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

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21 Abstract

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

37 I. INTRODUCTION

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

50 Rowan and Gray (2008) proposed a model, which showed that if the phase and level of sound
51 arriving at each cochlea from both BTs are known then this would allow for the potential
52 development of a cross-talk cancellation system. A system such as this could be used in
53 bilateral BCHA patients to restore the interaural level difference (Liao, 2010), a key component
54 for effective binaural hearing (Majdak et al., 2013). The ability to achieve cross-talk
55 cancellation relies on an increased understanding of the transfer functions between each bone
56 transducer and each cochlea, as well as understanding how this varies between patients (Zurek,
57 1986).

58 A common method for investigation of level is via threshold measurements in patients
59 with SSD to calculate transcranial attenuation (TA) (Nolan and Lyon, 1981). Transcranial
60 attenuation can be defined as the difference in thresholds between ipsilateral and contralateral
61 BT placement in an SSD patient (Stenfelt, 2012). This method of calculation makes several

62 assumptions, including assuming equal coupling and positioning on both mastoids, as well as
63 skull symmetry with the same resonance and antiresonance properties on both sides. However,
64 it is well known that there can be significant asymmetry in the skull on the right and left sides
65 (Wismer and O'Brien, 2010). Therefore, these assumptions may be useful for elucidating
66 appropriate bone conduction masking levels in audiological testing, but not for calculating the
67 precise interaural level difference in an individual patient. Since level can be higher at the
68 cochlea contralateral to the BCHA, it can be misleading to describe relative sound levels as
69 attenuation, so we will use the term interaural level difference (ILD). We have previously
70 demonstrated that it is possible to accurately measure ILD and interaural phase difference
71 (IPD) reaching the cochleae from a single BT in participants with binaural hearing (McLeod
72 and Culling, 2017).

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

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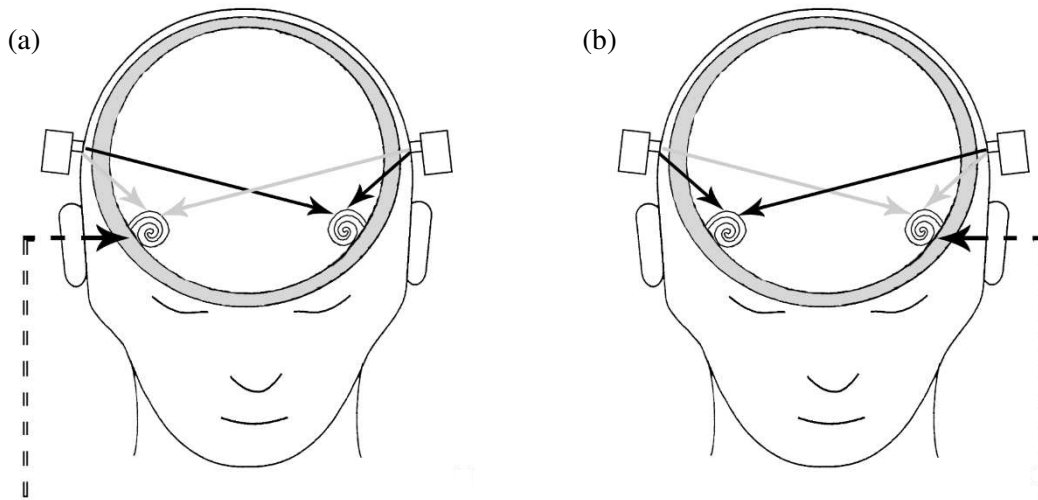


FIG 1 Panels (a) and (b) illustrates sound cancellation at the cochlea by interaction of the two BTs by destructive interference (black arrows). Panel (a) showing cancellation at the left cochlea and (b) at the right cochlea. The signals following interaction of the two adjusted BT signals (gray arrows).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

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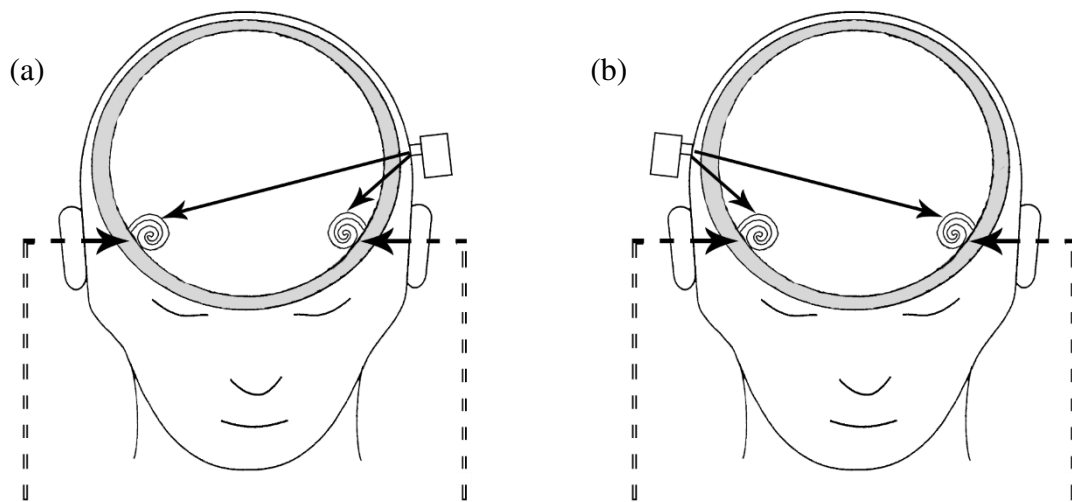


FIG 2 Panels (a) and (b) illustrate cancellation of a single left sided (a) and right sided (b) BT using ER2 earphones.

100 **II. METHODS**

101 **A. Apparatus**

102 Matlab™ 2012 software was used to generate pure tones at a sampling rate of 44.1 kHz over
103 four channels with the ability to vary the level and phase of each channel independently. An 8-
104 channel Echo Darla 24/96 DAC passed signals through an 8-channel Behringer Powerplay Pro-
105 8 Amplifier to Etymotic ER2 insert earphones and two Radioear™ B71 BTs for BC mastoid
106 stimulation. To minimize differences in BT placement between experimental sittings for the
107 same participant and between different participants, specially adapted lens-less glasses were
108 used which had attachments behind the ears holding both BTs in position. The glasses allowed
109 lower variation in BT placement as the superior portions of both pinnae and the bridge of the
110 nose were effectively used as a fixed-point reference tripod for the glasses to rest on. The
111 attachment for the BT onto the glasses positioned the BT 55mm behind the opening of the
112 external auditory canal. This is a typical surgical placement position (Battista and Ho, 2003;
113 Stenfelt et al., 2000). Testing was performed in a single-walled sound attenuating booth
114 (Industrial Acoustics Company) within a sound deadened room.

115 **B. Participants**

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

121 **C. Testing procedure**

122 The following experimental methodology was approved by Cardiff University Psychology
123 Department Ethics Committee. Prior to performing the outlined testing procedure, each

124 participant undertook at least 8 hours of practice sessions. In these sessions, participants
125 practiced cancellation of a pure-tone signal from a BT with ER2 earphones via adjustment of
126 the phase and level of each earphone independently. Participants also attempted multiple
127 frequencies between 0.5-8 kHz using the two-BT technique described below. The aim of this
128 extensive practice was twofold. Firstly, it was used to determine at which frequencies
129 participants could reliably perform the task and secondly for the participants to be familiar with
130 the task so that results of cancellation were reliable. It emerged that participants found the two-
131 BT task very challenging at frequencies below 1.5 kHz and consequently this was the lowest
132 test frequency chosen for the data collection sessions.

133 After deep insertion of ER2 earphones, the two BTs were placed on the left and right
134 mastoids, and held in place by adapted lens-less glasses as shown in [FIG 3](#). An elasticated
135 material band was then placed over the participant's head and the BTs achieving a pressure of
136 2.5-3N as described by Reinfeldt, Ostli, Håkansson, & Stenfelt (2010).



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

139 The one-BT method was used first. A pure tone was presented via the BT. A second
140 pure tone, 1 Hz higher than the tone from the BT was presented via the ipsilateral earphone. In

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

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

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

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

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

186 Once signal cancellation was completed in the left ear using two BTs, the quality of the
187 cancellation at that ear was verified in the following way. The sound at the right ear was also
188 cancelled using the earphone in the right ear. This was performed by first matching the
189 earphone level with that of the combined BT signals using the beating technique. Level and

190 phase at the earphone were then adjusted as before in order to cancel the entire signal. If
 191 participants had achieved cancellation throughout, then no signal would be audible at either
 192 ear, despite both bone transducers and a single earphone producing a pure tone. Feedback on
 193 the relative level of cancellation was collected using a grading system shown in Table I. The
 194 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)

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Table I. Grading system post attempted cancellation

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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

208 technique of 3 or greater. This included performing cancellation using the one- and two- BT
209 technique on the left and right side.

210 **D. Calculations**

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

220

221 FIG 4

222

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

226

227 FIG 4

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

231

232 FIG 4

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

$$236 \quad \alpha_L^L - \alpha_L^R = A_L \quad (1)$$

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

$$240 \quad \varphi_L^L - \varphi_L^R + \pi = \Phi_L \quad (2)$$

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

$$246 \quad \alpha_R^R + \alpha_L^L - \alpha_L^R = \text{Source gain} \quad (3)$$

247 The required phase shift of sound at the left BT for cancellation at the right cochlea is $\varphi_L^L -$
 248 $\varphi_L^R + \pi$ thus the phase shift from the left microphone to the right cochlea in that case is given
 249 by:

$$250 \quad \varphi_R^R + \varphi_L^L - \varphi_L^R + \pi = \text{Source phase shift} \quad (4)$$

251 The signals from left BT which have been shifted by phase (Φ_L) and level (A_L) can be
 252 combined with the unchanged signal from the right BT at the right ear by vector summation to

253 give the predicted phase and level of the resultant signal at the right ear. Calculation of the x, y
 254 components of the resultant vector are shown in Equations 5 and 6.

$$255 \quad \cos(\varphi_R^R + \varphi_L^L - \varphi_L^R + \pi) \times 10^{\frac{\alpha_L^L - \alpha_R^L - \alpha_R^R}{20}} + \cos(\varphi_R^L) \times 10^{\frac{\alpha_L^R}{20}} = x \quad (5)$$

256

$$257 \quad \sin(\varphi_R^R + \varphi_L^L - \varphi_L^R + \pi) \times 10^{\frac{\alpha_L^L - \alpha_R^L - \alpha_R^R}{20}} + \sin(\varphi_L^R) \times 10^{\frac{\alpha_L^R}{20}} = y \quad (6)$$

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

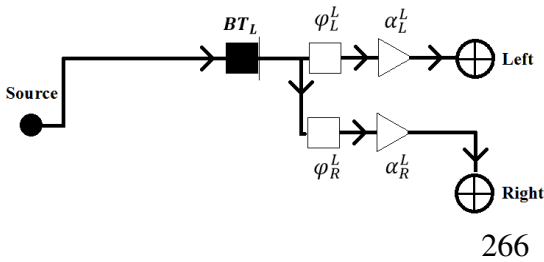
$$260 \quad \log_{10}(\sqrt{x^2 + y^2}) = \alpha_R \quad (7)$$

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

$$264 \quad \text{atan2}(x, y) = \varphi_R \quad (8)$$

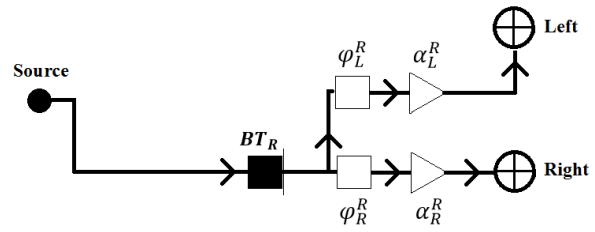
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(a)



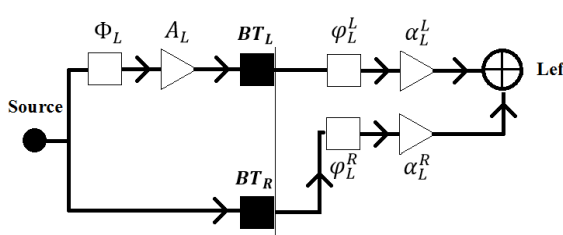
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(b)



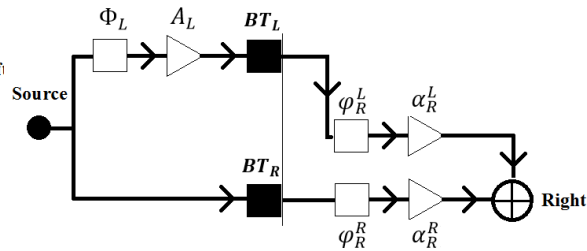
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(c)



268

(d)



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270 *FIG 4 Illustrations of cross-talk cancellation modified from Rowan and Gray (2008) and Zurek (1986).*
 271 *(a) Model of cross talk cancellation using two BTs (see text for details). (b) Model of left-BT stimulation with*
 272 *cancellation at the left and right ear. (c) Model of right-BT stimulation with cancellation at the left and right*
 273 *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.

274 E. Data comparison methodology

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

279 To minimize the effect of participant error on the evaluation of the equivalency of the
 280 two techniques, possible erroneous results were filtered. This was primarily motivated by the
 281 difficulty of the two-BT task, which meant that on some occasions participants could hear the
 282 tone again at the target cochlea after the contralateral sound was cancelled by the ER2
 283 earphones. Filtering was achieved via a two-step process. First, participants performed two-
 284 BT cancellation until they achieved four results with a cancellation score of 3 or more. Scores

285 of less than three were discarded. Second, via calculation of the median phase from the
286 remaining results at the cancellation cochlea in the two-BT technique. The three results closest
287 to the median were then included for further analysis. The same method was used in the one-
288 BT technique in order to filter spurious results (although they were less common than in the
289 two-BT technique). Thus, twelve results, (three from each side in the one-BT task) and a further
290 six results from the two-BT method (three from each side) were available for comparison at
291 each of the test frequencies for the three participants. The one-BT method results were then
292 paired (one left BT and one right BT). The paired phase and level results were utilized in
293 Equations 1-6 in order to predict the two-BT phase and level results necessary for cancellation
294 at the left and right cochlea from the one-BT results. The difference between predicted results
295 was then compared to measured results. The mean difference from six results (three from left
296 and three from right cancellation) was calculated for each participant at each frequency.

297 **III. RESULTS**

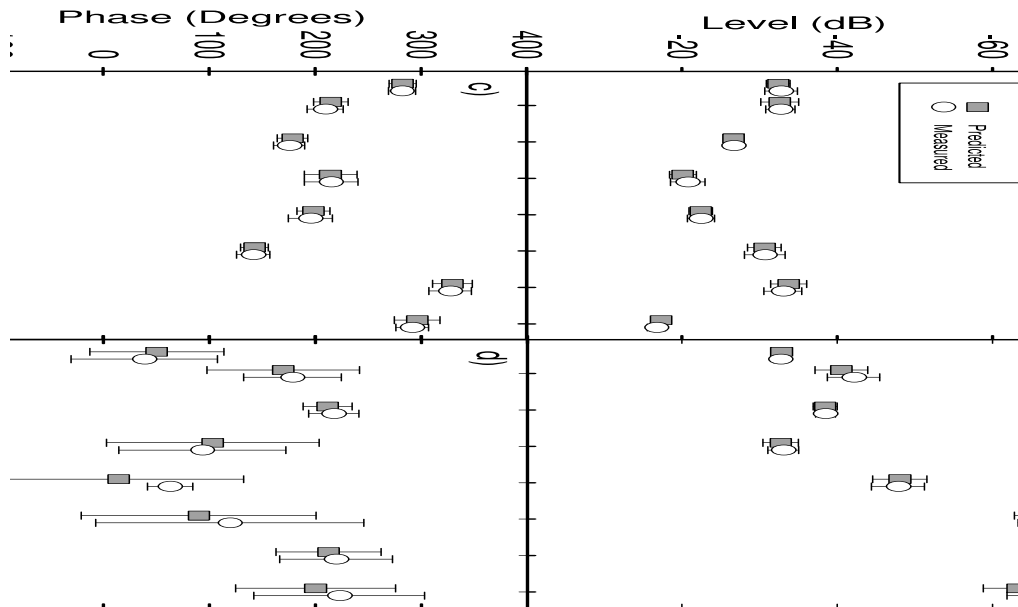
298 **A. Number of attempts needed at each frequency**

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

302 **B. Level difference between techniques**

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

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



311

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

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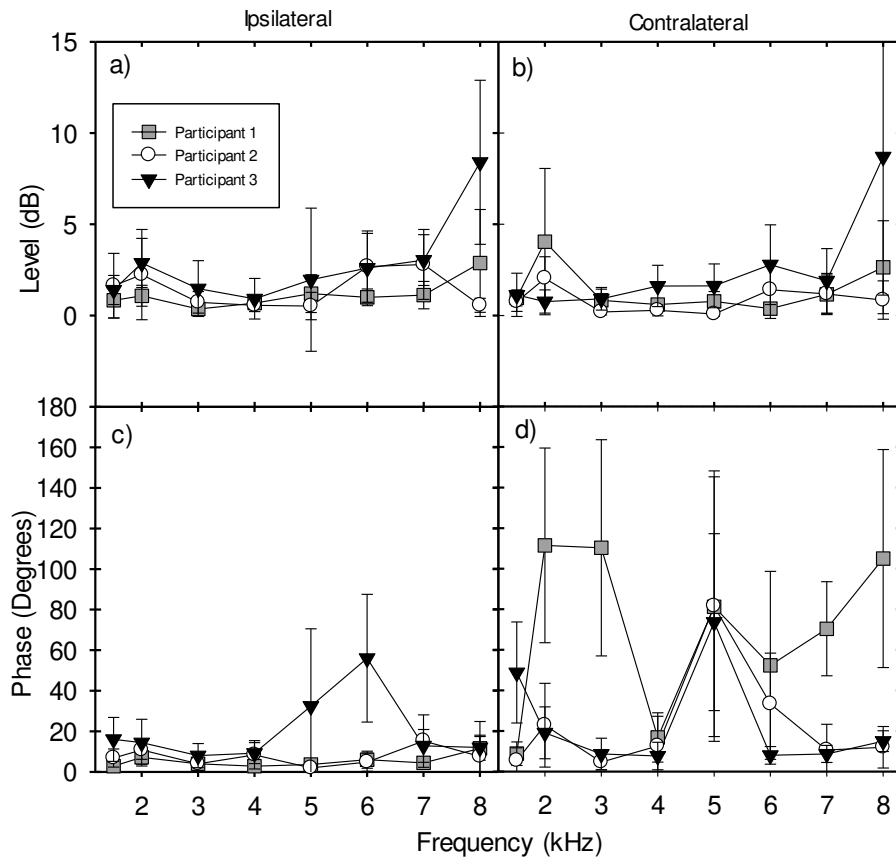
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317 **FIG 6** shows mean differences in phase and level as well as standard deviation of six
 318 comparisons actual and predicted result. **FIG 6a** shows the mean difference between
 319 techniques for each of the three individual participants for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

323 all frequencies was 1.81 dB. The highest frequencies had the greatest difference between
 324 techniques.

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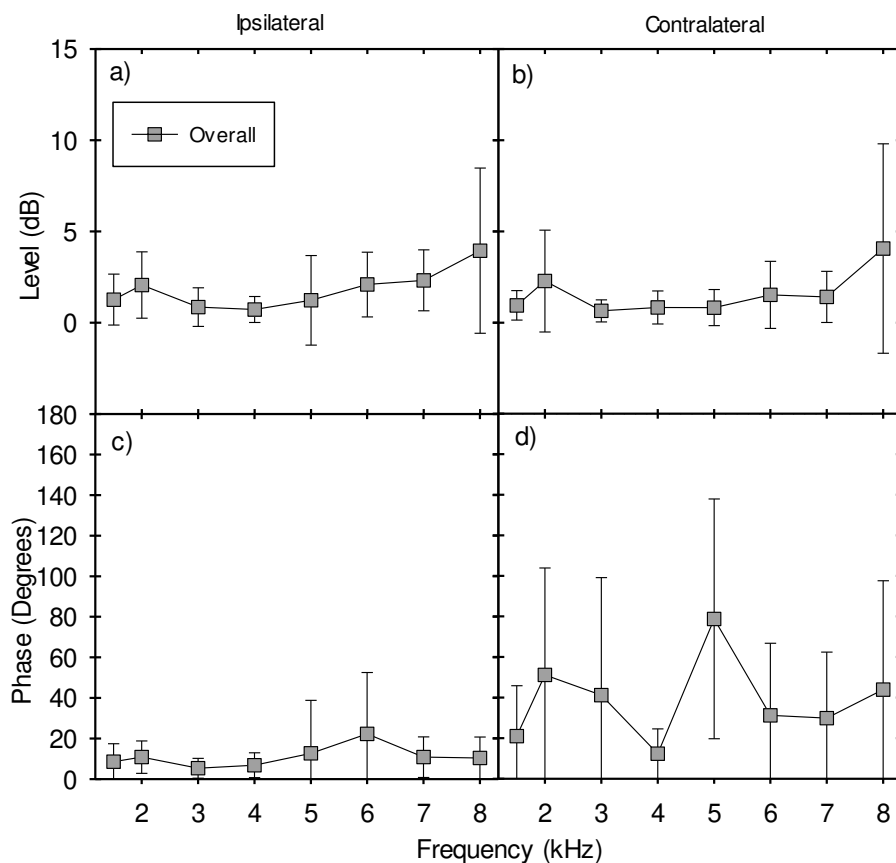
327 *FIG 6* Difference between the predicted level and phase using the one- and two-BT techniques for each
 328 participant. Error bars show the standard deviation of the differences between the two techniques ($n=6$ per
 329 frequency result).

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

335 C. Phase difference between techniques

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

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340

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

343 The phase-difference results in the contralateral cochlea had the greatest variation ([FIG 6](#)[FIG](#)
 344 [6d](#) and [FIG 7](#)[FIG-7d](#)). All participants were found to have a large difference in results from the
 345 two techniques at 5 kHz when compared to other frequencies. There was a mean difference of
 346 78.8° at this frequency and 38.4° overall. A paired two-tailed t-test showed that the phase
 347 differences in the cancellation cochlea were smaller than those in the contralateral cochlea
 348 ($p=0.01$).

349 **IV. DISCUSSION**

350 **A. Ipsilateral level and phase**

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

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

368 There are two possible explanations for why some participants found the task difficult
369 at particular frequencies. We have previously demonstrated that over a 0.3 kHz frequency
370 range there may be up to a 20 dB difference in the attenuation of sound at a given cochlea
371 (McLeod and Culling, 2017). Stenfelt et al (2000) described the frequencies over which these
372 large variations occur as areas of antiresonance. If one of these antiresonance frequencies were
373 close to the test frequency, then this would cause a large disparity in levels reaching the target

374 cancellation cochlea from each of the BTs. The large level difference makes the task
375 significantly harder to achieve, as level matching has to occur before phase changes between
376 the two BTs will cause enough destructive interference to induce lateralization. Another
377 situation in which the two-BT task can be challenging is when there is little or no IPD between
378 the two cochleae for each BTs. Thus, when one cochlea is cancelled there is also a degree of
379 cancellation at the opposite cochlea. This makes the task difficult, because a very small change
380 in phase can cause lateralization to change from one cochlea to the other. The most challenging
381 situation to encounter in the two-BT task is a combination of a small IPD and large level
382 difference.

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

398 needed for cancellation at other frequencies. Again this would make the psychoacoustic task
399 much easier to perform at multiple frequencies.

400 **B. Contralateral level and phase**

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

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

423 We have shown that there greater errors in the predicted and actual phase results at the
424 contralateral cochlea when compared to the ipsilateral. We believe this is primarily caused by
425 frequencies where there is little IPD. In such instances, small discrepancies between the
426 cancellation results of the one and two-BT techniques can result in large changes in the phase
427 at the contralateral cochlea. One instance where this is particularly noticeable is close to an ill
428 condition (partial destructive interference also at the contralateral cochlea). At these
429 frequencies, a small change in the two-BT technique can make a very large change in both the
430 phase and level at the contralateral cochlea. We believe that this is why overall the ipsilateral
431 phase and level results will always be more accurate than the contralateral. Fortunately,
432 knowledge of the contralateral phase of the resultant signal after cross-talk cancellation is of
433 less functional use. Since it is the ILD signal, which is the target of modification. We have
434 already shown that attempted manipulation of the phase differences at frequencies lower than
435 1.5 kHz may be of limited benefit.

436 V. CONCLUSION

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

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

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

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