Psychoacoustic measurement of phase and level for cross-talk cancellation using bilateral bone transducers: Comparison of methods

Robert W. J. Mcleod and John F. Culling, School of Psychology, Cardiff University, Tower Building, Park Place, Cardiff, CF10 3AT, U.K.

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Correspondence address: -

Robert Mcleod

School of Psychology,

Cardiff University,

Tower Building, Park Place,

Cardiff,

CF10 3AT

U.K.

mcleodrw@cf.ac.uk

Abstract

Two bone-conduction hearing aids (BCHAs) could deliver improved stereo separation using cross-talk cancellation. Sound vibrations from each BCHA would be cancelled at the contralateral cochlea by an out-of-phase signal of the same level from the ipsilateral BCHA. A method to measure the level and phase required for these cancellation signals was developed and cross-validated with an established technique that combines air- and bone-conducted sound. Three participants with normal hearing wore bone transducers (BTs) on each mastoid and insert earphones. Both BTs produced a pure tone and the level and phase were adjusted in the right BT in order to cancel all perceived sound at that ear. To cross-validate, one BT was stimulated with a pure tone and participants cancelled the resultant signal at both cochleae via adjustment of the phase and level of signals from the earphones. Participants achieved cancellation using both methods between 1.5-8 kHz. Levels measured with each method differed by <1 dB between 3-5 kHz. The phase results also corresponded well for the cancelled ear (11° mean difference) but poorly for the contralateral ear (38.4° mean difference). The first method is transferable to patients with middle-ear dysfunction, but covers a limited frequency range.

I. INTRODUCTION

Bone-conducted (BC) stimulation produces little interaural attenuation of signals across the two cochleae (Rowan and Gray, 2008; Stenfelt, 2012). This can be useful in patients fitted with a bone conduction hearing aid (BCHA) for single-sided deafness (SSD), for whom delivery of sound from the deaf side is a treatment objective. It is problematic, however, in patients with two working cochleae, but a bilateral conductive loss, where the aim is to restore the benefits of binaural hearing (Rowan and Gray, 2008). If two bone transducers (BTs) are used to stimulate right and left mastoids simultaneously, signals from each BT reach both the right and left cochleae. In order to estimate how large of an imapct cross-talk might have upon binaural processing Stenfelt and Zeitooni (2013) measured spatial release from masking (SRM) via Air Conduction (AC) and BC. They found that mean SRM for AC was almost twice (7.6 dB) that for BC (4.0 dB) when noise was presented from 90°, ndicating that cross-talk is indeed having an impact on binaural processing.

Rowan and Gray (2008) proposed a model, which showed that if the phase and level of sound arriving at each cochlea from both BTs are known then this would allow for the potential development of a cross-talk cancellation system. A system such as this could be used in bilateral BCHA patients to restore the interaural level difference (Liao, 2010), a key component for effective binaural hearing (Majdak et al., 2013). The ability to achieve cross-talk cancellation relies on an increased understanding of the transfer functions between each bone transducer and each cochlea, as well as understanding how this varies between patients (Zurek, 1986).

A common method for investigation of level is via threshold measurements in patients with SSD to calculate transcranial attenuation (TA) (Nolan and Lyon, 1981). Transcranial attenuation can be defined as the difference in thresholds between ipsilateral and contralateral BT placement in an SSD patient (Stenfelt, 2012). This method of calculation makes several assumptions, including assuming equal coupling and positioning on both mastoids, as well as skull symmetry with the same resonance and antiresonance properties on both sides. However, it is well known that there can be significant asymmetry in the skull on the right and left sides (Wismer and O'Brien, 2010). Therefore, these assumptions may be useful for elucidating appropriate bone conduction masking levels in audiological testing, but not for calculating the precise interaural level difference in an individual patient. Since level can be higher at the cochlea contralateral to the BCHA, it can be misleading to describe relative sound levels as attenuation, so we will use the term interaural level difference (ILD). We have previously demonstrated that it is possible to accurately measure ILD and interaural phase difference (IPD) reaching the cochleae from a single BT in participants with binaural hearing (Mcleod and Culling, 2017).

The present study compares that single-BT technique with a psychoacoustic method that employs only bone-conducted sound. The new method employs two bone transducers (BTs) with sound cancelled at one or other cochlea by varying the level and phase of the ipsilateral BT, resulting in a strongly lateralized percept (FIG 1~~FIG 1~~ a,b). Unlike the previous "one-BT" technique, this "two-BT" method could be used in a clinical population with conductive hearing loss. The effectiveness of cancellation was assessed by using an additional cancellation signal from the ipsilateral (uncancelled) earphone. If this signal could be adjusted in level and phase such that very little sound was heard, cancellation at the contralateral ear was deemed successful. The comparison method uses a single BT at a time with sound emitted from it cancelled at the cochlea via Etymotic ER2 earphones (FIG 2~~FIG 2~~ a,b). The two procedures were performed for each of the two techniques. The results of phase and level using the one-BT method were then used to calculate expected results from the two-BT method. Expected and actual results were then compared.

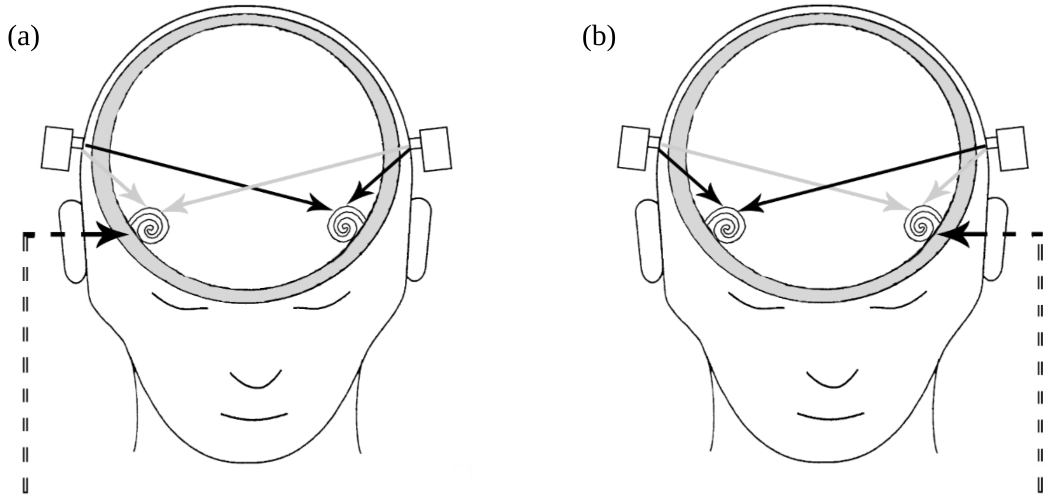

FIG 1 Panels (a) and (b) illustrates sound cancellation at the cochlea by interaction of the two BTs by destructive interference (black arrows). Panel (a) showing cancellation at the left cochlea and (b) at the right cochlea. The signals following interaction of the two adjusted BT signals (gray arrows). The resultant of these two signals is then cancelled with ER2 earphones at the opposite ear (dotted arrow).

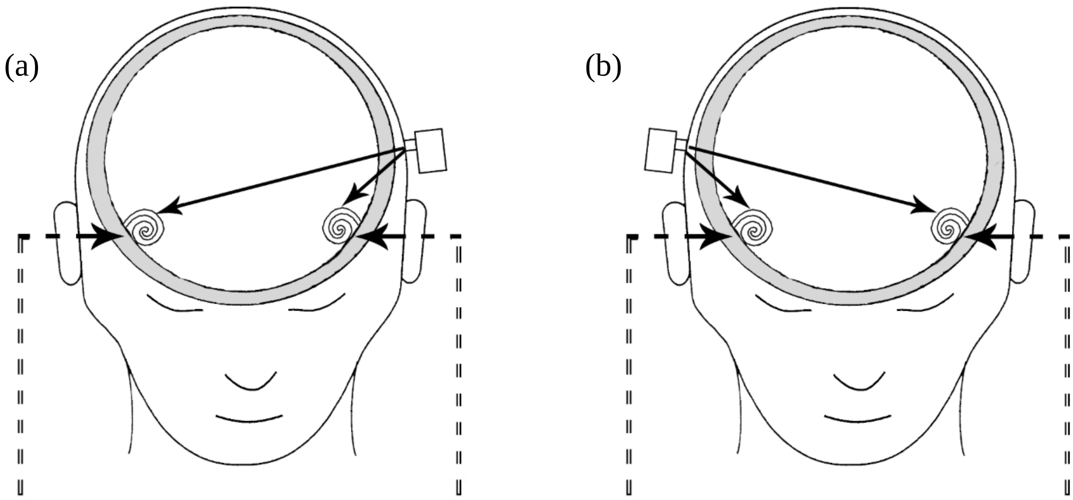

FIG 2 Panels (a) and (b) illustrate cancellation of a single left sided (a) and right sided (b) BT using ER2 earphones.

II. METHODS

A. Apparatus

Matlab™ 2012 software was used to generate pure tones at a sampling rate of 44.1 kHz over four channels with the ability to vary the level and phase of each channel independently. An 8-channel Echo Darla 24/96 DAC passed signals through an 8-channel Behringer Powerplay Pro-8 Amplifier to Etymotic ER2 insert earphones and two Radioear™ B71 BTs for BC mastoid stimulation. To minimize differences in BT placement between experimental sittings for the same participant and between different participants, specially adapted lens-less glasses were used which had attachments behind the ears holding both BTs in position. The glasses allowed lower variation in BT placement as the superior portions of both pinnae and the bridge of the nose were effectively used as a fixed-point reference tripod for the glasses to rest on. The attachment for the BT onto the glasses positioned the BT 55mm behind the opening of the external auditory canal. This is a typical surgical placement position (Battista and Ho, 2003; Stenfelt et al., 2000). Testing was performed in a single-walled sound attenuating booth (Industrial Acoustics Company) within a sound deadened room.

B. Participants

Three participants were used (age range 22-29) with normal hearing and no previous history of otitis externa or ear surgery. In order to prevent wax impaction, otological examination was performed on participants before deep insertion of ER1-14B eartips connected to the ER2 earphones. ER2 earphones where selected over open ear headphones to prevent air-borne sound emitted by the bone transducer from reaching the cochlea.

C. Testing procedure

The following experimental methodology was approved by Cardiff University Psychology Department Ethics Committee. Prior to performing the outlined testing procedure, each participant undertook at least 8 hours of practice sessions. In these sessions, participants practiced cancellation of a pure-tone signal from a BT with ER2 earphones via adjustment of the phase and level of each earphone independently. Participants also attempted multiple frequencies between 0.5-8 kHz using the two-BT technique described below. The aim of this extensive practice was twofold. Firstly, it was used to determine at which frequencies participants could reliably perform the task and secondly for the participants to be familiar with the task so that results of cancellation were reliable. It emerged that participants found the two-BT task very challenging at frequencies below 1.5 kHz and consequently this was the lowest test frequency chosen for the data collection sessions.

After deep insertion of ER2 earphones, the two BTs were placed on the left and right mastoids, and held in place by adapted lens-less glasses as shown in FIG 3~~FIG 3~~. An elasticated material band was then placed over the participant’s head and the BTs achieving a pressure of 2.5-3N as described by Reinfeldt, Ostli, Håkansson, & Stenfelt (2010).

FIG 3 Image of lens-less glasses with attached B71 bone transducers.

The one-BT method was used first. A pure tone was presented via the BT. A second pure tone, 1 Hz higher than the tone from the BT was presented via the ipsilateral earphone. In the initial phase, the participant was asked to vary the level of the earphone-presented tone in order to maximize the perceived beating effect as the two signals constructively and destructively interfered. Beating is known to be maximum when the level of the signals at the basilar membrane are equal (Wever and Lawrence, 1954). Beating maximization was achieved by changing the level of the earphone-presented sound. Adjustment was made by using a scroller on a computer mouse. Each step of the scroller changed the level by 0.2 dB. This method allowed the level of the two presented tones to be roughly matched at the cochlea. Once the participant had selected a maximal beating level, the cancellation phase could be estimated. The same levels were presented again but using the same frequency in both the earphone and the BT simultaneously. The participant was asked to change the phase of the ER2 presented tone to minimize the perceived sound in that ear. Phase adjustment was performed using the mouse scroller, with each scroll step changing the phase by 2°. To cancel the signal going to the contralateral ear, the same two processes of level adjustment followed by phase change were repeated using the contralateral earphone while the level and phase modified cancellation signal was simultaneously maintained on the ipsilateral earphone. In this way, the bone-conducted sound at both ears could be largely cancelled.

In the second phase, participants could make further refinements *ad libitum* to the level and phase of the earphones signals at each ear in order to continue reducing the perceived sound. A graphical user interface allowed the participant to switch between any of the four parameters (left level, left phase, right level, right phase) for adjustment or to indicate that they were satisfied that the perceived sound could be reduced no further. The resulting phases and levels from the earphones needed for cancellation in both ears were recorded for a given BT signal. The same method was repeated with stimulation of the opposite BT at the same frequency as shown in FIG 2~~FIG 2~~ FIG 1~~FIG 1~~.

Immediately following completion of the one-BT task, the two-BT task was performed. Care was taken to avoid any disturbance of the apparatus between the two tests that might alter the coupling of the transducers or the magnitude of the occlusion effect produced by the insert earphones.

In the two-BT task, both BTs presented the same pure tone at the same level and phase. Participants were asked to adjust the phase of the right BT in order to minimize the perceived sound in the left ear. Phase adjustment was performed via the mouse scroller using a 2° step size, as previously. Participants were then asked to adjust the level (with a 0.2 dB step size) of the right BT in order to minimize the perceived signal at the left ear. At high frequencies, this task corresponded directly to maximizing the lateralization of the percept towards the right ear through an ILD, but at lower frequencies, sensitivity to ITDs in pure tones made the lateralization cue ambiguous. Participants could make as many adjustments to the level and phase as deemed necessary to minimize the left ear signal.

At some frequencies, participants did not find that there was a variation in perceived lateralization when changing the phase. It was thought that this happens when there is a large level difference at the cancellation cochlea between the two BTs, preventing detection of destructive interference. In such cases, the level of the right BT was decreased by 3 dB in order to reduce the level difference and then phase adjustment was re-attempted. If this was unsuccessful, a 3 dB increase on the original BT signal was made and phase readjusted. This step down and step up by 3 dB level adjustment was repeated (i.e. with ±6 and then ±9 dB) until variation in perceived lateralization was achieved.

Once signal cancellation was completed in the left ear using two BTs, the quality of the cancellation at that ear was verified in the following way. The sound at the right ear was also cancelled using the earphone in the right ear. This was performed by first matching the earphone level with that of the combined BT signals using the beating technique. Level and phase at the earphone were then adjusted as before in order to cancel the entire signal. If participants had achieved cancellation throughout, then no signal would be audible at either ear, despite both bone transducers and a single earphone producing a pure tone. Feedback on the relative level of cancellation was collected using a grading system shown in Table I. The grade was used to exclude results when poor cancellation has been performed.

Grade	Description
1	As loud as start of task
2	Slightly quieter than bone transducer alone
3	Much quieter than bone transducer alone
4	Only slightly audible
5	Total cancellation (nothing audible)

Table I. Grading system post attempted cancellation

Each condition was attempted at least four times by the three participants. This was performed at eight different frequencies (1.5 kHz and in 1 kHz step between 2-8 kHz) with both left- and right-sided cancellation, and using both the one- and two-BT techniques. Each testing session lasted approximately 45 min and only tested one frequency. The order at which each frequency was attempted was counterbalanced between subjects in order to minimize practice effects. In seven testing sessions, participants could not achieve cancellation using the two-BT technique. On these occasions, a different frequency was attempted and the participant reattempted the failed frequency on the next occasion. This required differing numbers of attempts for some participants. In order for data from a single frequency to be included for analysis, four complete sets of data were required with cancellation grades of the two-BT technique of 3 or greater. This included performing cancellation using the one- and two- BT technique on the left and right side.

D. Calculations

Mathematical models have been produced showing how two-BT sounds can interact (Rowan and Gray, 2008; Zurek, 1986). In our equations (which focus on left-sided cancellation only), lower-case Greek symbols represent phase shift and gain values at the left or right cochlea (which are directly measured in the one-BT method), while corresponding upper-case Greek symbols represent adjusted values of input signals in the two-BT method. Superscripts R and L refer to the side of the BT and subscripts to the side of the cochlea. Symbols without a superscript correspond to differences between the two-BTs or cochleae at the defined subscript. For instance sound from left BT arrives at the left cochlea with a resultant phase difference (φ_L^L) and level difference (α_L^L). The diagram in

FIG 4

~~FIG 4~~ a) illustrates this condition (where squares represent phase changes and triangles represent level changes). Similarly, the right side BT signal will arrive at the left cochlea with a phase (φ_L^R) and level difference (α_L^R) as shown in

FIG 4

~~FIG 4~~ b). In order to achieve full signal cancellation at the left cochlea using the two-BT method (as shown in

FIG 4

~~FIG 4~~ c), the 'source' interaural level difference (A_L) of the BTs must complement the difference in transmission gain to the left cochlea between the two transducers. As shown by:

$$\alpha_L^L - \alpha_L^R = A_L \qquad (1)$$

Similarly, the 'source' interaural phase difference (Φ_L) must compensate and oppose the phase difference between the sounds reaching the left cochlea from both bone transducers, as shown by:

$$\varphi_L^L - \varphi_L^R + \pi = \Phi_L \qquad (2)$$

The resultant level and phase of sound at the right cochlea after left-cochlea cancellation (as shown in FIG 4~~Fig. 4~~ d) can by predicted from the one-BT method by addition of the two individual BT results with the phase (Φ_L) and level (A_L) shifted signal. Equation 1 shows that the level of the left BT needed for cancellation is $\alpha_L^L - \alpha_L^R$. Thus, the gain from the left BT to the right cochlea in that case can be given by:

$$\alpha_R^R + \alpha_L^L - \alpha_L^R \;\; = \mathit{Source\ gain} \qquad (3)$$

The required phase shift of sound at the left BT for cancellation at the right cochlea is $\varphi_L^L - \varphi_L^R + \pi$ thus the phase shift from the left microphone to the right cochlea in that case is given by:

$$\varphi_R^R + \varphi_L^L - \varphi_L^R + \pi = \mathit{Source\ phase\ shift} \qquad (4)$$

The signals from left BT which have been shifted by phase (Φ_L) and level (A_L) can be combined with the unchanged signal from the right BT at the right ear by vector summation to give the predicted phase and level of the resultant signal at the right ear. Calculation of the x, y components of the resultant vector are shown in Equations 5 and 6.

$$cos(\varphi_R^R + \varphi_L^L - \varphi_L^R + \pi) \times 10^{\frac{\alpha_L^L - \alpha_R^L - \alpha_R^R}{20}} + cos(\varphi_R^L) \times 10^{\frac{\alpha_L^R}{20}} = x \qquad (5)$$

$$sin(\varphi_R^R + \varphi_L^L - \varphi_L^R + \pi) \times 10^{\frac{\alpha_L^L - \alpha_R^L - \alpha_R^R}{20}} + sin(\varphi_L^R) \times 10^{\frac{\alpha_L^R}{20}} = y \qquad (6)$$

The level of the resultant signal at the right cochlea after cancellation at the left cochlea is calculated by:

$$log10(\sqrt{x^2 + y^2}) = \alpha_R \qquad (7)$$

The predicted phase at the right cochlea is given by arctangent of the x, y components, where atan2 refers to the commonly used programming function that returns the four-quadrant acrtangent.

$$atan2(x, y) = \varphi_R \qquad (8)$$

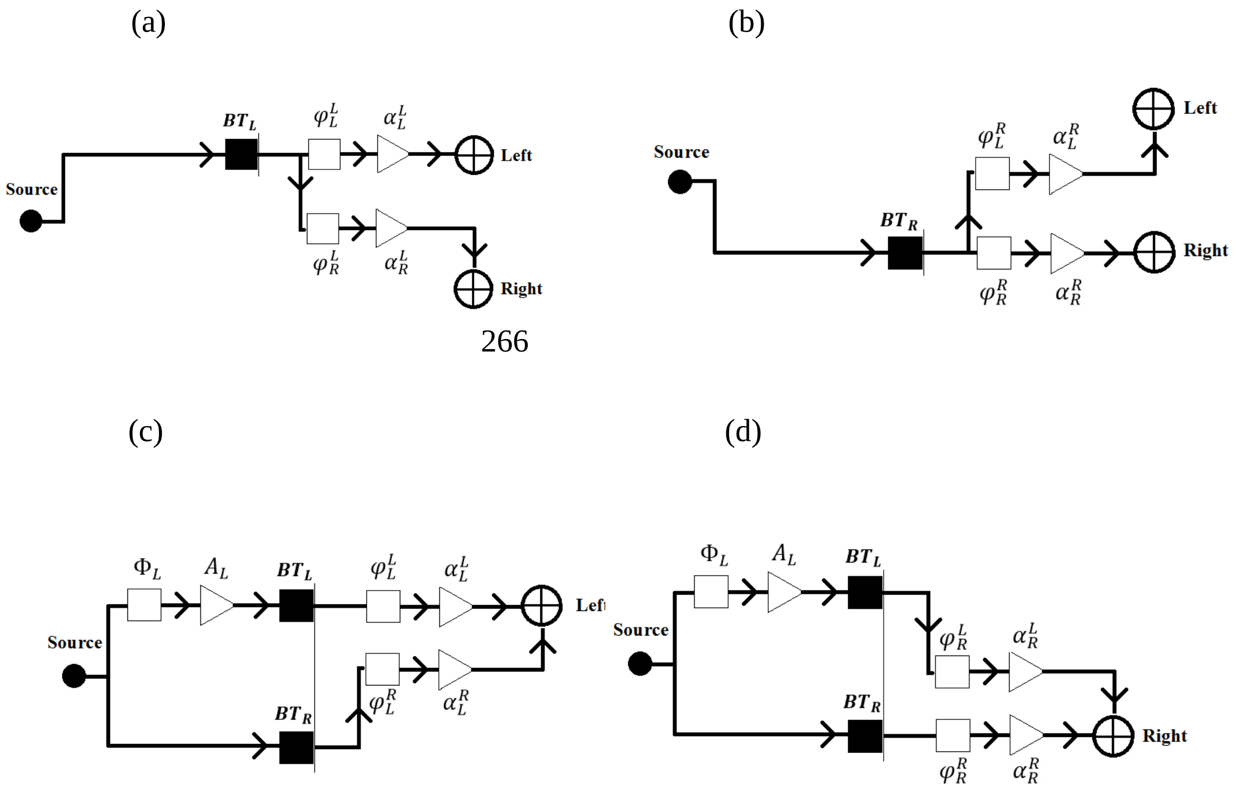

FIG 4 Illustrations of cross-talk cancellation modified from Rowan and Gray (2008) and Zurek (1986). (a) Model of cross talk cancellation using two BTs (see text for details). (b) Model of left-BT stimulation with cancellation at the left and right ear. (c) Model of right-BT stimulation with cancellation at the left and right ear. (d) Model of two-BT stimulation with cancellation at the left cochlea and the two signals interacting to give a phase and level at the contralateral (right) cochlea.

E. Data comparison methodology

The one- and two-BT phase and level results were compared via differences between pairs of one- and two-BT results of the same frequency. In order to avoid averaging of positive and negative results (which would likely identify a mean of no difference between the techniques) only absolute differences were recorded.

To minimize the effect of participant error on the evaluation of the equivalency of the two techniques, possible erroneous results were filtered. This was primarily motivated by the difficulty of the two-BT task, which meant that on some occasions participants could hear the tone again at the target cochlea after the contralateral sound was cancelled by the ER2 earphones. Filtering was achieved via a two-step process. First, participants performed two-BT cancellation until they achieved four results with a cancellation score of 3 or more. Scores of less than three were discarded. Second, via calculation of the median phase from the remaining results at the cancellation cochlea in the two-BT technique. The three results closest to the median where then included for further analysis. The same method was used in the one-BT technique in order to filter spurious results (although they were less common than in the two-BT technique). Thus, twelve results, (three from each side in the one-BT task) and a further six results from the two-BT method (three from each side) were available for comparison at each of the test frequencies for the three participants. The one-BT method results were then paired (one left BT and one right BT). The paired phase and level results were utilized in Equations 1-6 in order to predict the two-BT phase and level results necessary for cancellation at the left and right cochlea from the one-BT results. The difference between predicted results was then compared to measured results. The mean difference from six results (three from left and three from right cancellation) was calculated for each participant at each frequency.

III. RESULTS

A. Number of attempts needed at each frequency

For the two-BT cancellation task participants 1 and 2 required two attempts at 1.5 kHz. Participant 2 also required four attempts at 3 kHz before being able to achieve cancellation and participant 3 required three attempts at 6 kHz.

B. Level difference between techniques

The predicted phases and levels needed for cancellation using the two-BT technique were calculated using data from the one-BT technique. The difference in predicted and actual phases and levels were calculated. In order to give an overview of the raw results the mean predicted and actual phase and level results from a single participant is shown in FIG 5 Mean predicted and measured level and phase using the one- and two-BT techniques for a single participant. Error bars show the standard deviation (n=4 per frequency result).~~FIG 5 Mean predicted and~~

~~measured level and phase using the one- and two-BT techniques for a single participant. Error bars show the standard deviation (n=4 per frequency result).~~

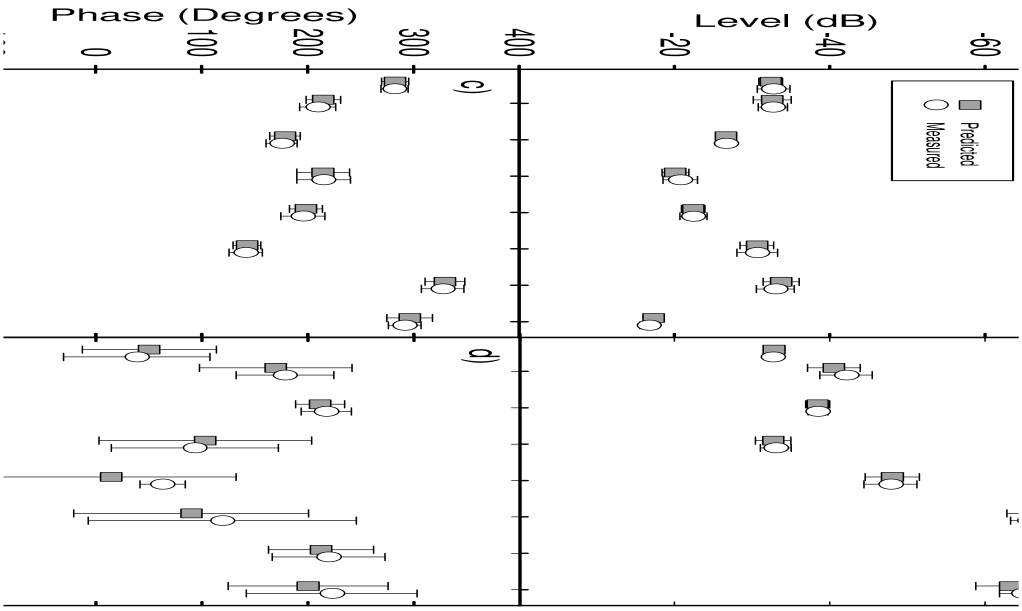

FIG 5 Mean predicted and measured level and phase using the one- and two-BT techniques for a single participant. Error bars show the standard deviation (n=4 per frequency result).

FIG 6~~FIG 6~~ shows mean differences in phase and level as well as standard deviation of six comparisons actual and predicted result. FIG 6~~FIG 6~~a shows the mean difference between techniques for each of the three individual participants for the cancellation cochlea in the two-BT technique (ipsilateral) and FIG 7~~FIG 7~~a shows mean differences overall. The smallest level difference between techniques was found at frequencies between 3 and 5 kHz where there was a mean difference of 0.93 dB. The mean difference in level at the ipsilateral cochlea over all frequencies was 1.81 dB. The highest frequencies had the greatest difference between techniques.

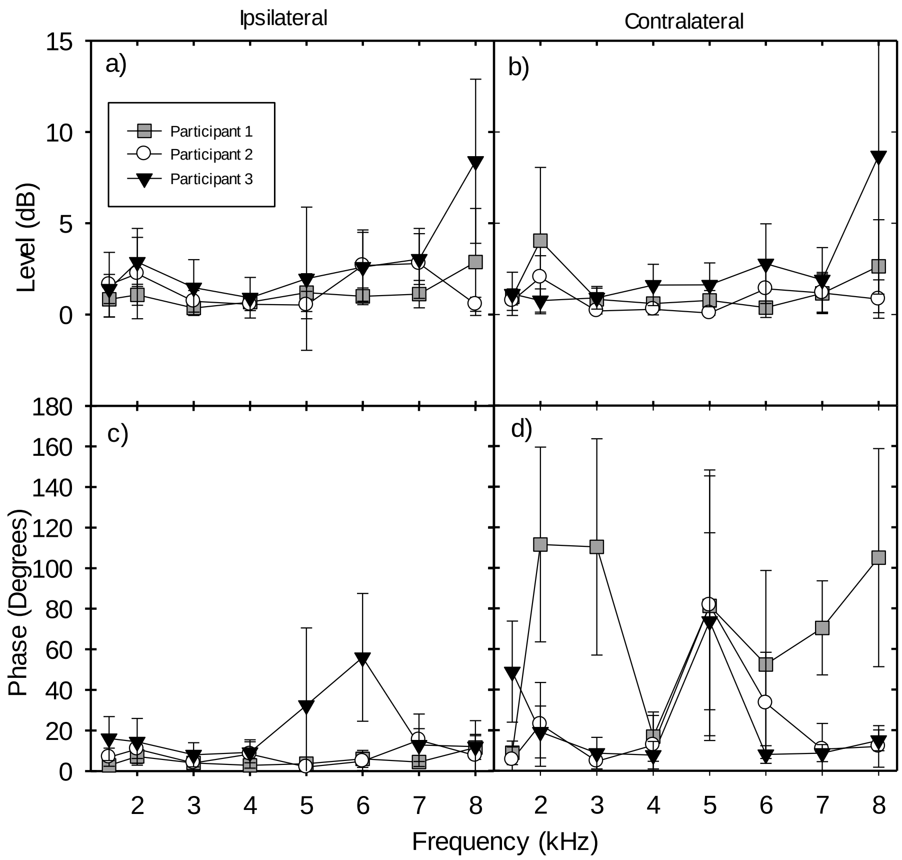

FIG 6 Difference between the predicted level and phase using the one- and two-BT techniques for each participant. Error bars show the standard deviation of the differences between the two techniques (n=6 per frequency result).

FIG 6~~FIG 6~~b and FIG 7~~FIG 7~~b show the level differences between the two techniques for the contralateral cochlea. The highest correspondence between techniques was again at 3-5 kHz. The mean difference was 0.77 dB within this range and 1.14 dB over all the test frequencies. A paired two tailed t-test showed that the difference between the two techniques was smaller in the contralateral cochlea when compared to the cancellation cochlea (p=0.03).

C. Phase difference between techniques

FIG 6~~FIG 6~~c and FIG 7~~FIG 7~~c show the difference between techniques in phase at the ipsilateral cochlea. Differences in technique were again smallest over the 3-5 kHz range. The mean difference was 8.3° within this range and 11° over all the tested frequencies.

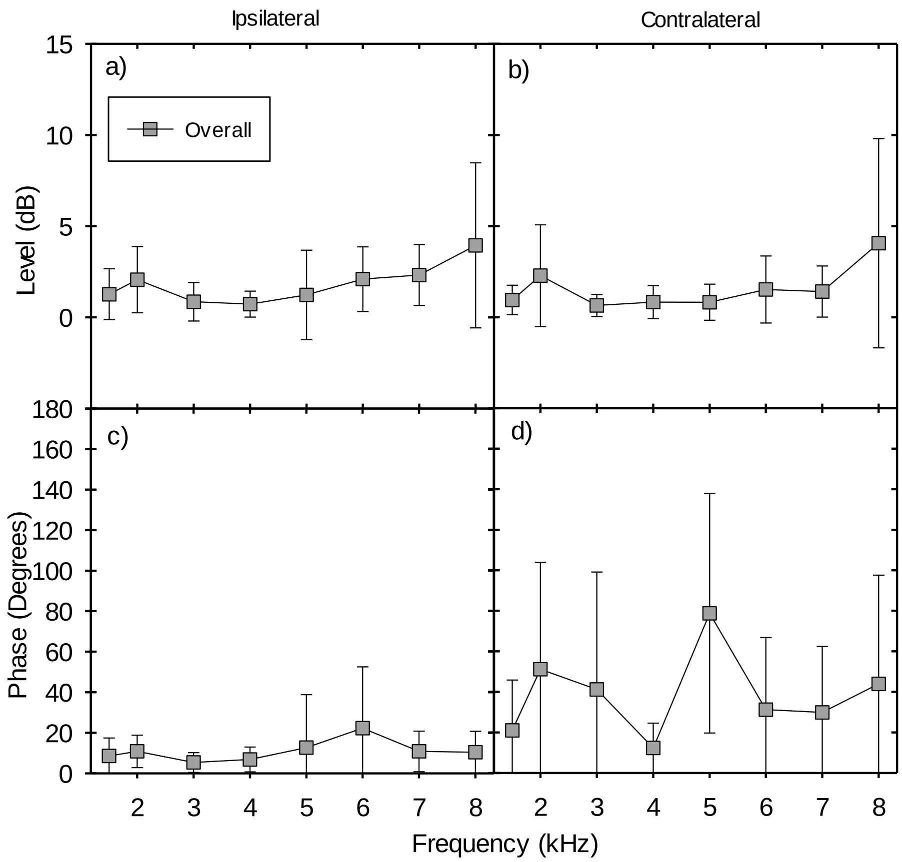

FIG 7 Mean absolute differences between the results from the two techniques. Error bars show the standard deviation across participants of the differences between the two techniques (n=18).

The phase-difference results in the contralateral cochlea had the greatest variation (FIG 6~~FIG 6~~d and FIG 7~~FIG 7~~d). All participants were found to have a large difference in results from the two techniques at 5 kHz when compared to other frequencies. There was a mean difference of 78.8° at this frequency and 38.4° overall. A paired two-tailed t-test showed that the phase differences in the cancellation cochlea were smaller than those in the contralateral cochlea (p=0.01).

IV. DISCUSSION

A. Ipsilateral level and phase

We have shown that it is possible to perform psychoacoustic measurements of phase and level in order to measure the cross-talk signal using both the one- and two-BT methods. There was a high degree of concordance between results from the two techniques at the cancellation cochlea for both phase and level. Thus, in the two-BT technique we have shown that participants are able to detect lateralization from ILDs between frequencies of 1.5 and 8 kHz. Phase and level differences between techniques were smallest at frequencies between 3 and 5 kHz. The greatest differences were found at higher frequencies. One possible explanation for these findings may be related to the greater change in phase at higher frequencies even if the error in time was the same. For example, an equal time difference at 2 and 6 kHz would result in a three times phase difference.

Participants found the two-BT technique more challenging than the one-BT task with some participants requiring reattempts of particular frequencies on a different sitting. Participant 2 had three attempts at 3 kHz before on the fourth sitting being able to produce reliable results. Participant 3 also had two attempts at 6 kHz before successfully completing the task on the third attempt. There was no apparent agreement between participants as to which frequencies were hard to perform except at 1.5 kHz where participants 1 and 2 both had two attempts.

There are two possible explanations for why some participants found the task difficult at particular frequencies. We have previously demonstrated that over a 0.3 kHz frequency range there may be up to a 20 dB difference in the attenuation of sound at a given cochlea (Mcleod and Culling, 2017). Stenfelt et al (2000) described the frequencies over which these large variations occur as areas of antiresonance. If one of these antiresonance frequencies were close to the test frequency, then this would cause a large disparity in levels reaching the target cancellation cochlea from each of the BTs. The large level difference makes the task significantly harder to achieve, as level matching has to occur before phase changes between the two BTs will cause enough destructive interference to induce lateralization. Another situation in which the two-BT task can be challenging is when there is little or no IPD between the two cochleae for each BTs. Thus, when one cochlea is cancelled there is also a degree of cancellation at the opposite cochlea. This makes the task difficult, because a very small change in phase can cause lateralization to change from one cochlea to the other. The most challenging situation to encounter in the two-BT task is a combination of a small IPD and large level difference.

We have previously shown that it is possible to accurately measure the phase and level of sound reaching the ipsilateral and contralateral cochleae using the one-BT technique (Mcleod and Culling, 2017). However, the ultimate aim of accurate measurement of phase and level is to allow the creation of a cross-talk cancellation system for bilateral BCHA users. This rules out the use of earphones because most patients with bilateral BCHAs are prescribed them due to conductive hearing loss, which obstructs airborne sound from reaching the cochlea. Thus, in order for this technique to be clinically applicable, a BCHA-only measurement technique is needed. Within this study, we have shown that the two-BT method can give equivalent results between 1.5-8 kHz to the one-BT method. Further research is needed in order to make collection of these data easier to perform. Firstly, whether is it possible to extrapolate phase and level data from direct measurements. This approach could include using measurements from within the external auditory canal, which could result in making the psychoacoustic task easier. If it were possible to automatically identify antiresonance frequencies, then the two-BT task could potentially be much easier to perform. Secondly, it may be possible to use previous phase and level results to extrapolate and predict the values needed for cancellation at other frequencies. Again this would make the psychoacoustic task much easier to perform at multiple frequencies.

B. Contralateral level and phase

At the cochlea contralateral from cancellation, there was high concordance between techniques with regard to the level (mean difference 0.77 dB) but poor correspondence for the phase (mean difference 38.3°). Having an accurate method of predicting or measuring level at the cochlea contralateral from cancellation is of lesser importance. It could be of use for correcting sound level in a full cross-talk cancellation system. However, bilateral BCHAs currently produce uncontrolled interference, so it is unclear whether the addition of cross-talk cancellation would cause any greater spectral distortion. Cancellation will introduce notches at frequencies where there is relatively little IPD difference (<30°), because part of the desired signal will be cancelled at both ears. In order to correct for this, the level of both sides would need to be increased, but bone transducers currently have quite limited maximum power, so such correction would be challenging to implement. On the other hand, when the IPD is close to being out of phase a degree of signal summation will occur, but this undesired peak in the transfer function cannot exceed 6 dB.

We showed previously that at low frequencies (<0.75 kHz) there is little or no IPD (Mcleod and Culling, 2017). Therefore, signal summation is greatest over this frequency range. Since cross-talk cannot be performed if the IPD is small (a cross-talk ill condition) it has been suggested that it may be of benefit to match the phase in order to cause maximal signal summation (Deas et al., 2010). This could have potential clinical benefits, since many patients with bilateral BCHAs do not have a pure conductive loss, (Bosman et al., 2001). In such instances when an ill condition is met then summation could be desired in order to make the signal louder (Deas et al., 2010). Further work needs to be performed to investigate how often contralateral cancellation and summation happens between 0.25-8 kHz.

We have shown that there greater errors in the predicted and actual phase results at the contralateral cochlea when compared to the ipsilateral. We believe this is primarily caused by frequencies where there is little IPD. In such instances, small discrepancies between the cancellation results of the one and two-BT techniques can result in large changes in the phase at the contralateral cochlea. One instance where this is particularly noticeable is close to an ill condition (partial destructive interference also at the contralateral cochlea). At these frequencies, a small change in the two-BT technique can make a very large change in both the phase and level at the contralateral cochlea. We believe that this is why overall the ipsilateral phase and level results will always be more accurate than the contralateral. Fortunately, knowledge of the contralateral phase of the resultant signal after cross-talk cancellation is of less functional use. Since it is the ILD signal, which is the target of modification. We have already shown that attempted manipulation of the phase differences at frequencies lower than 1.5 kHz may be of limited benefit.

V. CONCLUSION

These findings show that cross-talk signals can be measured accurately using the two methods to give equivalent results. This is significant since accurate measurements of phase and level at the cochleae over a wide frequency range have not been previously possible. It is these values that are required for implementing cross-talk cancellation.

The two-BT method is potentially applicable in a clinical population with conductive hearing loss as it does not employ earphones. Unfortunately, participants found the two-BT method more challenging to perform when compared to the one-BT method. A further drawback of the two-BT method is that it can be very challenging to perform reliably at frequencies less than 1.5 kHz. However, there is less potential to implement cancellation at these frequencies, making such measurement relatively unimportant.

The one-BT technique (similar to the method Békésy described in 1947) can be used over the full frequency spectrum but is not clinically applicable to a conductive hearing loss population (since earphones are required) and takes longer to perform than the two-BT method. Further research is needed to investigate methods of making the two-BT procedure easier and faster to perform.. If employed in bilateral BCHA users, this could have significant benefits in terms of speech understanding in background noise as well as sound localization.

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