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Supplementary Digital Content 2

Levels of function reported with the HUI3 and the YBHRQL

(This document is supplementary to the paper by Summerfield, Kitterick, and Goman entitled 'Development and critical evaluation of a condition-specific preference-based measure sensitive to binaural hearing in adults: the York Binaural Hearing-related Quality of Life System'.)

1. Introduction

1.1. This Supplementary Digital Content describes analyses of the levels of function that were reported by participants in Experiment 2 using the YBHRQL, HUI3 and EQ-5D-3L. There are six aims: first, to present the data which underpin the values of health utility and binaural utility that are reported in the paper; second, to throw light on the reasons for differences in utility between groups and between conditions; third, to compare the capacity of the HUI3 and YBHRQL to register differences in binaural hearing; fourth, to compare the sensitivity of the YBHRQL and the HUI3 to pain/discomfort which has been reported to be a short-term side-effect of implantation; fifth, to report additional analyses comparing the gains in utility measured with the YBHRQL, the HUI3, and the EQ-5D-3L; and sixth, to generate hypotheses for the size of the loss of quality of life due to the imperfect hearing associated with unilateral implantation, and the for the sizes of the gains in quality of life due to improved hearing associated with the use of a second device.

2. HUI3

2.1. Levels of function

(1) Table 1 (from Horsman et al. 2003) lists the descriptions of the levels of the eight attributes of the HUI3. For each of four attributes – *Emotion, Ambulation, Dexterity,* and *Pain* – a single multiple-choice question determines the level. For these attributes, the wording of the descriptions matches the wording of questions with only minor differences. For each of four other attributes – *Vision, Hearing, Speech,* and *Cognition* – two multiple-choice questions are posed. For these four attributes, classification functions map the responses to the two questions onto a single level of the attribute. The description of the level combines the wording of the two questions.

(2) The resulting levels of the *Hearing* attribute are such that only a subset would be expected to characterize the functional hearing of bilaterally severely-profoundly deaf candidates for implantation or users of implants. Levels 1, 2, and 4 would not be used because each of them entails hearing in noise and/or quiet without using a hearing aid, but someone with that ability would not be a candidate for implantation. Instead, one would expect Levels 3, 5, and 6 to characterize the functional hearing of the majority of bilaterally severely-profoundly deaf people. As a result, Level 3 defines the upper limit of the HUI3's sensitivity to variation in the functional hearing of most users of implants.

(3) Those expectations are borne out in Table 2 which lists the levels of the *Hearing* attribute reported by 147 patients who received unilateral implants in the UK (Summerfield & Barton 2019). Levels 3, 5, or 6 were used to report the functional hearing of 139/147 (95%) before implantation and 145/147 (99%) after implantation. Of particular importance to considerations of bilateral implantation, 107 of the 147 patients placed themselves at Level 3 after unilateral implantation. Given that Levels 1 and 2 are unattainable, those patients would not have had the headroom to report any improvement in hearing were they to receive a second implant. This ceiling effect

imposes a hard limit on the sensitivity of the HUI3 *Hearing* attribute to bilateral implantation.

(4) Against the background of those considerations, we now discuss the levels of function reported by participants in Experiment 2.

2.2. Unilateral Group

(1) The members of the Unilateral Group completed the HUI3 under nominally identical conditions on two successive days. On each day, they were asked to consider their function over a two-week time span: "think about your health and your ability to do things on a day-to-day basis, during the past two weeks".

(2) Table 3a lists the levels of function reported on the first day of testing. There is one line of data for each participant. Following an identifier (e.g. UNI01) are the levels of the eight attributes. A value of one represents good function while increasingly large numbers represent increasingly poor function. On the far right is the index value from the HUI3 (the value of health utility). The maximum possible value of the index is unity, corresponding to the state of full health. A value of zero corresponds to the state of being dead.

(3) Table 3b lists corresponding data obtained on the second day of testing and Table 3c lists the differences between the Day-1 and Day-2 values calculated by subtracting the Day-1 value from the Day-2 value. A *negative* difference for an attribute in Table 3c means that function was reported as better on Day 2 than Day 1, while a *positive* difference in the HUI3 Index means that health utility was higher on Day 2 than Day 1. Instances have been highlighted in green where function was better, or health utility was higher, on Day 2 than Day 1. Conversely, instances have been highlighted in amber where function was worse, or health utility was lower, on Day 2 than Day 1.

(4) The members of the Unilateral Group undertook performance tests, and completed questionnaires, while thinking about themselves in the same condition on both days – using a unilateral implant with no stimulation of the contralateral ear. In principle, their levels of function and resulting values of health utility should have been the same on both days. In that case, Table 3c would have contained only zeros. In practice, the reported levels and resulting values of health utility are similar, but not identical. Seven of the 64 levels (=8 attributes x 8 participants) differ between Day 1 and Day 2 and only four of the eight members of the Unilateral Group were assigned the same health utility on both days. Three of the other four members were assigned a lower value on Day 2 than Day 1, while one was assigned a higher value.

(5) The most striking differences are in the *Hearing* attribute where three participants (UNI02, UNI06, UNI07) shifted between levels 3 and 5, in one direction or the other. Both levels are characterized by being "able to hear what is said in a conversation with one other person in a quiet room with a hearing aid and/or cochlear implant(s)". The levels are distinguished by whether the participant declares that they are, or are not, "able to hear what is said in a group conversation with at least three other people with a hearing aid and/or cochlear implant(s)".

(6) There are at least three reasons why different levels of function might be reported from one day to the next when respondents' mode of aiding did not change. First, a participant may judge that they are close to the boundary between being able, and not being able, to perform the function; the ability which they report reflects random fluctuation in their judgement. Second, the questions about hearing are ambiguous insofar as it is not clear whether the "ability to hear what is said" in a conversation

refers to understanding speech or to detecting speech. As a result, there may be confusion among the response options. Third, participants may not have complied fully with the instruction to consider their function over the preceding two weeks. Instead, they may have weighted their experience of listening on the day of testing more heavily than their experience over the preceding fortnight. Their experience may fluctuate from day to day with the result that they report different levels of function. Together, the three reasons generate noise in the decision process which may result in random differences in reports of function from day to day.

(7) In summary, responses to the HUI3 questionnaire can fluctuate from day to day, and such fluctuations can include the *Hearing* attribute. We cannot rule out the possibility that similar fluctuations affected the responses made by the Bimodal and Bilateral Groups.

2.3. Bimodal Group

(1) Tables 4a, 4b, and 4c list the levels of function reported by the Bimodal Group using one device (their implant on its own in Table 4a), or two devices (their implant with a contralateral acoustic hearing aid in Table 4b), and the differences calculated by subtracting the one-device values from the two-device values (Table 4c).

(2) Nine of the 72 levels (=8 attributes x 9 participants) differ between the one-device condition and the two-device condition. The level of function of the *Hearing* attribute improved for two members of the group and remained the same for the other seven members. Health utility improved for three members of the group, stayed the same for three, and worsened for three.

2.4. Bilateral Group

(1) Tables 5a, 5b, and 5c list the levels of function determined for the Bilateral Group using one device (their first implant on its own in Table 5a), or two devices (their two implants together in Table 5b), and the difference calculated by subtracting the one-device values from the two-device values (Table 5c).

(2) Seven of the 88 levels (=8 attributes x 11 participants) differ between the one-device condition and the two-device condition. The level of function of the *Hearing* attribute improved for four of the eleven members of the group and remained the same for the other seven members. Health utility improved for five members of the group, stayed the same for five, and worsened for one.

3. YBHRQL

3.1. Bimodal Group

(1) Tables 6a, 6b, and 6c list levels of the YBHRQL and the resulting 10- and 50-year values of binaural utility when members of the Bimodal Group considered their function using one device (their implant on its own in Table 6a) and two devices (their implant and a contralateral acoustic hearing aid in Table 6b), and the differences calculated by subtracting the one-device values from the two-device values (Table 6c).

(2) Of the 27 (=3 dimensions x 9 participants) comparisons of level, 10 show improvements, 16 show no change, and 1 shows a worsening. Binaural utility increased for six of the nine participants and did not change for the other three.

3.2. Bilateral Group

(1) Tables 7a, 7b, and 7c list corresponding data for the members of the Bilateral Group.

(2) Of the 33 (=3 dimensions x 11 participants) comparisons of level, 25 show improvements, 7 show no change, and 1 shows a worsening. Binaural utility increased for all 11 members of the group.

4. Comparison of the HUI3 with the YBHRQL

4.1. Sensitivity to changes in hearing

(1) The main difference between the HUI3 and the YBHRQL is the greater consistency of improvement in binaural utility than health utility when patients used two devices rather than one. The difference is shown by the higher proportion of members of the Bimodal and Bilateral Groups whose binaural utility improved (.85 = 17/20) than whose health utility improved (.40 = 8/20) (McNemar's Test, p=.012, 2-sided). The same result is found if the comparison is restricted to measures of hearing, where the proportion whose binaural utility from the YBHRQL improved (.85 = 17/20) is greater that the proportion whose level of the *Hearing* attribute improved (.30 = 6/20) (McNemar's Test, p=.001, 2-sided).

(2) Four factors may have contributed to the difference. First, clearer questions in the YBHRQL than the HUI3 may result in less noise in the decision process. Second, finer granularity among levels of hearing function in the YBHRQL than the HUI3 may allow smaller improvements to be registered. Third, the YBHRQL is less subject to a ceiling effect on hearing function than is the HUI3. Fourth, in principle, the YBHRQL detects changes on three dimensions relevant to binaural hearing whereas the HUI3 detects changes on only one – speech in noise.

(3) Evidence compatible with the fourth factor is reported in the paper where it was noted that values of health utility from the HUI3 correlated significantly with the performance measure of speech in noise, but not with the performance measure of localization. In comparison, values of binaural utility from the YBHRQL correlated significantly with both measures.

(4) We conducted a further test of the hypothesis by asking which of the three dimensions of the YBHRQL best predicted whether a participant placed themselves at level 3 or level 5/6 of the *Hearing* attribute of the HUI3. The dependent variable was the level of the *Hearing* attribute (Level 3 or Level 5/6). With 20 participants each completing the HUI3 questionnaire twice (once when considering their function with one device and once when considering their function with two devices), there were 40 items of data to predict. The predictor variables were the levels of the three dimensions of the YBHRQL. The logistic regression model was statistically significant, chi-squared(3) = 23.950, p<.001. The model explained 68.7% (Nagelkerke R^2) of the variance in the level of the *Hearing* attribute and correctly classified 90.0% of cases. Only one predictor was significant: a better level on the YBHRQL Speech-in-Noise dimension was associated with an increased likelihood of being at a better level (i.e. Level 3 rather than Level 5 or 6) of the HUI3 *Hearing* attribute (Wald(1) = 4.064, p=.044); in comparison Wald(1) = 2.228, p = .136 for the Localization dimension and Wald(1) = .079, p = .778 for the Effort & Fatigue dimension).

(5) The results of this analysis corroborate the rather obvious conclusion that the response of the HUI3 to the change from monaural to binaural hearing is determined primarily by the extent of its sensitivity to the ability to understand speech in noise.

(6) We then tested the hypothesis that the dimension of the YBHRQL which is the best predictor of whether hearing is monaural or binaural is the Localization dimension rather than the Speech-in-Noise dimension. We performed a second binary logistic

regression. The dependent variable was the number of devices (two or one) and the predictor variables were the levels of the three dimensions of the YBHRQL. The logistic regression model was statistically significant, chi-squared(3) = 17.993, p<.001. The model explained 48.3% (Nagelkerke R^2) of the variance in the number of devices and correctly classified 75.0% of cases. Only one predictor was significant: a better level on the YBHRQL Localization dimension was associated with an increased likelihood of using two devices rather than one (Wald(1) = 7.412, p=.006); in comparison Wald(1) = .879, p = .349 for the Speech-in-Noise dimension and Wald(1) = .126, p = .723 for the Effort & Fatigue dimension).

(7) The results of this second analysis are compatible with the idea that the greater benefit of binaural hearing is an improvement in the ability to localize rather than to improve speech intelligibility in noise. The HUI3, however, is primarily sensitive to changes in the ability to perceive speech in noise rather than changes in the ability to localize. That, therefore, is a further limitation to the sensitivity of the HUI3 to improvements in binaural hearing.

4.2. Sensitivity to pain

(1) Of the changes in the level of attributes of the HUI3 other than *Hearing,* the one with the greatest potential importance is the shift by two members of the Bilateral Group (BIL03, BIL05) from Level 1 of the *Pain* attribute in the one-device condition to Level 2 in the two-device condition. Level 1 is described as "Free of pain and discomfort". Level 2 is described as "Mild to moderate pain or discomfort that prevents no activities". We do not know whether this change reflects a genuine increase in pain/discomfort or is the result of noise in the decision process. We note, however, that Summerfield and Barton (2019) found that significant increases in pain associated with unilateral implantation were found in responses to generic PBMs. It is possible, therefore, that the increase in pain reported by BIL03 and BIL05 is a real effect.

(2) Given that a concern about condition-specific PBMs is that they may be insensitive to negative side effects, we examined whether the YBHRQL is sensitive to variation in pain and discomfort. To do that, we performed a third binary logistic regression analysis. The dependent variable was the level of the *Pain* attribute in the HUI3 (Level 1 vs any other level) and the predictor variables were the levels of the three dimensions of the YBHRQL. The logistic regression model was not significant, chi-squared(3) = 1.345, p<.719. The model explained only 4.4% (Nagelkerke R^2) of the variance in the level of the Pain attribute and correctly classified only 57.5% of cases.

(3) This result shows that the YBHRQL is not sensitive to one of the side effects of implantation. It should be emphasized that increases in pain/discomfort occur for only a minority of patients in those studies where changes in pain/discomfort have been reported (Summerfield et al., 2006; Summerfield & Barton, 2019). Nonetheless, the insensitivity of the YBHRQL to changes in pain and discomfort limits the scope of the YBHRQL to influence resource-allocation decisions, as discussed in the General Discussion of the paper.

5. Gains in utility

5.1. A primary aim of creating a PBM that is specific to a condition is to overcome the limited sensitivity of generic PBMs to treatments for that condition. A key test of the YBHRQL was whether it recorded a larger gain in utility than either the EQ-5D-3L or the HUI3 when considering the difference between listening with two devices or one. In the paper, we

reported the results of Wilcoxon signed-rank tests of that hypothesis. Here, we compare the results of those non-parametric tests with results from additional tests.

(1) Table 8 lists the gains in utility (the binaural advantages) between listening with one device and listening with two devices reported by individual participants in the Bimodal Group using the YBHRQL [Column A], HUI3 [Column B], and EQ-5D-3L [Column C]. A positive value means that the participant reported a higher value of utility when listening with two devices. The difference between the gain recorded with the YBHRQL and the gain recorded by the HUI3 is listed in Column D, and with the EQ-5D-3L in Column E. At the foot of each column are the median, inter-quartile range, mean, and 95% confidence interval of the mean for each measure. The latter two statistics were estimated by bootstrapping (3,000 samples per analysis, bias-corrected and accelerated). Table 9 lists corresponding data for the Bilateral Group.

(2) For the Bimodal Group, the gain recorded by the YBHRQL (median=.020, IQR .000 to .046) [Column A in Table 8] is not larger than the gain recorded by the HUI3 (.000, -.046 to .191) [Column B] when assessed by a Wilcoxon Signed Ranks Test (N=9, z=.280, exact p = .422, 1-tailed) or the gain recorded by the EQ-5D-3L (.000, .000 to .075) [Column C] (N=9, z=.169, exact p = .469, 1-tailed). Considering the statistics estimated by bootstrapping, the confidence interval of the mean gain in utility from the YBHRQL [Column A] does not include zero, so the gain can be considered significant, whereas the gains in utility from the HUI3 [Column B] and EQ-5D-3L [Column C] both do include zero, so they cannot be considered significant. Turning to the differences between the gain recorded by the YBHRQL and the gains recorded by the HUI3 [Column D] and EQ-5D-3L [Column E], the confidence interval of the mean difference in gains includes zero in both cases. Thus, for the Bimodal Group, the results of the parametric tests underpinned by bootstrapping and the non-parametric tests are compatible in providing no evidence that the YBHRQL recorded a larger gain in utility between one and two devices than did the HUI3 or the EQ-5D-3L.

(3) For the Bilateral Group, the gain recorded by the YBHRQL (median=.107, IQR .035 to .162) [Column A in Table 9] falls short of being significantly larger than the gain recorded by the HUI3 (.000, .000 to .170) [Column B] when assessed by a Wilcoxon Signed Ranks Test (N=11, z=1.689, exact p=.051, 1-tailed), but is significantly larger than the gain recorded by the EQ-5D-3L (.000, .000 to .000) [Column C] (N=11, z=2.312, exact p = .009, 1-tailed). Considering the statistics estimated by bootstrapping, the confidence intervals of the mean gains recorded with the YBHRQL and the HUI3 both exclude zero, so each gain can be considered significant, whereas the confidence interval of the mean gain recorded by the EQ-5D-3L includes zero, so the gain cannot be considered significant. Turning to the difference between the gain recorded by the YBHRQL and the gain recorded by the HUI3 [Column D], the confidence interval of the mean difference includes zero, while the corresponding mean difference in comparison with the EQ-5D-3L [Column E] excludes zero. For the Bilateral Group, therefore, there is good evidence that the YBHRQL recorded a larger gain in utility between one and two devices than did the EQ-5D-3L, whereas there is uncertainty about the relative sizes of the gains recorded by the YBHRQL and the HUI3. The difference between the gains of .044 is neither significant, nor does it fall within the range of ±.03 which would be the first requirement for the two gains to be considered statistically equivalent (Lakens 2017; Supplementary Digital Content 5).

(4) The comparison of the gains is a test of the difference between two differences. In simulations, we estimated that with a two-tailed alpha of 5% (the Type 1 error rate)

and 11 participants (the number of members of the Bilateral Group), the probability of failing to reject the null hypothesis under the alternative hypothesis (beta, the Type II error rate) was 76%. To achieve a conventional value of beta of 20% would require 48 participants. In summary, therefore, Experiment 2 was under-powered to provide a reliable test of the hypothesis that the gain in binaural utility measured with the YBHRQL is larger than the gain in health utility measured by the HUI3.

6. Losses and Gains in Quality of Life

6.1 Here, we use data from the YBHRQL and the HUI3 to converge on estimates of the reduction in quality of life that can be attributed to the loss of hearing associated with unilateral implantation, and the increase in quality of life that can be attributed to the additional hearing associated with using a second device. The purpose in making these estimates is to identify hypothesis that might be tested in a study of bimodal aiding and bilateral implantation with greater statistical power than was possessed by Experiment 2.

(1) The YBHRQL is intended to provide a relatively pure measure of the contribution of binaural hearing to quality of life. The HUI3 in comparison provides an overall measure of health-related quality of life which includes a contribution from hearing. In the paper, we were concerned to establish whether the YBHRQL exaggerated the loss of quality of life due to impaired hearing. To that end, we compared the losses of utility recorded by the YBHRQL and the HUI3. We did that by using data from the HUI3 to estimate the loss of quality of life relative to full health that can be attributed solely to imperfect hearing in three states: using a unilateral implant, using bimodal aiding, and using bilateral implants. We then made comparisons with analogous estimates made with data from the YBHRQL.

(2) The average health utility reported by the 28 participants in Experiment 2 with the HUI3 when they used their first or only implant was .664. Treating that value as a proportion, and converting it to a percentage (66.4%), would mean that the average loss of quality of life relative to full health experienced by users of unilateral implants was 33.6% (=100-66.4). It would be inappropriate to attribute all of that loss to less-than-perfect hearing, given that 26 of 28 participants reported less than perfect vision, and 17 of 28 reported less than perfect function on at least one attribute other than vision or hearing. Those age-related impairments added to impaired hearing in lowering the value of their health utility.

(3) In the paper, we proposed that an estimate of the loss of health utility attributable to impaired hearing could be obtained from the HUI3 by subtracting *the value of health utility with all attributes at their observed levels* from *the value of health utility with the hearing attribute at its highest level and all other attributes at their observed levels.* We proposed that a comparable measure could be obtained from the YBHRQL by subtracting the observed value of binaural utility from the highest attainable value which is 0.96. Table 10 lists these values for individual participants together with summary statistics (medians, inter-quartile ranges, means, and 95% confidence intervals, with the latter two values estimated by bootstrapping).

(4) Consider first the estimates of the loss of utility in the condition where participants used their first or only implant. Summary statistics for the whole group of 28 participants are included at the bottom of Column A for estimates derived from the HUI3, and at the bottom of Column B for estimates derived from the YBHRQL. The median losses of .148 (HUI3) and .174 (YBHRQL) do not differ significantly (Wilcoxon Signed Ranks Test, N=28, z=1.586, exact p=.115, 2-tailed). This analysis is reported in the paper to provide

evidence that the YBHRQL does not exaggerate losses of utility when compared with the HUI3. The mean losses estimated by bootstrapping are .197 (HUI3) and .178 (YBHRQL). The difference between them is .020 with a confidence interval which includes zero (-.043 to .002). Thus, the evidence from bootstrapping supports the conclusion of the non-parametric analysis that the YBHRQL does not exaggerate the size of losses of utility due to impaired hearing.

(5) If the data of the individual groups are analyzed, no significant differences are found between estimates of losses from the HUI3 and YBHRQL. Thus, there is consistent evidence that the HUI3 and YBHRQL provide similar estimates of the loss of utility attributable solely to impaired hearing.

(6) Turning to the size of the losses, and acknowledging that there is variation between the groups and some differences that are not statistically significant, the mean loss of utility attributable to impaired hearing when participants used their first or only implant is about 18 to 20 percentage points. The data for the Bimodal Group show that bimodal aiding may reduce the loss by 3 percentage points. The data for the Bilateral Group show that bilateral implantation may reduce the loss by 6 to 10 percentage points.

(7) The latter reduction is large in relation to estimates which can be derived from the published literature. If the gain in health utility measured with the HUI3 in each of the studies in Table 1 in the paper is weighted by the number of participants contributing, then the overall mean gain is .039, suggesting that a second implant reduces the loss by about 4 percentage points (i.e. between a fifth and a quarter).

(8) In summary, the data from Experiment 2 lead to the hypothesis that the loss of quality of life due to limitations in hearing with a unilateral implant amounts to 18 to 20 percentage points, of which up to a sixth is made up by bimodal aiding and between a quarter and a half may be made up by bilateral implantation.

7. Summary

7.1 Nine conclusions can be drawn from the data and analyses which are reported in this Supplementary Digital Content:

(1) Noise in the decision process adds a random element to the levels of HUI3 attributes reported by participants.

(2) The majority of patients who are candidates for implantation or users of implantation report that their hearing function is at one of only three of the six levels of the HUI3 *Hearing* attribute.

(3) The highest of these levels represents a ceiling above which a user of an implant could not report that they functioned.

(4) Two thirds of users of unilateral implants have reported that they function at the ceiling level, leaving no headroom for demonstrating an improvement in hearing function were their second ear to be stimulated.

(5) Some of the remaining users of unilateral implants move to the ceiling level – reflecting a change from being unable to understand speech in noise to being able to understand speech in noise – when their second ear is stimulated.

(6) A further limitation of the HUI3 is that it is primarily sensitive to changes in the ability to perceive speech in noise rather than changes in localization, whereas the ability to localize is more strongly associated with changes in binaural hearing.

(7) A limitation of the YBHRQL is that it is insensitive to differences in pain and discomfort which have been found in one study to be associated with implantation in the short term.

(8) Experiment 2 was underpowered to detect a significant difference between the gains in utility associated with bilateral implantation measured with the YBHRQL and the HUI3. An appropriately powered study would recruit at least 48 participants in each group.
(9) That study could also test the hypothesis that the loss of quality of life due to limited hearing associated with the use of only one implant amounts to 20 percentage points, of which up to 3 percentage points are restored by bimodal aiding and up to 10 percentage points by bilateral implantation.

8. References

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Table 1 Descriptions of the levels of function of the attributes of the HUI3 (from Horseman et al. 2003)[a]

ATTRIBUTE	LEVEL	DESCRIPTION
VISION	1	Able to see well enough to read ordinary newsprint and recognize a friend on the other side of the street, without glasses or contact lenses.
	2	Able to see well enough to read ordinary newsprint and recognize a friend on the other side of the street, but with glasses.
	3	Able to read ordinary newsprint with or without glasses but unable to recognize a friend on the other side of the street, even with glasses.
	4	Able to recognize a friend on the other side of the street with or without glasses but unable to read ordinary newsprint, even with glasses.
	5	Unable to read ordinary newsprint and unable to recognize a friend on the other side of the street, even with glasses.
	6	Unable to see at all.
HEARING	1	Able to hear what is said in a group conversation with at least three other people, without a hearing aid and/or cochlear implant(s).
	2	Able to hear what is said in a conversation with one other person in a quiet room without a hearing aid and/or cochlear implant(s), but requires a hearing aid and/or cochlear implant(s) to hear what is said in a group conversation with at least three other people.
	3	Able to hear what is said in a conversation with one other person in a quiet room with a hearing aid and/or cochlear implant(s), and able to hear what is said in a group conversation with at least three other people, with a hearing aid and/or cochlear implant(s).
	4	Able to hear what is said in a conversation with one other person in a quiet room, without a hearing aid and/or cochlear implant(s), but unable to hear what is said in a group conversation with at least three other people even with a hearing aid and/or cochlear implant(s).
	5	Able to hear what is said in a conversation with one other person in a quiet room with a hearing aid and/or cochlear implant(s), but unable to hear what is said in a group conversation with at least three other people even with a hearing aid and/or cochlear implant(s).
	6	Unable to hear at all.
SPEECH	1	Able to be understood completely when speaking with strangers or friends.
	2	Able to be understood partially when speaking with strangers but able to be understood completely when speaking with people who know me well.
	3	Able to be understood partially when speaking with strangers or people who know me well.
	4	Unable to be understood when speaking with strangers but able to be understood partially by people who know me well.
	5	Unable to be understood when speaking to other people (or unable to speak at all).
AMBULATION	1	Able to walk around the neighbourhood without difficulty, and without walking equipment.
	2	Able to walk around the neighbourhood with difficulty; but does not require walking equipment or the help of another person.
	3	Able to walk around the neighbourhood with walking equipment, but without the help of another person.
	4	Able to walk only short distances with walking equipment, and requires a wheelchair to get around the neighbourhood.
	5	Unable to walk alone, even with walking equipment. Able to walk short distances with the help of another person, and requires a wheelchair to get around the neighbourhood.
	6	Cannot walk at all.
DEXTERITY	1	Full use of two hands and ten fingers.
	2	Limitations in the use of hands or fingers, but does not require special tools or help of another person.
	3	Limitations in the use of hands or fingers, is independent with use of special tools (does not require the help of another person).
	4	Limitations in the use of hands or fingers, requires the help of another person for some tasks (not independent even with use of special tools).
	5	Limitations in use of hands or fingers, requires the help of another person for most tasks (not independent even with use of special tools).
	6	Limitations in use of hands or fingers, requires the help of another person for all tasks (not independent even with use of special tools).
EMOTION	1	Happy and interested in life.
	2	Somewhat happy.
	3	Somewhat unhappy.
	4	Very unhappy.
	5	So unhappy that life is not worthwhile.
COGNITION	1	Able to remember most things, think clearly and solve day to day problems.
	2	Able to remember most things, but have a little difficulty when trying to think and solve day to day problems.
	3	Somewhat forgetful, but able to think clearly and solve day to day problems.
	4	Somewhat forgetful, and have a little difficulty when trying to think or solve day to day problems.
	5	Very forgetful, and have great difficulty when trying to think or solve day to day problems.
	6	Unable to remember anything at all, and unable to think or solve day to day problems.
PAIN	1	Free of pain and discomfort.
	2	Mild to moderate pain that prevents no activities.
	3	Moderate pain that prevents a few activities.
	4	Moderate to severe pain that prevents some activities.
	5	Severe pain that prevents most activities.

[a]The original wording of questions about hearing included the words 'hearing aid' but not 'cochlear implant'. The wording has been changed in studies of unilateral cochlear implantation to 'hearing aid or cochlear implant' and in studies of bilateral cochlear implantation to 'hearing aid and/or cochlear implant(s)'.

Table 2 Numbers of patients who placed themselves each level of the *Hearing* attribute in the HUI3 before and after unilateral implantation (from Summerfield and Barton (2019), N=147) and with a unilateral implant and with two devices (from Experiment 2, N=20).

Level	Description	Summerfield & Barton (2019)		Experiment 2	
		Before implantation	With a unilateral implant	With a unilateral implant	With two devices
1	Able to hear what is said in a group conversation with at least three other people, without a hearing aid and/or cochlear implant(s).	3	-	-	-
2	Able to hear what is said in a conversation with one other person in a quiet room without a hearing aid and/or cochlear implant(s), but requires a hearing aid and/or cochlear implant(s) to hear what is said in a group conversation with at least three other people.	1	2	-	-
3	Able to hear what is said in a conversation with one other person in a quiet room with a hearing aid and/or cochlear implant(s), and able to hear what is said in a group conversation with at least three other people, with a hearing aid and/or cochlear implant(s).	11	107	13	18
4	Able to hear what is said in a conversation with one other person in a quiet room, without a hearing aid and/or cochlear implant(s), but unable to hear what is said in a group conversation with at least three other people even with a hearing aid and/or cochlear implant(s).	4	-	-	-
5	Able to hear what is said in a conversation with one other person in a quiet room with a hearing aid and/or cochlear implant(s), but unable to hear what is said in a group conversation with at least three other people even with a hearing aid and/or cochlear implant(s).	56	33	7	2
6	Unable to hear at all.	72	5	-	-

Table 3 Levels of attributes of the HUI3 reported by the Unilateral Group on Day 1 (Part A of the table), Day 2 (Part B), and the differences between Day 2 and Day 1 (Part C). Where the level of an attribute, or the HUI3 utility, was better (worse) on Day 2 than Day 1, the entry in Part C is highlighted with green (amber).

A. Day 1									HUI3
Participant	Vision	Hearing	Speech	Ambulation	Dexterity	Emotion	Cognition	Pain	utility
UNI01	2	3	1	1	1	1	3	1	0.765
UNI02	2	5	1	2	1	1	1	2	0.517
UNI03	2	5	2	1	1	2	4	3	0.292
UNI04	2	3	1	1	1	1	1	1	0.825
UNI05	2	3	1	1	1	1	3	2	0.720
UNI06	2	3	1	1	1	1	1	1	0.825
UNI07	2	3	1	1	2	3	4	3	0.350
UNI08	2	3	1	1	1	1	1	1	0.825
B. Day 2									HUI3
Participant	Vision	Hearing	Speech	Ambulation	Dexterity	Emotion	Cognition	Pain	utility
UNI01	2	3	1	1	1	1	3	1	0.765
UNI02	2	3	1	2	1	1	1	2	0.697
UNI03	2	5	3	1	2	2	4	2	0.265
UNI04	2	3	1	1	1	1	1	1	0.825
UNI05	2	3	1	1	1	1	3	2	0.720
UNI06	2	5	1	1	1	1	1	1	0.623
UNI07	2	5	1	2	2	3	4	3	0.187
UNI08	2	3	1	1	1	1	1	1	0.825
C. Difference: Day 2 – Day 1									HUI3
Participant	Vision	Hearing	Speech	Ambulation	Dexterity	Emotion	Cognition	Pain	Utility
UNI01	0	0	0	0	0	0	0	0	0.000
UNI02	0	-2	0	0	0	0	0	0	0.180
UNI03	0	0	1	0	1	0	0	-1	-0.027
UNI04	0	0	0	0	0	0	0	0	0.000
UNI05	0	0	0	0	0	0	0	0	0.000
UNI06	0	2	0	0	0	0	0	0	-0.202
UNI07	0	2	0	1	0	0	0	0	-0.164
UNI08	0	0	0	0	0	0	0	0	0.000

Table 4 Levels of attributes of the HUI3 reported by the Bimodal Group using one device (their implant only) (Part A of the table), two devices (their implant and their hearing aid) (Part B), and the differences between using 2 devices and 1 device (Part C). Where the level of an attribute, or the HUI3 utility, was better (worse) with 2 devices rather than 1, the entry in Part C is highlighted with green (amber).

A. One device (implant only)									HUI3
Participant	Vision	Hearing	Speech	Ambulation	Dexterity	Emotion	Cognition	Pain	Utility
BIM01	2	5	1	2	1	1	4	2	0.366
BIM02	1	3	1	1	2	1	1	1	0.788
BIM03	2	5	2	1	1	2	1	2	0.481
BIM04	2	5	1	1	1	2	3	3	0.437
BIM05	2	3	1	1	1	1	1	1	0.825
BIM06	2	3	1	1	1	1	1	2	0.777
BIM07	2	3	1	1	1	1	1	2	0.777
BIM08	2	3	1	1	1	1	1	2	0.777
BIM09	1	3	2	1	1	1	1	2	0.730
B. Two devices (implant and hearing aid)									HUI3
Participant	Vision	Hearing	Speech	Ambulation	Dexterity	Emotion	Cognition	Pain	Utility
BIM01	2	5	1	1	1	1	1	2	0.583
BIM02	2	3	1	1	2	1	1	1	0.765
BIM03	2	3	1	1	1	2	1	2	0.720
BIM04	2	3	1	1	1	2	3	3	0.600
BIM05	2	3	1	1	1	1	1	1	0.825
BIM06	2	3	1	1	1	2	3	2	0.665
BIM07	2	3	2	1	1	1	1	2	0.708
BIM08	2	3	1	1	1	1	1	2	0.777
BIM09	1	3	2	1	1	1	1	2	0.730
C. Difference: 2 Devices – 1 Device									HUI3
Participant	Vision	Hearing	Speech	Ambulation	Dexterity	Emotion	Cognition	Pain	Utility
BIM01	0	0	0	-1	0	0	-3	0	0.218
BIM02	1	0	0	0	0	0	0	0	-0.023
BIM03	0	-2	-1	0	0	0	0	0	0.238
BIM04	0	-2	0	0	0	0	0	0	0.164
BIM05	0	0	0	0	0	0	0	0	0.000
BIM06	0	0	0	0	0	1	2	0	-0.112
BIM07	0	0	1	0	0	0	0	0	-0.069
BIM08	0	0	0	0	0	0	0	0	0.000
BIM09	0	0	0	0	0	0	0	0	0.000

Table 5 Levels of attributes of the HUI3 reported by the Bilateral Group using one device (their 1st implant only) (Part A of the table), two devices (their 1st and 2nd implants) (Part B), and the differences between using 2 devices and 1 device (Part C). Where the level of an attribute, or the HUI3 utility, was better (worse) with 2 devices rather than 1, the entry in Part C is highlighted with green (amber).

A. One device (1st implant only)									HUI3
Participant	Vision	Hearing	Speech	Ambulation	Dexterity	Emotion	Cognition	Pain	Utility
BIL01	2	5	1	1	3	1	1	2	0.469
BIL02	2	5	1	2	1	2	1	1	0.507
BIL03	2	6	3	2	1	1	1	1	0.307
BIL04	2	3	1	1	1	1	1	1	0.825
BIL05	2	3	1	1	1	1	1	1	0.825
BIL06	2	3	1	1	1	1	1	1	0.825
BIL07	2	3	1	1	1	1	1	1	0.825
BIL08	2	3	1	1	1	1	1	1	0.825
BIL09	2	5	1	1	1	1	1	1	0.623
BIL10	2	3	1	1	1	1	1	1	0.825
BIL11	2	3	1	1	1	1	1	2	0.777
B. Two devices (1st and 2nd implants)									HUI3
Participant	Vision	Hearing	Speech	Ambulation	Dexterity	Emotion	Cognition	Pain	Utility
BIL01	2	3	1	1	3	1	1	2	0.639
BIL02	2	3	1	2	1	2	1	1	0.685
BIL03	2	5	3	2	1	1	1	2	0.419
BIL04	2	3	1	1	1	1	1	1	0.825
BIL05	2	3	1	1	1	1	1	2	0.777
BIL06	2	3	1	1	1	1	1	1	0.825
BIL07	2	3	1	1	1	1	1	1	0.825
BIL08	2	3	1	1	1	1	1	1	0.825
BIL09	2	3	1	1	1	1	1	1	0.825
BIL10	1	3	1	1	1	1	1	1	0.849
BIL11	2	3	1	1	1	1	1	2	0.777
C. Difference: Two devices – One device									HUI3
Participant	Vision	Hearing	Speech	Ambulation	Dexterity	Emotion	Cognition	Pain	Utility
BIL01	0	-2	0	0	0	0	0	0	0.170
BIL02	0	-2	0	0	0	0	0	0	0.178
BIL03	0	-1	0	0	0	0	0	1	0.112
BIL04	0	0	0	0	0	0	0	0	0.000
BIL05	0	0	0	0	0	0	0	1	-0.048
BIL06	0	0	0	0	0	0	0	0	0.000
BIL07	0	0	0	0	0	0	0	0	0.000
BIL08	0	0	0	0	0	0	0	0	0.000
BIL09	0	-2	0	0	0	0	0	0	0.202
BIL10	-1	0	0	0	0	0	0	0	0.024
BIL11	0	0	0	0	0	0	0	0	0.000

Table 6 Levels of dimensions of the YBHRQL and values of binaural utility reported by the Bimodal Group using one device (their implant only) (Part A of the table), two devices (their implant and their hearing aid) (Part B), and the differences between using 2 devices and 1 device (Part C). Where the level of an attribute, or the binaural utility, was better (worse) with 2 devices rather than 1, the entry in Part C is highlighted with green (amber).

A. One device (implant only)				
Participant	SpiN	Loc	E&F	Binaural utility
BIM01	5	5	5	0.685
BIM02	3	5	3	0.768
BIM03	4	4	2	0.799
BIM04	3	5	4	0.739
BIM05	3	4	1	0.829
BIM06	3	3	2	0.829
BIM07	1	4	1	0.876
BIM08	3	3	2	0.829
BIM09	2	3	2	0.848
B. Two devices (implant and hearing aid)				
Participant	SpiN	Loc	E&F	Binaural utility
BIM01	5	5	5	0.685
BIM02	2	3	2	0.848
BIM03	4	2	3	0.813
BIM04	3	4	4	0.759
BIM05	3	4	1	0.829
BIM06	2	2	2	0.874
BIM07	1	4	1	0.876
BIM08	2	2	2	0.874
BIM09	2	2	2	0.874
C. Difference: Two devices – One device				
Participant	SpiN	Loc	E&F	Binaural utility
BIM01	0	0	0	0.000
BIM02	-1	-2	-1	0.081
BIM03	0	-2	1	0.015
BIM04	0	-1	0	0.020
BIM05	0	0	0	0.000
BIM06	-1	-1	0	0.046
BIM07	0	0	0	0.000
BIM08	-1	-1	0	0.046
BIM09	0	-1	0	0.026

Table 7 Levels of dimensions of the YBHRQL and values of binaural utility reported by the Bilateral Group using one device (their 1st implant only) (Part A of the table), two devices (their 1st and 2nd implants) (Part B), and the differences between using 2 devices and 1 device (Part C). Where the level of an attribute, or the binaural utility, was better (worse) with 2 devices rather than 1, the entry in Part C is highlighted with green (amber).

A. One device (1st implant only)				
Participant	SpiN	Loc	E&F	Binaural utility
BIL01	5	5	2	0.764
BIL02	4	4	3	0.774
BIL03	5	5	5	0.685
BIL04	2	5	1	0.831
BIL05	3	5	1	0.812
BIL06	4	4	4	0.744
BIL07	2	4	2	0.829
BIL08	4	3	2	0.821
BIL09	4	5	5	0.698
BIL10	4	4	4	0.744
BIL11	2	3	3	0.822
B. Two devices (1st and 2nd implants)				
Participant	SpiN	Loc	E&F	Binaural utility
BIL01	2	1	1	0.932
BIL02	3	4	2	0.809
BIL03	3	3	1	0.847
BIL04	2	2	1	0.903
BIL05	2	1	1	0.932
BIL06	1	2	2	0.898
BIL07	1	2	1	0.932
BIL08	2	4	2	0.829
BIL09	2	1	3	0.868
BIL10	3	2	2	0.851
BIL11	2	3	2	0.848
C. Difference: Two devices – One device				
Participant	SpiN	Loc	E&F	Binaural utility
BIL01	-3	-4	-1	0.168
BIL02	-1	0	-1	0.035
BIL03	-2	-2	-4	0.162
BIL04	0	-3	0	0.073
BIL05	-1	-4	0	0.121
BIL06	-3	-2	-2	0.154
BIL07	-1	-2	-1	0.103
BIL08	-2	1	0	0.008
BIL09	-2	-4	-2	0.170
BIL10	-1	-2	-2	0.107
BIL11	0	0	-1	0.026

Table 8 Values of gains in binaural utility and health utility, and differences between gains, for the Bimodal Group.

	[A]	[B]	[C]	[D] [=A-B]	[E] [=A-C]
		Gain in Utility		Difference between Gains	
Participant	YBHRQL (Binaural Utility)	HUI3 (Health Utility)	EQ-5D-3L (Health Utility)	YBHRQL – HUI3	YBHRQL – EQ-5D-3L
BIM01	.000	.218	-.12	-.218	0.120
BIM02	.081	-.023	.00	.104	0.081
BIM03	.015	.238	.00	-.224	0.015
BIM04	.020	.164	.00	-.144	0.020
BIM05	.000	.000	.00	.000	0.000
BIM06	.046	-.112	.00	.158	0.046
BIM07	.000	-.069	.00	.069	0.000
BIM08	.046	.000	.20	.046	-0.154
BIM09	.026	.000	.15	.026	-0.124
Median	.200	.000	.000	.026	.015
IQR	.000 to .046	-.046 to .191	.000 to .075	-.181 to .087	-.062 to .063
Mean	.026	.046	.026	-.020	.000
95% CI	.011 to .042	-.029 to .130	-.024 to .083	-.113 to .071	-.058 to .052

Table 9 Values of gains in binaural utility and health utility, and differences between gains, for the Bilateral Group.

	[A]	[B]	[C]	[D] [=A-B]	[E] [=A-C]
		Gain in Utility		Difference between Gains	
Participant	YBHRQL (Binaural Utility)	HUI3 (Health Utility)	EQ-5D-3L (Health Utility)	YBHRQL – HUI3	YBHRQL – EQ-5D-3L
BIL01	0.168	0.170	-0.07	-0.003	0.238
BIL02	0.035	0.178	0.00	-0.143	0.035
BIL03	0.162	0.112	0.00	0.050	0.162
BIL04	0.073	0.000	0.00	0.073	0.073
BIL05	0.121	-0.048	0.00	0.168	0.121
BIL06	0.154	0.000	0.00	0.154	0.154
BIL07	0.103	0.000	0.00	0.103	0.103
BIL08	0.008	0.000	0.15	0.008	-0.142
BIL09	0.170	0.202	0.00	-0.031	0.170
BIL10	0.107	0.024	0.00	0.082	0.107
BIL11	0.026	0.000	0.00	0.026	0.026
Median	.107	.000	.000	.050	.107
IQR	.035 to .162	.000 to .170	.000 to .000	-.003 to .103	.035 to .162
Mean	.102	.058	.007	.044	.095
95% CI	.067 to .135	.011 to .113	-.020 to .043	-.006 to .094	.032 to .149

Table 10 Losses of utility due to impaired hearing measured with the HUI3 and YBHRQL by the Unilateral, Bimodal, and Bilateral Groups, both combined and individually.

		[A]	[B]	[C]	[D]	[E]	[F]
Group	Participant	With 1st or only implant		With bimodal aiding		With bilateral implants	
		HUI3	YBHRQL	HUI3	YBHRQL	HUI3	YBHRQL
Unilateral	UNI01	.140	0.148				
	UNI02	.222	0.192				
	UNI03	.228	0.250				
	UNI04	.148	0.131				
	UNI05	.135	0.150				
	UNI06	.249	0.212				
	UNI07	.143	0.192				
	UNI08	.148	0.221				
	Median	*.148*	*.192*				
	IQR	*.141 to .227*	*.149 to .219*				
	Mean	*.177*	*.187*				
	95% CI	*.144 to .209*	*.156 to .218*				
Bimodal	BIM01	.259	.275	0.335	0.275		
	BIM02	.143	.192	0.140	0.112		
	BIM03	.299	.161	0.135	0.147		
	BIM04	.284	.221	0.120	0.201		
	BIM05	.148	.131	0.148	0.131		
	BIM06	.142	.131	0.128	0.086		
	BIM07	.142	.084	0.133	0.084		
	BIM08	.142	.131	0.142	0.086		
	BIM09	.136	.112	0.136	0.086		
	Median	*.143*	*.131*	*.136*	*.112*		
	IQR	*.142 to .272*	*.121 to .207*	*.131 to .145*	*.086 to .174*		
	Mean	*.188*	*.160*	*.157*	*.134*		
	95% CI	*.142 to .235*	*.125 to .201*	*.132 to .201*	*.098 to .178*		
Bilateral	BIL01	.295	.196			0.125	0.028
	BIL02	.309	.186			0.131	0.151
	BIL03	.434	.275			0.278	0.113
	BIL04	.148	.129			0.148	0.057
	BIL05	.148	.148			0.142	0.028
	BIL06	.148	.216			0.148	0.062
	BIL07	.148	.131			0.148	0.028
	BIL08	.148	.139			0.148	0.131
	BIL09	.349	.262			0.148	0.092
	BIL10	.148	.216			0.151	0.109
	BIL11	.142	.138			0.142	0.112
	Median	*.148*	*.186*			*.148*	*.092*
	IQR	*.148 to .309*	*.138 to .216*			*.142 to .148*	*.028 to .113*
	Mean	*.220*	*.185*			*.155*	*.082*
	95% CI	*.169 to .277*	*.157 to .213*			*.140 to .181*	*.058 to .106*
ALL							
	Median	.148	.174				
	IQR	.142 to .257	.131 to .216				
	Mean	.197	.178				
	95% CI	.171 to .227	.159 to .198				