here.

Nine patients with bilateral percutaneous abutments volunteered to participate. Patients with abutments were recruited because these allowed us to attach our own transducers to the snap connectors, bypassing any other hearing aid processing. The patients were recruited from the Queen Elizabeth Hospital Birmingham. Ethical approval for these participants was granted by the Harrow Research Ethics Committee of the NHS Human Research Authority (project ID 319,750). Of the nine, patient #145 completed all stages of the study, and patient #127 was able to complete part of the programme of research before the study closed. Among the other seven patients, four withdrew for practical reasons (time commitments/travel distance). One of these patients showed very consistent calibration data before they withdrew. The remaining three patients found the tasks difficult. One patient was unable to understand the task, one was completely unfamiliar with computer interfaces, and one found that their tinnitus made a calibration task using tones of similar pitch too confusing. Table 1 summarises the patients' demographic details and hearing-loss aetiology.

2.2. Apparatus

The unimpaired listeners used two B71W audiological bone vibrators (Radioear, Middelfart, Denmark) held in place by a purpose-designed, 3D-printed pair of spectacle frames and the bone vibrators were pressed against the scalp using an elasticated headband, adjusted to a comfortable pressure. The spectacle frames were used to try to maintain a consistent positioning for the bone vibrators at the typical position for a percutaneous abutment from one experimental session to another. Fig. 2 illustrates this arrangement, mounted on a B&K HATS (Bruel & Kjær, Nærum, Denmark). For the simulated crosstalk procedures,

Table 1
Demographic details and aetiology of the patients with bilateral bone-conduction hearing aids.

Patient	Gender	Age (years)	Aetiology	BC Hearing thresholds (dBHL) (L/R)
102	F	57	Bilateral microtia	50–80 / 0–35
108	F	48	Bilateral meatal atresia	0–30 / 10–50
115	F	29	CHARGE syndrome	15–35 / 10–20
127	F	47	Bilateral otosclerosis	25–35 / 20–36
140	F	34	Chronic ear infections	17–35 / 17–35
141	F	50	Conductive HL – unknown aetiology	5–25 / 0–10
142	M	66	Conductive HL – unknown aetiology	25–40 / 25–35
145	F	61	Bilateral tympanic perforations	20–35 / 30–50
146	F	29	Conductive HL – unknown aetiology	0–25 / 20–26

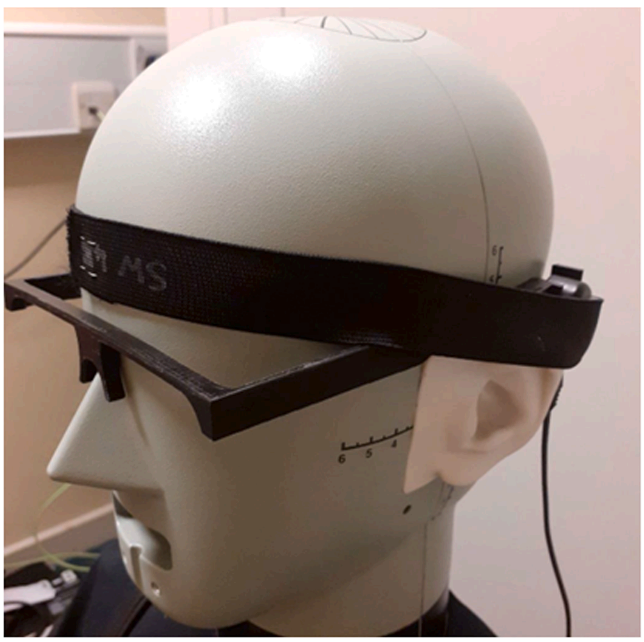

Fig. 2. Transducer mounting for the unimpaired participants, featuring 3D-printed spectacle frames that hold the bone vibrator against the temporal bone and an elastic strap to maintain pressure.

conventional headphones (Audio-Technica ATH-M50X, Tokyo, Japan) were used.

The patient volunteers used the transducers from a Cochlear® Baha 5 SuperPower® (Cochlear Bone-Anchored Systems, Gottenburg, Sweden), with the cable adapted by the manufacturer to terminate in a conventional 3.5-mm audio jack plug. These transducers could be attached to the patients' percutaneous abutment using the snap-connector system. The 3.5-mm jack socket was used to connect to a Presonus HP4® headphone amplifier (Baton Rouge, U.S.). Both these Baha transducers and the B71W transducers will be collectively referred to as bone transducers.

For both groups of participants, signals were generated digitally at 16-kHz sampling frequency by a custom MATLAB® program (Mathworks, Natick, U.S.) on a laptop and converted to analogue signals by an ESI Maya44 USB+ audio interface (ESI Audiotechnik, Stuttgart, Germany). The analogue output was led directly to the B71Ws, but through the headphone amplifier to the Baha transducers.

The phase and amplitude adjustments were made using the scroll wheel of a Logitech G502 mouse (Lausanne, Switzerland). The scroll wheel of this model can be unlocked so that it turns freely rather than in steps.

2.3. Measurements

For both unimpaired listeners and the users of bilateral BCHAs, the experiment had a calibration and a measurement stage. For the calibration stage, listeners would adjust the phase and level of a tone applied to one bone vibrator until it cancelled a tone of the same frequency applied to the other bone vibrator. These measurements would be made at 17 frequencies at 62.5-Hz intervals across a 1-kHz band in order to maximally exploit the resolution of the available digital filter. For the measurement stage, the calibration data was used to design an FIR filter for each ear. These two filters were applied to the signal at each ear but in each case added to the contralateral input to cancel the crosstalk from this signal at the contralateral cochlea.

In the calibration stage, listeners were required to maximise the laterality of pure tones between 1.5 and 7.5 kHz. In separate sessions, frequency bands of 1.5–2.5 kHz, 2.5–3.5 kHz, 3.5–4.5 kHz, 4.5–5.5 kHz, 5.5–6.5 kHz and 6.5–7.5 kHz were calibrated. The tone frequencies were above the limit of sensitivity to their interaural time delay, so any lateralisation will be evidence of an ILD. Since an ILD will always be greatest when the signal at one cochlea is as small as possible, degree of laterality is a good perceptual index of signal cancellation at one cochlea.

At each of the 17 frequencies within a band, tones of the same frequency were presented to each bone transducer. The phase and amplitude of the signal on the test side were placed under the control of the participant through a graphical user interface (GUI) and the unlocked mouse scroll wheel. The GUI allowed participants to alternate between adjustments of the phase in 1° steps and the amplitude in 0.1-dB steps, adjusting each for maximum laterality before switching over to the other parameter and readjusting it until satisfied with the overall result.

Using the calibration data for a given side, these data were used to design an individualised cancellation filter using the host-window method (Abed and Cain, 1984). The phase and amplitude changes introduced by this 256-point finite-impulse-response filter at each frequency were designed to be as close as possible to those selected by the participants.

In the measurement stage, a tone was generated at the middle frequency the of the 1-kHz-wide band of frequencies that had been calibrated, i.e., at 2, 3, 4, 5, 6 or 7 kHz. A 1-kHz-wide band of noise that matched this range of frequencies was also generated. In a control condition, the tone and the noise were then presented directly via the two bone transducers to different sides. In the experimental condition, the tone and noise were each presented directly to different sides, but also through the corresponding cancellation filters to their contralateral sides. The crosstalk cancellation was thus applied to both sides simultaneously.

After some initial training, unimpaired listeners attended between 2 and 4 one-hour sessions for each of the six frequency bands. During a session, phase and amplitude selections at the 17 frequencies within a band, and for each side, were collected. Repeated sessions allow for an evaluation of changes in crosstalk parameters with repositioning of the transducers (the calibration). Patients attended a variable number of sessions, all of them focussed on the 2.5–3.5 kHz band and a 3 kHz target tone. Since stimulation was delivered via a fixed percutaneous abutment, repeated sessions evaluated the stability of the crosstalk parameters with no repositioning. Changes were assessed both through recalibration and through changes in the effectiveness of the resulting crosstalk cancellation.

2.4. Procedure

In the main calibration procedure, continuous tones of identical frequency were presented via the two transducers, and the participants selected the phase and level of the tone at one ear for which they could no longer hear anything on that side. Since the tone at the other ear was still present, this situation was perceived as strong lateralisation to the other side of the head, generated by an interaural level difference. The task is potentially challenging because there is a two-dimensional search space (phase and level), within which good cancellation occurs only within a narrowly defined combination of the two parameters.

The listeners used the GUI to separately adjust the phase and level of the tone at one ear. The listeners could switch between adjustment of each parameter. Fig. 3 shows a typical search path for such adjustment though the 2-dimensional search space, during which this participant switched four times between level and phase adjustment. The figure illustrates the challenge of a 2-dimensional search, within which the noticeable perceptual changes may not occur until both parameters are quite close to the solution.

The unimpaired listeners received initial training in this task using a simulation of crosstalk. The simulation was created by deliberately mixing the left- and right-ear signals using randomly selected artificial phase and/or amplitude shifts. This calibration procedure was presented over headphones. Aside from allowing the participants the opportunity to practice the task using comfortable headphones rather than the relatively uncomfortable bone transducer apparatus, the use of simulated crosstalk offered the opportunity to confirm that the participants were deriving the correct values, as these were known parameters of the simulation. The experimenter could also listen-in to the stimulus during the parameter selection process using a headphone splitter, which enabled additional coaching advice to be delivered. Once, the unimpaired listeners had demonstrated reliable recovery of the simulated crosstalk parameters they moved on to the formal calibration procedure.

The simulation was not possible for the patients, because it relies on a crosstalk-free mode of input. The only way to verify that the patients had calibrated correctly, therefore, was using the measurement phase of the experiment. To help induct the patients into the calibration task, a different method was employed; they were initially given a task that involved automatic sweeping the stimulus parameters. This task not only enabled them to hear the fluctuation in laterality, but also to create an initial estimate of the cancellation parameters. The tone at the target ear would initially be swept continuously in phase compared to the other ear with a 12-second cycle. The patients were instructed to press a button when they perceived maximum lateralisation, and that phase value would then be frozen. This could only be done after the first sweep had completed a full cycle. The tone would then be swept in level

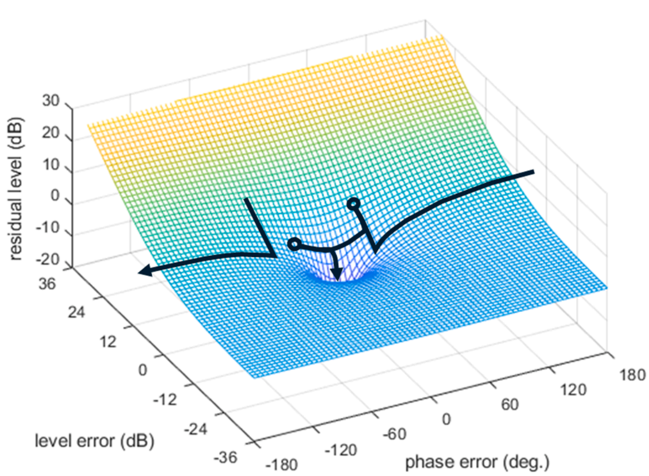

Fig. 3. An example search path with simulated crosstalk. The mesh shows the residual level at the ear targeted for cancellation, relative to the level at the non-target ear (i.e., the resultant interaural level difference) as a function of the cancellation signal settings. The settings are shown as phase and level errors with respect to those needed for perfect cancellation. The black arrows show how the settings changed over time. Two reversals in the direction of adjustment are illustrated as tight circular U-turns.

between +10 dB and - 40 dB relative to the opposite side. The sweeps went up and down between these extremes in a triangle-wave pattern (scaled in dB) with an 8-second sweep in each direction. Again, the participants pressed a key when maximum lateralisation was experienced, but only after the first cycle was complete. These phase and amplitude values were then used as the starting point in the main calibration procedure, so that they should already be close to the correct solution.

The main calibration procedure was implemented using the GUI exactly as for the unimpaired listeners. Two radio buttons allowed the participant to toggle between cancelling at the left or the right ear. Buttons marked “Phase” and “Level” enabled participants to switch between adjustment of phase or the level of the signal at the ear to be cancelled. Adjustment of each parameter was performed using the scroll wheel of the mouse. When the participant decided that no further improvement could be achieved, they would click on the “Done” button and the frequency would automatically change by 62.5 Hz. When all 17 frequencies had been cancelled at both ears, the process was terminated by clicking on “Finish.”

In the measurement phase, masked thresholds were measured with a tone presented via one bone transducer and a masking noise presented via the contralateral transducer. In bilateral cancellation, the crosstalk from both signal and noise were cancelled while for unilateral cancelation only the crosstalk from the noise was cancelled. In terms of Fig. 1, unilateral cancellation would only feature a dashed-line signal path of one color, that color corresponding to the side receiving the masking noise. Thresholds were measured using a 2-interval, 2-alternative, forced-choice task and an adaptive staircase with 12 reversals for unimpaired listeners and 8 reversals for impaired listeners. Threshold was taken as the average of the last 6 reversals in both. There were four conditions, which were each measured once. These conditions measured masked threshold with and without the cancellation signal and with the noise on the left and target tone on the right or vice versa.

3. Results

Nine unimpaired listeners achieved successful cancellation of simulated crosstalk when it varied in both interaural phase (0–360°) and interaural level (+10 to −40 dB). They required a total of between 1 and 3 sessions of training. Success was evaluated by comparing the matched phase and amplitude values to those embedded in the simulation. Success was defined as a phase error of <10° and a level error of <1 dB, which should be sufficient accuracy to obtain >10 dB of crosstalk cancellation.

These nine listeners, plus the first author, went on to using the bone transducers and five of these (including the first author) were able to commit the time for more extensive testing. They were further trained until they produced reliable cancellation using the bone vibrators. Since repositioning of the bone vibrators causes calibration changes from session to session, reliability was indexed through the results of the subsequent threshold testing. Thresholds with and without cancellation filters were measured twice at the end of each session. Formal data collection commenced once listeners produced threshold improvements of at least 5 dB in the cancellation-filter condition across two consecutive sessions or until no further improvement was seen. At this point listeners had received between 3 and 20 sessions of training.

Fig. 4 shows the mean improvement in threshold achieved by the five unimpaired listeners across the six test frequencies and for each ear. At most test frequencies, these five listeners repeated both phases of the experiment four times (6 frequencies × 5 listeners × 4 repeats with and without cancellation), which were then averaged across repeats. One participant did not do the 1.5–2.5 kHz band and there were four cases in which one of the listeners only did three repeats.

Since repeat measurements were made, it is possible to examine the degree of session-to-session variability. Fig. 5 shows the changes in the level and phase settings produced by each participant at each frequency

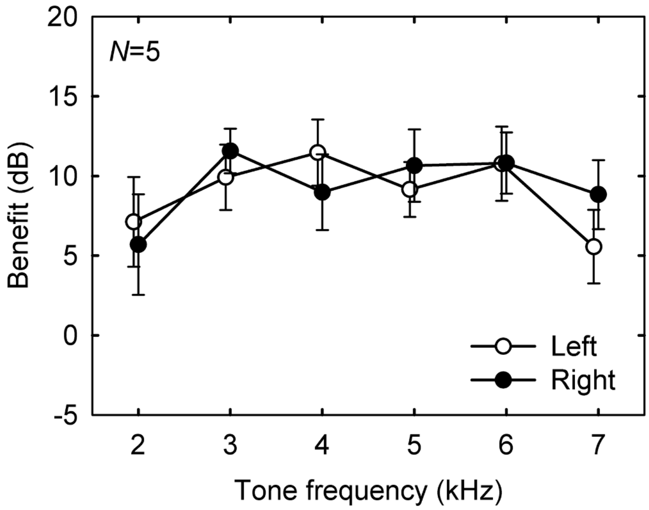

Fig. 4. Mean improvement in masked threshold for tones in a 1-kHz-wide band of noise. Means are for 5 individuals at most frequencies, but only 4 at 2 kHz.

from one session to another for the 2.5–3.5 kHz band. As previously observed (Mcleod and Culling, 2020), measurements can change dramatically from session to session despite the experimenter's best efforts to place the transducers in a consistent position. These session-to-session changes are also apparent in sudden cross-spectral discontinuities in the level and phase settings at the boundaries of the ranges of frequencies measured in each session (e.g., Mcleod and Culling, 2017, Fig. 4). It is notable that while this calibration changed greatly, the resulting benefit from crosstalk cancellation was quite consistent, indicating that the recalibration was both necessary and effective.

Patients #127 and #145 were each tested over multiple sessions, but only with the 2.5–3.5 kHz band. Patient #145 was tested with cancellation applied on each side as well as both sides simultaneously. Patient #127 was only tested with cancellation to the left. They were recalibrated during each session like the unimpaired listeners, but they were tested using filters derived both from this new calibration and with calibration data from previous sessions. Fig. 6 shows changes in calibration from one session to another for each of the two patients for the same frequency band as Fig. 5 for the unimpaired listener. Across all measurements (3 ears) the root-mean-squared change in level for the patients was 33° for phase and 3.3 dB for level. For the same frequency band, the equivalent numbers for the unimpaired listeners (10 ears) were 52° and 6.9 dB, suggesting that the abutments do provide greater stability in the calibration measurements.

Fig. 7 shows the effect on the measured benefit of unilateral crosstalk cancellation using a freshly calibrated filter compared to a filter derived from a previous experimental session. Depending on time constraints, measurements were taken between one and four times. Each individual measurement is shown with circles with line regression lines to illustrate the downward trend in benefit. Only the left ear was tested in this way for each patient. For both patients and for all three filters, a progressive decline in benefit was observed when a filter derived during one session was used again in later sessions.

For patient 145, two other sets of measurements were made. First, unilateral crosstalk cancellation was applied to the right side with a filter derived during the same session. On two successive sessions, the thresholds were measured twice, and the benefit of crosstalk cancellation was consistently smaller than for the left side (in Fig. 7), averaging 2.5 and 3.2 dB, respectively. This right-side data is not plotted. Second, bilateral crosstalk cancellation was applied using the filters for each side simultaneously (Fig. 8). The results of bilateral cancellation were consistent with the unilateral results with the greater benefit again being observed with left-side cancellation than with right-side cancelation. There is a slight decline in benefit, but much smaller than when the same filter was used across successive sessions.

4. Discussion

For both unimpaired listeners and bilaterally fitted BCHA users, the application of crosstalk cancellation produced improvements in masked thresholds when signal and masker were applied to transducers on different sides. These improvements imply that the crosstalk cancellation has been effective and has improved the stereo separation of sound by the same number of dB.

The results from the unimpaired listeners show that it is possible to obtain improvements in stereo separation of around 10 dB in both ears simultaneously and across a wide frequency range using an individually

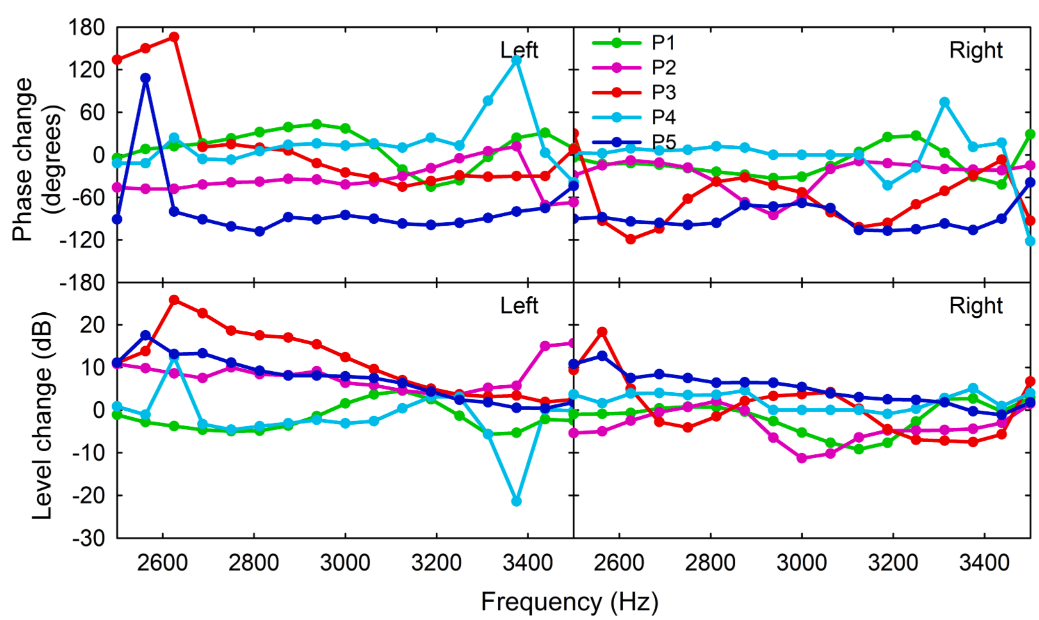

Fig. 5. Changes in the phase and level settings for signal cancellation at each ear and by each of the five unimpaired listeners from one testing session to a second session for the same frequency band.

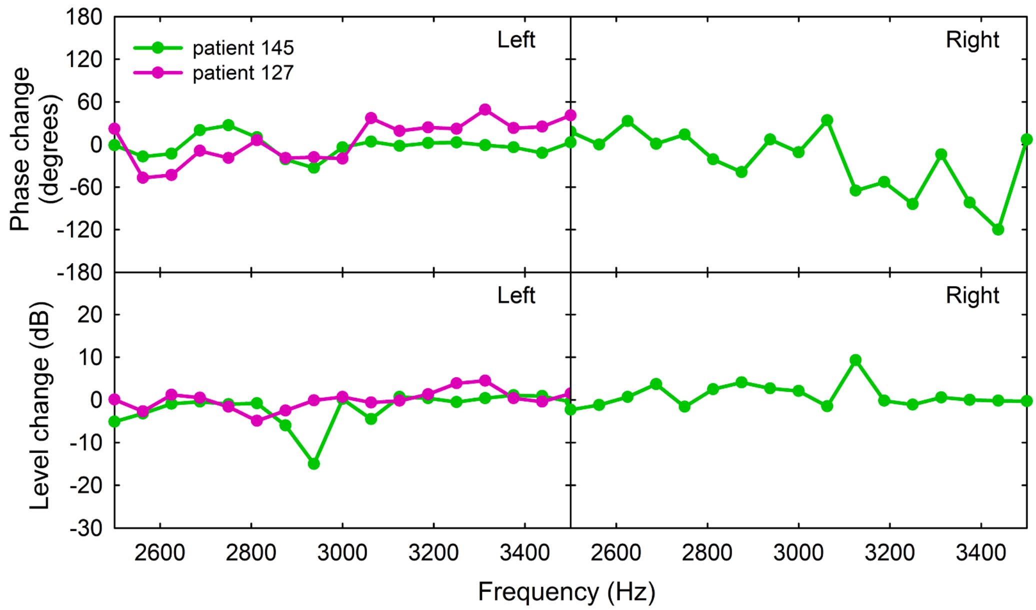

Fig. 6. Changes in the phase and level settings for signal cancellation at each ear and by each of the patients from one testing session to a second session for the same frequency band.

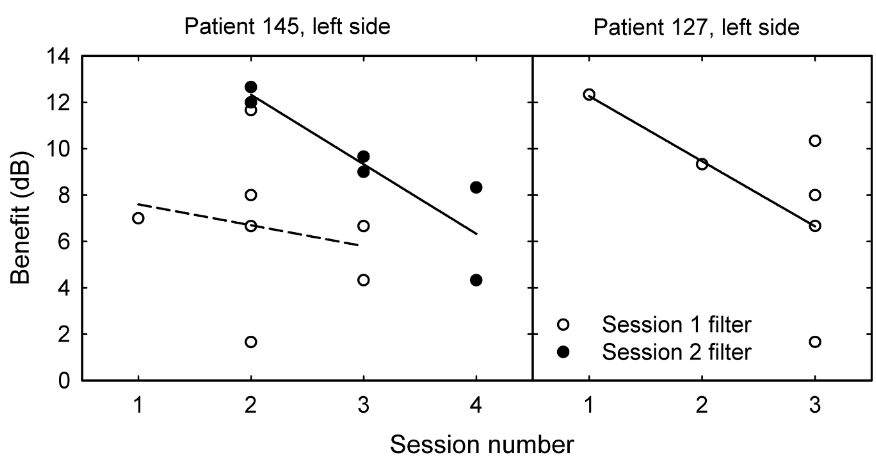

Fig. 7. Benefit of unilateral crosstalk cancellation applied to the left side using the same cancellation filter across multiple experimental sessions. Linear regression lines illustrate the across-session downward trend in benefit using the same filters.

calibrated, 256-point, FIR filter. These improvements replicate those previously achieved for unilateral cancellation by Mcleod & Culling (2020) using much more detailed filters. These improvements could potentially help patients with bilateral bone-conduction hearing aids to better understand speech in background noise and to localise the sources of sounds.

The results from both the patients show that the method can be translated to produce similar improvements in patients. The results from patient #145 demonstrated benefits in both ears, although one ear showed a much smaller benefit. The patient benefit was moderately stable over time, but with larger benefits observed in each session using recalibrated filters than when using filters from a previous session.

Evidence from repeated sessions also indicate that the calibration is more stable with abutments than when using bone vibrators, even when the latter are carefully positioned using a device (the spectacle frames) to guide them to the same positions in successive sessions. A potential objection to this observation is that the calibration methods were different for patients and unimpaired listeners, invalidating comparison of the two sets of data. However, the primary difference in the method was that while the unimpaired listeners began their calibration using parameters from the previous session, the patients started from scratch using a sweeping level or phase cycle. One might expect that this difference would, if anything, reduce the changes from session to session for the unimpaired listeners compared to the patients, but the effect appears to be in the other direction.

Although the abutments seemed to provide relatively stable calibration, there was clear evidence that effectiveness of the derived filters was reduced in subsequent sessions. This outcome suggests that the positioning and coupling of the transducers may not be the only factor than changes between sessions. Other possibilities include the patient's physiological state, such as the intracranial pressure (Sohmer, 2000; Sohmer and Freeman, 2004) and the coupling at the stage of the snap connector. However, experiments with cadaver heads indicate that intracranial pressure has little influence (Dobrev et al., 2019). A possibility that we considered with respect to the coupling was that the orientation of the bone vibrator might change, resulting in a change in the direction of vibration. However, within the BAHA Superpower® transducer that we used, the orientation of the vibrator is perpendicular to the skull and its orientation about this axis of vibration is therefore unlikely to alter the transmitted vibration in any way.

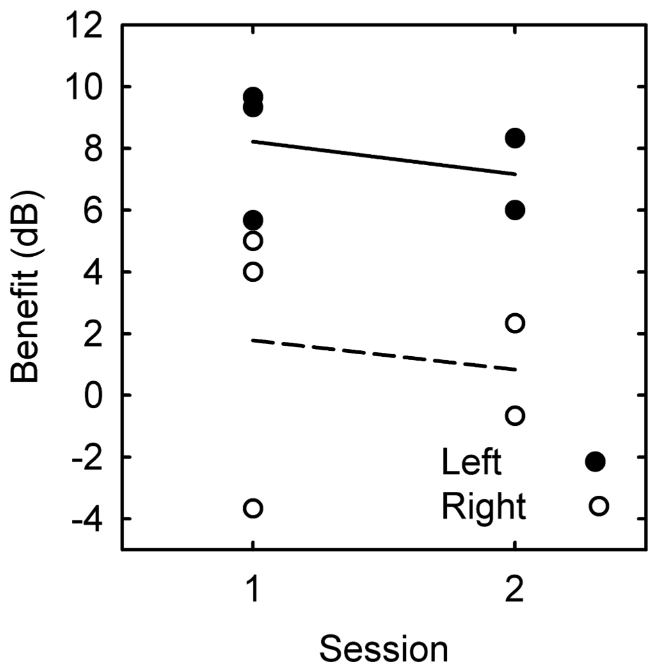

Fig. 8. Mean benefit of bilateral crosstalk cancellation on each side during two different sessions for patient #145. Regression lines show a slight downward trend in benefit using freshly generated filters in each session.

Patient #145 displayed only a rather modest benefit of crosstalk cancellation at the right ear. This smaller benefit was observed during two sessions with independent calibration for both unilateral and bilateral (simultaneous) cancellation. There are two possibilities. The patient may, by chance, have only achieved relatively poor calibration at that ear on each occasions or they may have had an undiagnosed sensorineural loss. In the latter case, an elevated threshold of cochlear origin might have made it difficult to perform the calibration because the target tone would fall below detection threshold before the noise was fully cancelled. It is noteworthy that diagnosis of unilateral cochlear hearing loss is difficult in patients who only have access to bone-conducted sound, because they always hear sound with both cochleae and at a ratio that is difficult to predict. The present method may, therefore, also offer an opportunity to make such diagnosis.

Both the patients and the unimpaired listeners found the calibration task quite challenging but improved considerably with practice. If the technique were to be developed clinically, improvements in the usability and perhaps gamification of the calibration process will be desirable. In addition, greater use of predictive algorithms, such as those developed by Mcleod and Culling (2020) may be able to accelerate the calibration process. Some alternative methods have been developed in the literature, that rely on objective measurements and so do not require mastery of a psychoacoustic task.

Irwansyah et al. (2022) measured the bone-conducted sound that is emitted by the ear-canal wall at each ear on the assumption that, at least at low frequencies, this sound would share phase and level characteristics with the nearest cochlea. A masked threshold benefit of ~10 dB was measured in a similar way to the present study, but for frequencies up to 1000 Hz. The study was limited to frequencies below 1000 Hz because the distance between the cochlea and ear canal is likely to introduce larger phase differences between ear canal and cochlea as frequency increases. The observed 10-dB benefit seems to contradict Mcleod and Culling (2020), who remarked that crosstalk cancellation was probably not feasible at low frequencies. Mcleod and Culling argued that the difference in phase between the ears would be too small, with the result that the cancellation signal would largely cancel the desired ipsilateral input at the same time as the crosstalk. It may be that Irwansyah et al.'s masked-threshold benefits were, as a result, obtained at quite low sensations levels. If it turns out that sufficient sensation level can be generated at low frequencies, the method could be used to complement the present psychoacoustic technique by extending it to lower frequencies. It would, however, only be possible to do so in patients who have an ear canal. Moreover, Surendran and Stenfelt (2023), who developed an alternative psychoacoustic method that can be implemented at low frequency, found evidence contrary to their assumption that the phases are similar at the cochlea and in the ear canal.

Wang et al. (2023) used a comparison of the otoacoustic emissions evoked by each bone vibrator at each ear to measure the stimulation at the corresponding cochleae. The data was used to generate crosstalk cancellation filters that yielded improvement in sound localization performance in the horizontal plane. The study demonstrates the potential to improve sound localization, but measurement of otoacoustic emissions relies on an intact conductive pathway from the cochlea to the measurement point in the ear canal, so would not be suitable for the majority of bilateral BCHA users. The technique could, nonetheless, find clinical use in BCHA users with sensorineural loss who were unable to use conventional hearing aids due to cerumen build-up or skin irritation.

Finally, Irwansyah et al. (2024) have started to develop a method using 3-D printed heads with a silicone skin layer and an in-built accelerometer at the position of the cochlea. The work is at an early stage, but, if successful, may offer a way to physically model of an individual patient's head and measure the expected crosstalk signal. Even if unsuccessful, it offers the prospect of better understanding the relationship between skull size/shape and bone-conducted crosstalk.

There are now a number of BCHAs on the market that are fully implantable (Reinfeldt et al., 2015). In the present study a percutaneous abutment and an isolated transducer were advantageous for gaining full computer control of the stimulus presentation. There is no technical barrier to creating hearing-aid controlled calibration procedures using either percutaneous of implanted systems, but the latter would need to be implemented by the manufacturer in the hearing-aid software.

5. Conclusions

Crosstalk cancellation can be successfully implemented for bilaterally implanted users of bone-conduction hearing aids using psychoacoustic measurements to calibrate the crosstalk-cancellation filters. To work optimally, the fitting will require periodic recalibration. With the resulting improved stereo separation at the cochleae, there is a prospect to better characterise asymmetric cochlear hearing losses.

CRediT authorship contribution statement

Ryan D. Barnsley: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **John F. Culling:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Data availability

Data are available upon reasonable request.

Data availability

Data will be made available on request.

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