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A longitudinal study in adults with sequential bilateral cochlear implants: Time course for individual ear and bilateral performance

Ruth M Reeder,

Department of Otolaryngology – Head and Neck Surgery, Washington University School of Medicine in St. Louis

Jill B Firszt,

Department of Otolaryngology – Head and Neck Surgery, Washington University School of Medicine in St. Louis

Laura K Holden, and

Department of Otolaryngology – Head and Neck Surgery, Washington University School of Medicine in St. Louis

Michael J Strube

Department of Psychology, Washington University School of Medicine in St. Louis

Abstract

Purpose—Examine rate of progress in the second implanted ear as it relates to the first implanted ear and to bilateral performance in adult sequential cochlear implant recipients. Additionally, identify factors that contribute to patient outcomes.

Methods—A prospective longitudinal study in 21 adults who received bilateral, sequential cochlear implants. Testing occurred at six intervals: pre-bilateral through 12 months post-bilateral implantation. Measures evaluated speech recognition in quiet and noise, localization and perceived benefit.

Results—Second ear performance was similar to first ear performance by six months post-bilateral implantation. Bilateral performance was generally superior to either ear alone. However, participants with shorter second ear length of deafness (< 20 years) had more rapid early improvement and better overall outcomes than those with longer second ear length of deafness (> 30 years). All participants reported bilateral benefit.

Conclusions—Adult cochlear implant recipients demonstrated benefit from second ear implantation for speech recognition, localization and perceived communication function. Since performance outcomes were related to length of deafness, shorter time between surgeries may be warranted to reduce negative length-of-deafness effects. Future study may clarify the impact of other variables such as pre-implant hearing aid use, particularly for individuals with longer periods of deafness.

Keywords

adults; bilateral; cochlear implant; localization; sequential; speech recognition; SSQ

Introduction

Only a small percentage of the more than 219,000 cochlear implant (CI) recipients worldwide have been implanted bilaterally; however, the rate of bilateral implantation is on the rise (National Institute on Deafness and Other Communication Disorders, 2011). Typically, individuals seek a second implant to improve speech understanding in noise and sound localization. These well recognized binaural hearing benefits have been documented in bilaterally implanted adults using various study designs: 1) bilateral compared to unilateral implants in the same individual (Dunn, Tyler, Witt, Ji, & Gantz, 2012; Laszig et al., 2004; Litovsky, Parkinson, Arcaroli, & Sammeth, 2006; Müller, Schön, & Helms, 2002; Nopp, Schleich, & D'Haese, 2004; Tyler, Dunn, Witt, & Noble, 2007; Verschuur, Lutman, Ramsden, Greenham, & O'Driscoll, 2005), 2) bilateral implants compared to the better performing ear implant (Buss et al., 2008; Laske et al., 2009; Ricketts, Grantham, Ashmead, Haynes, & Labadie, 2006; Schön, Müller, & Helms, 2002), and 3) group comparisons of bilateral and unilateral implant recipients (Dunn, Tyler, Oakley, Gantz, & Noble, 2008; Tyler, Perreau, & Ji, 2009).

In most published studies, individuals received simultaneous implants placed during one procedure. The majority of adult bilateral patients, however, have received their devices sequentially; that is, after some time with the first implant, the second ear was implanted (Peters, Wyss, & Manrique, 2010). Only a few studies have reported outcomes in adults with sequentially placed devices and results have varied. This variability may be due, in part, to differing amounts of participant implant experience among and within studies. For example, Schleich, Nopp and D'Haese (2004), in one of the first published studies with a relatively large number of participants (21 adults, 18 sequential), reported bilateral effects with participants who had from one month to four years bilateral experience. Laske et al. (2009) reported significant summation effects; however, information about length of bilateral experience was only identified as a minimum of six months. Although these studies support bilateral sequential implantation, little can be deduced about the time course for bilateral improvement or the effect of second ear experience on bilateral outcome measures.

Two retrospective reports using the same relatively large patient pool provided information about performance at three (Zeitler et al., 2008) and 12 months post-implant (Budenz, Roland, Babb, Baxter, & Waltzman, 2009). Both studies included results from 22 sequentially implanted adults; most appear to be the same individuals based on the authors' participant descriptions. After three months bilateral experience, the mean scores for the second CI approximated those of the first CI for both Consonant-Vowel Nucleus-Consonant (CNC; Peterson & Lehiste, 1962) monosyllabic words and Hearing in Noise Test (HINT; Nilsson, Soli, & Sullivan, 1994) sentences administered in quiet. Mean CNC word scores for each CI continued to be comparable after twelve months.

Ramsden et al. (2005) presented speech recognition findings from a multicenter study with 28 sequentially implanted adults. Testing occurred after one week, three months and nine months of bilateral device use. Duration of profound hearing loss for each ear was 15 years or less and time between surgeries ranged from 1–7 years. Across intervals and various measures, the second implanted ear performed poorer than the first and little improvement in the second implanted ear was noted after three months. No bilateral benefit was evident in quiet; however, for City University of New York (CUNY; Boothroyd, Hnath-Chisolm, Hanin, & Kishon-Rabin, 1988) sentences in noise, a significant bilateral advantage was present at three and nine months.

In addition to speech recognition, localization abilities have been studied in bilateral, sequential adult recipients using a variety of test paradigms (Laszig et al., 2004; Schön, Müller, Helms, & Nopp, 2005). Generally speaking, localization in the horizontal plane is improved in the bilateral versus the unilateral condition; however, tremendous variability exists and performance is poorer compared to normal hearing listeners (Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007; Kerber & Seeber, 2012). In some studies, poor localization for individual participants has been attributed to profound hearing loss in early childhood (Schön et al., 2005). Localization improved after bilateral implantation for two sequentially implanted adults, one postlingually deafened with six years between surgeries and one deafened as a youth with four years between surgeries (Nava et al., 2009). Better localization was apparent after one month for the postlingually deafened adult but not until after 12 months for the patient who was deafened as a child. The authors suggested that the recovery rate for spatial hearing may be dependent on previous binaural experience. At this time, large group data are not available to address whether spatial hearing can be achieved with bilateral implantation for adults with early onset deafness.

With respect to patient perceptions, 24 adults with one to six years of unilateral experience prior to second ear implantation noted improvements on the Speech, Spatial and Qualities of Hearing scale (SSQ; Gatehouse & Noble, 2004) after three months of bilateral experience (Summerfield et al., 2006). The perceived benefit was maintained but did not improve after nine months of bilateral experience. The greatest improvement was in the spatial domain with smaller improvements in the speech and quality domains. Comparison of SSQ ratings between bilateral, sequentially implanted and unilaterally implanted adults (matched for age at implantation, duration of implant use and gender) showed higher ratings for the bilateral group but differences were not statistically significant (Laske et al., 2009). Other reports suggested significant increases on SSQ subscales, pre- to post-implant for patients with two versus one implant (Noble, 2010; Noble, Tyler, Dunn, & Bhullar, 2009); however, results were not differentiated for sequentially and simultaneously implanted participants.

Outcome variability among unilaterally implanted patients is well documented. In general, we expect individuals with short duration hearing loss in the implanted ear to progress faster and potentially achieve better outcomes than individuals implanted with long duration hearing loss, particularly if there was poor amplification benefit (Blamey et al., 1996; Blamey et al., 2013; Holden et al., 2013; Rubinstein, Parkinson, Tyler, & Gantz, 1999). Few studies have investigated patient characteristics that may be related to second CI or bilateral performance. Those that have, focused primarily on the effect of time between surgeries and

found no relationship (review by Smulders, Rinia, Rovers, van Zanten, & Grolman, 2011). The exception was Laske et al. (2009) who reported the length of time between surgeries correlated with differences in first and second ear performance. Two other studies examined post-implant bilateral performance and found no relationship with age at second surgery or duration of deafness for either ear (Zeitler et al., 2008) or with duration of deafness of the first CI ear or length of second CI use (Laske et al., 2009). It is unknown whether the same factors that affect first implanted ear performance can be assumed for a second ear or for bilateral performance. Likewise, it is unknown whether and how first ear performance influences second ear performance.

At this time, second ear CI candidacy follows similar criteria as first ear candidacy (Peters et al., 2010); however, to aid in determining potential benefit for patients considering a second CI, additional longitudinal data are needed regarding possible influential outcome factors and rate of progress. The objectives of the current longitudinal study in adults who received bilateral sequential implants were threefold: 1) to monitor second implanted ear rate of progress using measures of speech recognition in quiet and noise, localization and assessment of perceived benefit, 2) to examine performance over time for each implanted ear individually as well as bilaterally, and 3) to identify factors that contribute to outcomes.

Research Design and Methods

Participants

The Human Research Protection Office at Washington University School of Medicine (WUSM) reviewed and approved the study protocol. Adults who had received a unilateral CI through the Adult Cochlear Implant and Hearing Rehabilitation Program at WUSM, had open-set CI speech recognition, and were in the process of obtaining a second CI at WUSM were invited to participate. A power analysis to determine the number of participants necessary to detect clinically meaningful change over an 18-month period, assuming power of .80 and a significance level of .05, indicated a target sample size of 31. Interim analyses at 12 months with 21 participants indicated larger than anticipated change over time, justifying the current interim report. The target sample size, once completed, will allow broader exploration of moderators of performance change; the current report focuses on the moderator length of deafness (LOD) in the second implanted ear. At the time of this interim analysis, 24 adults met inclusion criteria and had been invited to participate; however, three declined enrollment for transportation or health reasons. The 21 study participants were 36–74 years of age (mean 48.5 yrs, SD 8.7 yrs) at the first CI surgery and 44–75 years of age (mean 53.8 yrs, SD 8.0 yrs) at the second CI surgery. Time between surgeries ranged from one to 17 years (mean 5.2 yrs; SD 4.6 yrs). Three participants had early onset (before age five) of severe to profound sensorineural hearing loss (SPHL). All others had post-lingual onset of SPHL, although two participants had onset as pre-teens. The LOD ranged from less than one year to 45 years for the first ear (mean 16.8 yrs, SD 14.6 yrs) and from less than one year to 55 years for the second ear (mean 21.4 yrs, SD 16.8 yrs). Two participants had not consistently worn hearing aids (HA) in either ear prior to CI surgery due to lack of benefit, and three others had no HA experience in the second ear. Table 1 provides participants' demographic and hearing history information.

At the time of clinical evaluation for the second CI, all participants had SPHL in the nonimplanted ear and were evaluated with a well fit HA. Table 2 shows pre-implant mean hearing thresholds for the second ear and frequency-modulated (FM) tone, soundfield threshold levels for the first implanted ear prior to second side surgery. Unaided means 4 to 8k Hz and aided means 3 to 6k Hz may be underestimations; lack of responses at audiometer limits were coded as 5dB above the limit. Table 3 has information about implant devices and speech processor programs. In general, second ear program parameters matched those of the first CI; although, for some participants, optimal speech recognition and balanced loudness required differences in program parameters. All reported good sound quality in the unilateral and bilateral conditions.

Following the standard clinical practice at the WUSM CI program, all participants completed aural rehabilitation including weekly clinic sessions and activities for practice at home. Typically, these individuals had aural rehabilitation for 8–10 weeks at the time of the first CI and 4–6 weeks at the time of the second CI surgery. The therapy plans were individualized and included activities with the second CI alone as well as in the bilateral CI condition.

Procedures

Soundfield Detection Threshold and Speech Recognition Measures—All testing was completed in double-walled sound-attenuated booths. FM-tone, soundfield threshold levels were obtained for each ear at .25, .5, .75, 1, 1.5, 2, 3, 4 and 6 kHz. The speech recognition test protocol included a range of measures and conditions to minimize floor and ceiling effects that have been present with CI recipients (Firszt et al., 2004; Gifford, Shallop, & Peterson, 2008).

Three tests were administered at fixed presentation levels: CNC words, HINT sentences (four to six words in length, first grade reading level, clearly spoken by a male talker) and TIMIT sentences (King, Firszt, Reeder, Holden, & Strube, 2012; Lamel, Kassel, & Seneff, 1986) (four to eight words in length, sixth grade reading level, several male and female talkers from several dialectical regions). Two CNC word lists of 50 words each were administered at 60 dB SPL in quiet. Two lists of HINT sentences (10 per list) and two lists of TIMIT sentences (20 per list) were administered at 60 dB SPL in 4-talker babble (4TB) using a +8 dB signal-to-noise ratio (SNR). Additionally, TIMIT sentences were presented at a softer level of 50 dB SPL in quiet. All test and noise stimuli were presented from the front and scored as the percentage of words correct.

Two adaptive level measures were administered. HINT sentences were presented using the procedure recommended by Nilsson et al. (1994) via the R-Space™ (Revit, Schulein, Killion, Compton, & Julstrom, 2002). The R-Space™ system used eight loudspeakers (45° apart) that surrounded the listener and simulated a busy restaurant environment. The restaurant noise (Compton-Conley, Neuman, Killion, & Levitt, 2004) was presented from all loudspeakers at a fixed 60 dB SPL. Each test administration included two lists presented from the front loudspeaker at a level that varied adaptively. Specifically, the first sentence was at 72 dB SPL (+ 12 dB SNR). If the sentence was repeated incorrectly, the SNR was increased until the sentence was repeated correctly or, if it was still not understood at the

maximum SNR (+22 dB), a score of +22 dB was assigned. After each correct response, the SNR was decreased (made more difficult); after each incorrect response, the SNR was increased (made easier). The score was an estimate of the SNR for 50% sentence recognition (SNR-50). The Bamford-Kowal-Bench Speech-In-Noise (BKB-SIN) test (Etymotic Research, 2005) was the other measure using varied SNRs. Sentences were presented at a fixed 65 dB SPL in 4TB. Two 16-sentence lists were presented at an initial +21 dB SNR. Twice for each list, the noise level was increased incrementally by 3 dB from +21 to 0 dB SNR across eight sentences. Following procedures in the administration manual, the number of key words correct determined an SNR-50. Sentences were presented from the front. The 4TB was presented from the front and each side, $\pm 90^\circ$ azimuth, resulting in three noise conditions: speech front/noise front, speech front/noise right, speech front/noise left.

Localization—A general description of the localization task is provided here (see Potts, Skinner, Litovsky, Strube & Kuk, 2009 for additional details). The participant was seated facing an arc of 15 loudspeakers positioned 10° apart and numbered from 1 (-70°) to 15 ($+70^\circ$). Two lists of 100 monosyllabic words were presented randomly from each of 10 active loudspeakers ($\pm 70^\circ$, $\pm 50^\circ$, $\pm 30^\circ$, $\pm 20^\circ$, and $\pm 10^\circ$ azimuth) at a roved 60 dB SPL (± 3 dB) level. Unaware that five loudspeakers were inactive, the participant identified the source location loudspeaker number (1–15) after each presented word but was not asked to repeat the word. For each list, an RMS error score was calculated based on the source location and responses (i.e., the mean difference between the correct loudspeaker location and that identified by the participant, irrespective of the direction of the error).

Self-Report Outcome Measure—The Speech, Spatial and Qualities of Hearing Scale (SSQ) is a patient report measure intended to reflect real-world listening situations. Items are rated on a continuum of 0–10 (higher scores reflect greater ability). There are three sections: a speech domain (14 items) addresses hearing speech in competing contexts such as reverberation and multiple talkers, a spatial domain (17 items) addresses directional and distance hearing and a qualities domain (18 items) probes segregation of sounds, naturalness/clarity and listening effort.

Test Schedule—Speech recognition measures were administered at six intervals: pre-bilateral (prior to second ear cochlear implantation) and at 1, 3, 6, 9, and 12 months of bilateral implant use. All measures were administered to each ear separately, and all, except the monosyllabic word test, were administered bimodally (CI and HA, pre-bilateral) or bilaterally (both CIs, post-bilateral). Monosyllabic words, HINT sentences and TIMIT sentences in quiet were administered at each interval. TIMIT sentences in noise and HINT sentences in the R-Space™ were administered at all intervals except one month. The BKB-SIN was given pre-bilateral and at three, six and 12 months. Localization testing occurred at the pre-bilateral, six- and 12-month intervals. Ear condition order and test lists were pseudorandomized across participants and intervals. The SSQ was administered at all test intervals. Note that after completion of the pre-bilateral SSQ, participants were provided the previous interval responses as a reference. At each interval, participant ratings reflected their current everyday listening condition.

Device Verification—Pre-bilateral testing was completed with the participant's own or a clinic-owned HA worn in the non-implanted ear. All HA fittings were verified to fit NAL targets with the Audioscan Verifit for 50, 65 and 80 dB inputs. If a clinic-owned HA provided benefit (i.e. speech was audible and the participant tolerated the amplification necessary for optimization), the participant wore the HA for several weeks prior to pre-bilateral testing. Participants unable to detect speech even with a well-fit, high-power HA were scored as 0% or the highest SNR possible for each HA-alone speech recognition measure. No HA-alone localization results were recorded in this circumstance. CI testing was conducted with the individual's most commonly used speech processor program and settings. CI soundfield threshold levels were verified at each test interval. If thresholds had declined or were outside the expected level (typically 30 dB HL from .25 – 6k Hz) the device was re-programmed prior to testing.

Data Analysis—Results were examined using standard analyses of variance (ANOVA; Keppel, 1991; Maxwell & Delaney, 1990) and the latest test interval (typically 12 months) for each participant under each CI condition (first-implanted ear [CI1], second-implanted ear [CI2], bilateral). Occasionally the last measure was not the 12-month interval, but the general approach of using the last measurement allowed an adequate sample size for analyses. These analyses used a repeated-measures ANOVA with CI condition as the repeated measure and Bonferroni corrected post-hoc comparisons when the overall F test was significant. The exception was the CNC word test which was not administered bilaterally.

The major analytic approach used to examine longitudinal effects, such as rate of improvement, was hierarchical linear modeling (HLM; Heck & Thomas, 2009; Hox, 2010; Raudenbush & Bryk, 2002; Snijders & Bosker, 2012). This approach was chosen because the data have a hierarchical structure, with the repeated measures over time nested within CI conditions, which are nested within participants. Thus a three-level growth curve model was used for each examined outcome, with both linear growth (i.e., growth rate of a tangent to the curve at specific intervals) and quadratic growth (i.e., change in linear growth over time or departure from an overall linear or straight line pattern) included. Analyses were conducted with data centered at each measurement period so that systematic differences between CI conditions in expected performance and linear growth could be assessed. HLM analysis was also chosen to allow for missing data across time that is common with longitudinal CI studies. (See appendix A for additional details regarding the HLM analysis.) For the various tests and conditions, data was available for 17–21 participants with the exception of CI2 at the nine-month interval for HINT sentences in noise (n=16) and pre-bilateral testing in the bimodal condition (ns from 13–15). At the study's initiation, prebilateral testing was not completed bimodally on measures for which a participant was at floor level. As the study progressed, all new participants were tested at the pre-bilateral interval in all three conditions (CI alone, HA alone, CI and HA) regardless of ability.

When HLM is used with smaller samples, standard errors may be reduced, although parameter estimates should not be biased (Raudenbush & Bryk, 2002). Accordingly, a more conservative significance level was used ($p = 0.005$). The overall test in the first hierarchical model (growth curves for each CI condition) determined if there was significant variation

among the three CI conditions for the intercept, the linear component, and the quadratic component (each component tested separately). If significant variation was found (by a χ^2 test), the three pair-wise comparisons for CI conditions were examined to determine the nature of the variation.

When the data are centered at a particular point in time, the intercept is the expected performance at that point in time and the linear component is the growth rate (the tangent to the growth curve) at that point in time. The quadratic component indicates the curvilinearity over time (i.e., how the HLM curve differs from a straight line). Figure 1 provides a theoretical example of two HLM curves (dotted and dashed black lines) and the analyzed components. In this theoretical example, significant differences might be found between the intercept of the two curves at the earliest time point, (1) versus (a) but not at the third time point, (3) versus (d). Or the rate of change (linear slope) for the third time point would likely be statistically similar for both curves, that is the slope of the line tangent to intercept (3) of the dotted curve versus the slope of the line that would be drawn tangent to intercept (d) of the dashed curve. Another theoretical finding might be that the curvilinearity is significantly different for the two curves, and only the dotted line is significantly different from a flat line. Analysis of these HLM components was used to identify significant differences between conditions (CI1, CI2, Bilateral) and at various time points.

The overall test for the second hierarchical model determined if there was significant variation in the intercept, linear, and quadratic components among the CI conditions for participants who were low or high on the candidate moderator, LOD in the second implanted ear. If significant variation was found (by a χ^2 test), the three pair-wise comparisons for CI conditions were examined separately for participants low or high on the moderator.

Results

Soundfield thresholds obtained from 0.25–6 kHz for CI1 and CI2 were similar and stable over time. The average thresholds across frequencies and participants ranged from 12.89 – 28.67 dB HL at three months and 11.56 – 28.89 dB HL at 12 months for CI1 and from 14.67 – 24.67 dB HL at three months and 14.22 – 27.11 dB HL at 12 months for CI2. The average difference between CI1 and CI2 at each frequency was 4.42 dB (SD = 4.02 dB) at three months and 4.14 dB (SD = 3.69 dB) at 12 months.

Speech Recognition

Scores from the latest test interval for the measures with fixed presentation levels are shown in Figure 2, Panel A. From left to right, these tests are CNC words at 60 dB SPL in quiet, HINT sentences at 60 dB SPL with 4TB at +8 dB SNR, TIMIT sentences at 60 dB SPL with 4TB at +8 dB SNR and TIMIT sentences at 50 dB SPL. Recall that HINT sentences are easier to understand than TIMIT sentences based on reading level and talker variability. For CNC words there was not a significant CI condition (CI1, CI2) effect, $F(1, 20) = 2.83, p > 0.05$. However, for the sentence measures with data from three CI conditions (CI1, CI2, bilateral), there was a significant CI condition effect, HINT in noise $F(2, 40) = 10.75, p < 0.001$; TIMIT in noise $F(2, 40) = 19.19, p < 0.001$; TIMIT in quiet $F(2, 40) = 22.15, p < 0.001$. Post-hoc analysis indicated significantly higher bilateral scores than either ear alone

for all three measures, HINT in noise $p < 0.01$; TIMIT in noise and TIMIT in quiet $p < 0.001$. As with CNC words, there were no significant differences between individual ear conditions ($ps > 0.05$).

Figure 2, Panel B shows mean SNR-50 scores (latest test interval) for the HINT in the R-Space™ with restaurant noise surrounding the participant and the BKB-SIN with 4TB from each of three locations, the front, the CI1 side and the CI2 side. Lower SNRs indicate better performance. The R-Space™ and BKB-SIN (noise front) results are similar to those with fixed presentation levels in that there was a significant CI condition effect, R-Space™ $F(2, 40) = 5.03$, $p < 0.05$; BKB-SIN noise front $F(2, 40) = 7.62$, $p < 0.01$. Post-hoc analysis again indicated no significant difference between CI1 and CI2 ($p > 0.05$) while bilateral performance was significantly better than either ear alone (R-Space™ $p < 0.05$; BKB-SIN noise front $p < 0.01$). BKB-SIN results with noise presented to CI1 and to CI2 are shown to the right of Panel B. When noise was presented to CI1 or CI2, there was a significant CI condition effect [noise to CI1 $F(2, 40) = 12.53$; noise to CI2 $F(2, 40) = 33.49$, $ps < 0.001$]. Post-hoc analysis indicated that when testing each ear individually (CI1 or CI2), performance was significantly poorer if noise was directed toward the device than if noise was directed to the opposite ear without a device (CI1 $p < 0.05$, CI2 $p < 0.001$). Performance in the bilateral condition with noise to either side was significantly better than the unilateral condition with noise presented toward the unilateral device ($ps < 0.001$).

Figure 3, Panels A–F plot the group mean results over time for the three CI conditions by test measure. (Note that for clarity, actual means are provided in the figures rather than the generated HLM curves and components that were analyzed.) Percent correct (A–D) or SNR (E, F) are shown along the y-axis and time in months along the x-axis. Month zero refers to the pre-bilateral interval. Months 1–12 are post-bilateral intervals and are relative to the CI2 device activation date. For simplicity, these results refer to the three conditions as CI1, CI2 and bilateral even though pre-bilateral testing was conducted with the HA alone for the CI2 ear and bimodally for the bilateral condition. Table 4 provides a summary of the HLM analyses as it relates to this figure. The curvilinearity component indicates change in linear growth over time (i.e., departure from an overall linear or straight line pattern). The linear component is the growth rate for a particular condition and centering point (i.e., tangent to the curve at that point in time). The intercept is a value that is the estimated performance level for a particular condition and centering point based on the HLM analysis. As Figure 3 illustrates, the CI2 condition exhibited significant rapid early growth in performance that leveled off over time. Although values over time varied by measure and condition, the pattern of results was similar for all measures and is summarized here. The linear components (growth rates) for the CI2 condition were strongly and significantly positive for the fixed level measures and negative for the adaptive measures (lower SNR scores indicate improvement) in the early intervals. The growth rate became less steep at later intervals. By contrast, the CI1 condition showed no significant change over time and the bilateral condition only minor change over time. The CI1 condition only occasionally had significant growth rates (TIMIT in noise at nine months and TIMIT in quiet through three months). The bilateral condition showed gradual gains in performance over time with growth rates generally constant across test intervals and often statistically significant.

Variation among CI conditions was analyzed with χ^2 tests and follow-up pair-wise comparisons (results included in Table 4). The results indicated that for CNC words, the change over time (curvilinearity) and growth rate (linear components) at each test interval were significantly different between CI1 and CI2 (all $ps < 0.005$). The intercepts for CI1 and CI2 were significantly different at early test intervals ($ps < 0.005$) but were no longer significantly different ($p > 0.005$) by the six-month test interval. In other words, CNC word performance for CI2 was comparable to that of CI1 by six months post-bilateral. For HINT sentences, the relationship between CI1 and CI2 was similar to that for CNC words. The change over time and the growth rate at all intervals except the nine-month were significantly different between CI1 and CI2 ($ps < 0.005$). As with CNC words, the HINT sentence intercepts for CI1 and CI2 were significantly different at early intervals ($ps < 0.005$) but statistically similar by the six-month interval ($ps > 0.005$). Bilateral change over time was significantly different from CI2 ($p < 0.005$) but not CI1 ($p > 0.005$). Likewise, growth rates for bilateral were significantly different from CI2 at all intervals except nine months ($ps < 0.005$) and were not significantly different from CI1 at any interval ($ps > 0.005$). The intercepts for bilateral were significantly different from the intercepts for CI1 at the three-, nine-, and 12-month intervals ($ps < 0.005$) and for CI2 at the pre-bilateral and one-, three-, and 12-month intervals ($ps < 0.005$). This same pattern held true for the other four tests (Panels C–F). In general, CI2 performance improved rapidly becoming comparable to that of CI1 by six months and bilateral performance was significantly better than CI1 performance beginning at the three-month interval and continuing through the 12-month interval (except for sentences in the R-Space that continued through the nine-month interval, $ps < 0.005$).

Several variables were evaluated to identify relationships to speech recognition. CI2 LOD was selected as the first factor to be analyzed since LOD has been identified as a primary contributor to CI outcomes (Blamey et al., 1996; Blamey et al., 2013; Holden et al., 2013; Lazard et al., 2012; Rubinstein et al., 1999; UK Cochlear Implant Study Group, 2004). Results of ANOVAs with speech recognition scores from the latest test interval and including CI2 LOD as a covariate indicated a significant relation of CI2 LOD to all measures, CNC words $F(1, 19) = 51.59, p < 0.001$; HINT in noise $F(1, 19) = 42.62, p < 0.001$; TIMIT in noise $F(1, 19) = 27.81, p < 0.001$; TIMIT in quiet $F(1, 19) = 31.42, p < 0.001$; R-Space $F(1, 19) = 41.64, p < 0.001$; BKB-SIN noise front $F(1, 19) = 45.11, p < 0.001$. Figure 4 shows scatter plots and correlations between CI2 LOD and performance for the three CI conditions and the six speech recognition measures. All correlations were significant ($p < 0.01$) and ranged from -0.60 to -0.73 for CI1, from -0.78 to -0.92 for CI2 and from -0.74 to -0.81 for bilateral. Participants with longer CI2 LOD had poorer speech recognition performance in all three CI conditions. After accounting for CI2 LOD, there was not a significant main effect for other tested variables, most likely due to the relationship between these variables. The participants' CI2 LOD was significantly correlated with age at onset of hearing loss for each ear (-0.67 for CI1 and -0.59 for CI2, $p < 0.01$), age at onset of severe to profound hearing loss for each ear (-0.89 for CI1 and -0.91 for CI2, $p < 0.001$), CI1 LOD ($0.96, p < 0.001$) and time between ear surgeries ($0.47, p < 0.05$).

As indicated above, once CI2 LOD was statistically controlled, no other participant variables were related to performance measures. Accordingly, we focused on CI2 LOD for further examination as a moderator in the analyses. This variable was divided into two categories based on a natural participant grouping. Seven participants had CI2 LOD more than 30 years (range 31 – 55 years) and 14 participants had CI2 LOD less than 20 years (range < 1 – 18 years).

Figure 5 shows the means plotted separately for participants in the longer and shorter CI2 LOD categories. (Note that actual means are provided in the figures rather than the generated HLM curves and components that were analyzed.) Results are shown for measures given at fixed presentation levels in Panels A–D and for varied level measures in Panels E and F. Table 5 provides a summary of the HLM post-hoc pairwise comparisons as it relates to this figure. Analyses described here focus on the HINT sentences in noise (Figure 5, Panel B); similar patterns of results were obtained for the other measures. For participants with longer CI2 LOD, performance trends over time were largely linear. For these participants, there was a slight tendency for CI2 and bilateral performance to show early gains that leveled off over time, but no significant curvilinear components to the growth patterns were found for any of the CI conditions ($ps > 0.005$). Only CI2 and bilateral exhibited significant growth rates, primarily during the earlier test intervals ($ps = 0.005$). The most noticeable aspect of the data for these participants is that CI2 and bilateral were significantly different in their intercepts at each interval ($ps = 0.005$), indicating the general superiority of the bilateral listening condition. CI1 and CI2 were significantly different in their intercepts at the pre-bilateral, one-month and three-month test intervals ($ps = 0.005$). The growth rates at each interval were statistically similar ($ps > 0.005$) with one exception; at six months, the growth rates for CI1 and CI2 were significantly different ($p > 0.005$).

The growth patterns for the shorter CI2 LOD group showed more variability across CI conditions. For this group, a significant curvilinear component emerged for CI2 ($p = 0.005$), but not CI1 or bilateral ($ps > 0.005$). The degree of change over time for CI2 was significantly greater than for CI1 and bilateral ($ps = 0.005$). This difference in curvilinearity contributed to significant differences in growth rates for the different testing points. For test intervals up to and including six months, the growth rate was significantly more positive for CI2 than CI1 or bilateral ($ps = 0.005$). The intercepts were likewise quite different in the early testing periods, with CI2 being significantly different from bilateral through three months and significantly different from CI1 at pre-bilateral and one month ($ps = 0.005$). Importantly, CI2 achieved levels of performance that were not different from the other conditions after three months ($ps > 0.005$). The overall pattern of results as described here for the HINT sentences in noise is consistent with results for the other measures shown in Figure 5; the pattern shows that the benefit of a second implant is greatest among participants who had shorter CI2 LOD.

Localization

The average RMS error at three test intervals is shown by CI condition in Figure 6, Panel A. A 3 (test interval) x 3 (CI condition) repeated measures ANOVA identified significant effects for test interval and CI condition, test interval $F(2, 20) = 15.41$, $p < 0.001$; CI

condition $F(2, 20) = 7.78, p < 0.01$. Post-hoc analysis indicated improved bilateral localization at six- and 12-months compared to pre-bilateral ($p < 0.01$) and more accurate bilateral localization than with either ear alone ($p < 0.05$). There was also a significant interval by CI condition interaction, $F(4, 40) = 9.35, p < 0.001$. Performance was stable over time for CI1 ($p > 0.05$), whereas significant CI2 and bilateral improvements were seen between the pre-bilateral and six-month intervals ($p < 0.01$). No difference was seen between the six- and 12-month intervals ($p > 0.05$). Panel B shows the average RMS error at 12 months for the two CI2 LOD groups. There was a significant effect of CI2 LOD when it was included in the analysis, $F(1, 9) = 8.74, p < 0.05$. For the shorter CI2 LOD group, the bilateral condition provided significantly improved localization over CI1 ($p < 0.01$) or CI2 ($p < 0.05$). Results for the longer CI2 LOD group were best in the bilateral condition, but the CI condition differences were not statistically significant ($p > 0.05$).

Self-Reported Outcomes

Figure 7 shows group mean ratings over time for the three SSQ domains. Sixteen participants had completed the SSQ for at least four key intervals. Results are shown for these participants at these four intervals: pre-bilateral, one-month, 3–6 months and 9–12 months. A 3 (domain) $\times$ 4 (interval) ANOVA indicated a significant effect for both interval and domain, interval $F(3, 42) = 12.96, p < 0.001$; domain $F(2, 28) = 17.01, p < 0.01$. There was not a significant effect for CI2 LOD ($p > 0.05$). Post-hoc comparisons indicated significant improvement between pre-bilateral and 3–6 months. There were no significant differences between pre-bilateral and one month ($p > 0.05$) and no significant differences between 3–6 months and 9–12 months ($p > 0.05$). Post-hoc analysis also indicated that the qualities domain was significantly different from the speech and spatial domains ($p < 0.01$) which were not significantly different from each other ($p > 0.05$). There was a significant interaction between interval and domain, $F(6, 84) = 3.04, p < 0.05$, indicating that the relationship to interval was not the same for all three domains. As seen in the figure, the average rating was highest for quality and was lowest for spatial with ratings for all three domains improving over time (mean improvement in points of 2.05 for speech, 2.87 for spatial and 1.79 for quality). Differences between domains narrowed over time. The range reduced from 2.55 points at pre-bilateral to 1.47 points at 9–12 months. The latest SSQ ratings did not correlate significantly with the latest bilateral localization or speech recognition results ($p > 0.05$).

Discussion

The results of the present study detail the rate of second ear progress and how CI2 performance related to CI1 and bilateral performance over time in a group of sequentially implanted adults using speech recognition measures, a localization task, and a self-report measure. Several key findings from this longitudinal study of 21 bilateral cochlear implant recipients are discussed below.

Speech Recognition

Rate of CI2 progress compared to CI1 performance—Speech recognition with CI2 matched that of CI1 by six months of bilateral experience. For all speech recognition

measures, excluding BKB-SIN with noise from the side, the average latest test interval score was higher for CI1 than CI2; however, the difference was not statistically significant (Figure 2). Investigation of progress over time (HLM analysis) indicated that for all six speech recognition measures (words, sentences in quiet, sentences in noise), expected performance for CI1 was significantly better than for CI2 through three months, but by the six-month interval, performance for the two ears was expected to become statistically similar (Figure 3, Table 4).

Bilateral performance compared to each individual ear—Bilateral performance was superior to that of either ear individually for all sentence recognition measures except BKB-SIN with noise from the side. Results at the latest test interval as well as those comparing performance over time indicated improved bilateral over unilateral performance for sentences in quiet, sentences in noise at a fixed SNR and sentences in noise at varied SNRs. HLM results suggested bilateral performance could be expected to improve through the first six months of bilateral CI experience and should continue to be superior to unilateral CI performance beyond that point. This differs somewhat from the Ramsden et al. (2005) study in that they showed neither significant bilateral benefit over CI1 at three and nine months nor significant improvement in bilateral performance between three and nine months for speech in quiet at 70 dB SPL. However, for sentences in noise (speech and noise at 0° azimuth), they identified a bilateral advantage over CI1 at both intervals. It is possible that a bilateral advantage is not easily identified in quiet at raised presentation levels. In the current study sentences in quiet were presented at 50 dB SPL, a soft conversational level. Laske et al. (2009) reported significantly better bilateral scores over the poorer ear but not the better ear for Oldenburger sentences in quiet (n=23) and in noise (n=16) when speech and noise were presented from the same loudspeaker at 0° azimuth. Sentences were presented at 65 dB SPL, again a louder level in quiet than the current study. An additional difference that may attribute to discrepancies between the Laske and current studies is that the Laske study participants were tested at one point in time and had various amounts of bilateral experience rather than being tested over time at specific intervals. The current study results were consistent with findings of Buss et al. (2008) and Ricketts et al. (2006) who reported superior bilateral performance compared to the better ear scores of simultaneously implanted adults.

Improvements to CI1 after sequential bilateral implantation—Although this group of participants had from one to 17 years of CI1 experience (average > 5 years) prior to CI2 implantation, there was significant improvement in CI1 performance over time for TIMIT sentences in quiet but not for any sentence measures in noise. Previous studies have not reported a change in CI1 performance pre- to post-bilateral implantation. Zeitler et al. (2008, Figs. 1 and 2) showed a difference of approximately 1–2 percentage points for average CNC words and HINT sentences in quiet between the pre-bilateral to threemonth post-bilateral evaluations. Similar changes were noted between pre-bilateral and three- or ninemonth post-bilateral evaluations by Ramsden et al. (2005, Fig. 3). Although possible, it is unlikely that CI1 improvement over time in the current study is a result of practice or task familiarity since there was no improvement for measures in noise. Unless perhaps, practice was more useful in quiet since it is an easier task than listening in noise. In a recent study of adults

with asymmetric hearing loss who received cochlear implants in the poorer ear and maintained a HA in the better ear, some speech recognition scores improved in the HA ear, an ear that had been stable with respect to performance prior to cochlear implantation of the poorer ear (Firszt, Holden, Reeder, Cowdrey, & King, 2012). That study and the current study may suggest that improved bilateral hearing enhances the abilities of listeners when they revert to a single ear. Bilateral input and experience may provide a richer acoustic signal and allow the listener to more easily fill in missing cues when reliance on one ear is required.

Effect of hearing-history time-based factors—When considering only participants with shorter CI2 LOD, mean results of CI2 are expected to be comparable to those of CI1 by three months. This differs from results reported by Ramsden et al. (2005); average CI2 performance was significantly worse than CI1 at three and nine months for CNC words, CUNY sentences in quiet and CUNY sentences in noise. The authors reported this as an unexpected finding for their group of 27 recipients with duration of deafness no greater than 15 years for either ear. For CNC words their participant's mean ear difference at both three and nine months was 14.4 percentage points compared to the current study mean ear differences at three and nine months of 9.2 and 2.2 percentage points (and less than one percentage point for participants with < 20 years of CI2 deafness). Zeitler et al. (2008) did not specifically discuss first and second ear differences for their 19 participants; however, Figures 1 and 2 in their paper showed ear differences of approximately 4–6 percentage points respectively for CNC words and HINT sentences in quiet. Similarly, Figure 2 in Budzen et al. (2009) showed the 12-month mean CNC score for CI1 as approximately six percentage points higher than CI2 for a group of 18 sequentially implanted adults. The differences between CI1 and CI2 from the latter two studies are more similar to those of the current study. In the current study, a greater ear difference was evident for the group with longer CI2 LOD; the mean CI1 score at the latest test interval was higher than that of CI2 by 23 percentage points for CNC words and 13 percentage points each for HINT sentences in noise and TIMIT sentences in quiet. There was less difference for TIMIT sentences in noise, primarily due to lower scores for both ears.

A main effect of CI2 LOD was evident both in outcome and post-bilateral progress over time. CI2 LOD was inversely and highly correlated with the latest test interval scores (generally 12 months) for all speech recognition measures; participants with longer CI2 LOD had poorer CI1, CI2 and bilateral scores. These participants with longer CI2 LOD (30–55 years) performed more poorly and made slower progress over time than participants with shorter CI2 LOD (< 20 years). Notably, all participants in the longer CI2 LOD group also had longer CI1 LOD (> 25 years) and all participants in the shorter CI2 LOD group also had shorter CI1 LOD (< 18 years). Time-based factors in bilateral CI studies (i.e. age, LOD and time between surgeries) are often interrelated. Laske et al. (2009) used several measures to compare performance of the better ear, poorer ear and bilateral conditions and examined correlations between their test results and several time based variables: length of bilateral deafness prior to implantation of the first ear, time between CI surgeries, and length of bilateral CI experience. Time between surgeries was correlated with ear differences for sentence understanding in quiet with a trend toward the same result in noise. The authors

pointed out that due to the relationship between CI2 LOD and time between surgeries, their study results may have been related to CI2 LOD, which was not directly investigated. For the current study, the high correlations between CI2 LOD and other hearing-history time variables (e.g. CI1 LOD, age at onset SPHL, and time between surgeries) means that the effect noted in the results can not be attributed to CI2 LOD alone. The sample size was not sufficient to differentiate each time based hearing-history variable effect.

In spite of poorer performance overall, four of the seven participants in the current study with long-duration deafness developed useful CI2 open-set speech understanding (CNC scores 28–52% and HINT in noise scores 25–68% at 12 months). The CI2 ear of the three participants with minimal open-set speech understanding (CNC scores 0–11% and HINT in noise scores 3–29% at 12 months) had onset of SPHL by one year of age and had never been aided. Another three participants in this group with some open-set speech understanding had onset of SPHL as a youth (12–20 years) and at least some HA experience with the CI2 ear. The fourth had congenital SPHL but had consistently worn HAs in both ears from early childhood until the time of implantation. Although CI2 LOD was highly correlated with performance, it is likely that other factors, particularly HA experience may mitigate long-term deafness effects.

Localization

The current study also showed that localization significantly improved with bilateral CIs compared to either ear alone. This finding was expected and is consistent with previous studies (Litovsky et al., 2004; Nopp et al., 2004; Verschuur et al., 2005). The mean RMS error for the unilateral condition was 52° and 49° for CI1 and CI2 with the error reduced on average by more than 20° for the bilateral condition (mean 28°). The localization ability of bilateral CI recipients continues to be poorer than normal hearing adults. A group of normal hearing adults (n=24) evaluated in our laboratory on the same task had on average < 5° RMS error. Localization ability improved significantly in the bilateral condition from pre-bilateral-implant (mean 50° RMS) to six months (mean 30° RMS) ($p < 0.001$) without continued improvement at 12 months (mean 28° RMS). This same pattern was seen in a longitudinal study of simultaneously implanted adults (n =13) reported by Chang et al. (2010). Sound localization results using eight loudspeakers along a 108° arc (15.5° apart) and a variety of everyday sounds as stimuli revealed significant improvement between the pre-implant (mean 41° RMS) and sixmonth intervals (mean 29° RMS) with no significant additional improvement at 12 months (mean 23° RMS). Litovsky et al. (2004) and Litovsky, Parkinson and Arcaroli (2009) reported a group mean RMS error of 28° in the bilateral condition at three months post implant for a group of simultaneously implanted adults (n=17). Participants were seated in front of an eight loudspeaker array, 140° arc with loudspeakers 20° apart; noise burst were used as the stimuli. Together, these results suggest that localization abilities are developed fairly soon after bilateral implantation in postlingual adults, are stable over time, and do not differ substantially between simultaneously and sequentially implanted recipients.

Localization in the bilateral condition was poorer for participants with longer CI2 LOD than those with shorter CI2 LOD. This is consistent with results reported by Nopp et al. (2004)

who found a significant relationship between localization ability and LOD expressed as a fraction of age for both the first and second deafened ears; that is, the greater the percentage of life with SPHL, the poorer the localization ability. In the current study, the longer CI2 LOD group had lower (better) mean RMS scores for bilateral compared to either CI1 or CI2 but the difference was not statistically significant. Two participants from this group had bilateral RMS error scores (22–23°) comparable to the average of those with shorter CI2 deafness (22°). Both had onset of SPHL as a youth and at least some HA experience with the CI2 ear. The unique contribution of HA experience, CI1 LOD, CI2 LOD and the time between CI1 and CI2 surgeries on sequentially implanted bilateral CI patient outcomes needs additional study.

Self Reported Outcomes

Study participants perceived a significant reduction in disability by three to six months post-bilateral implant in all three domains of the SSQ, speech understanding, spatial hearing and quality of sound. The greatest improvement was in the spatial domain, a mean change of 2.87 points by the 9–12 month interval. Somewhat smaller improvements over this same time course were identified for the speech (2.05 points) and qualities (1.79 points) domains. Summerfield et al. (2006) reported SSQ results for participants whose speech recognition results were included in Ramsden et al. (2005). These participants also had significantly improved ratings from pre-bilateral to nine months post-bilateral in the spatial domain (mean 2.0 points) and smaller but significant improvements in the speech (just under 1 point) and qualities (just over 1 point) domains. Laske et al. (2009) compared SSQ scores of bilaterally implanted adults to unilaterally implanted adults (matched for age, CI experience and gender) and although the ratings were higher for the bilaterally implanted group, the difference was not significant. Identifying differences in perceived ability between groups may be more difficult than for the same individuals over time. For example, it is noteworthy that the SSQ was the one measure in the current study for which there was not a significant difference between the two CI2 LOD groups. The 12-month average ratings of participants with longer CI2 LOD (range speech 4.3–8.6; spatial 2.7–8.4; quality 5.0–8.8) were indistinguishable from ratings of participants with shorter CI2 LOD (range speech 4.9–8.5; spatial 1.3–9.3; quality 5.6–8.8). It is important to note that even though there were significantly improved SSQ ratings with bilateral implantation, there continued to be substantial perceived disability for understanding speech, spatial hearing and quality of sound.

Clinical Implications

Study findings suggest several clinical implications for adults considering second ear cochlear implantation. CI2 LOD was significantly correlated with the other hearing-history time variables (e.g. CI1 LOD, age at onset SPHL for CI1 and CI2) and all measures. These hearing-history time variables are therefore important factors to consider when discussing post-implant expectations. Most postlingually deafened adults can expect second ear outcomes similar to that of the first ear within 3–6 months of bilateral device use. Early post-implant differences between ears may be observed but are expected to diminish relatively quickly. Bilateral performance was superior to that of either ear alone on almost every measure which is a strong indicator that second ear implantation should be considered

for unilateral CI recipients who are unable to achieve a bimodal advantage when using a HA contralateral to the CI. Since LOD is an important variable related to outcome, a shorter time between surgeries is warranted. Patients with longer periods of deafness (in this study, greater than 30 years for CI2) should be counseled that speech recognition performance may be lower and progress slower in the second ear relative to the first implanted ear. For some individuals with longer periods of deafness, CI2 performance may not equal that of CI1, even after 12 months time. Whether this gap narrows with more experience and the impact of HA experience is unknown. Although individual results in the current study varied, particularly for participants with longer periods of deafness, all participants reported bilateral CI benefit.

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Appendix A

At Level 1 of the statistical model, performance for a particular participant within a particular CI condition was estimated as a quadratic polynomial growth curve. This can be described by the following model, using HINT sentences in noise performance as the example outcome:

$$\text{HINT}_{tij} = \pi_{0ij} + \pi_{1ij} \text{Time}_{tij} + \pi_{2ij} \text{Time}_{tij}^2 + e_{tij}$$

where the HINT sentences in noise performance at time t (e.g., three months) under CI condition i (e.g., bilateral) for participant j is estimated to be a function of an intercept (π_{0ij}), a linear component for time (π_{1ij}), and a quadratic component for time (π_{2ij}). The coefficients are expected to vary systematically across CI conditions. At Level 2 of the model, the coefficients from Level 1 are viewed as outcomes that depend on CI condition:

$$\begin{aligned}\pi_{0ij} &= \beta_{01j} D_{1ij} + \beta_{02j} D_{2ij} + \beta_{03j} D_{3ij} + r_{0ij} \\ \pi_{1ij} &= \beta_{11j} D_{1ij} + \beta_{12j} D_{2ij} + \beta_{13j} D_{3ij} + r_{1ij} \\ \pi_{2ij} &= \beta_{21j} D_{1ij} + \beta_{22j} D_{2ij} + \beta_{23j} D_{3ij} + r_{2ij}\end{aligned}$$

The three equations represent the intercept, linear component, and quadratic component of growth, respectively. The variables D_{1ij} , D_{2ij} , and D_{3ij} , are dummy codes that represent the particular CI conditions under which a score was obtained, with the subscript i indicating the CI condition (1 = first implanted ear, 2 = second implanted ear, 3 = bilateral) and subscript j indicating the particular participant. Measures collected for the first-implanted ear were thus indicated by a value of 1 for D_1 , and values of 0 for D_2 and D_3 . Measures collected for the second-implanted ear were indicated by a value of 1 for D_2 and values of 0 for D_1 and D_3 . Measures collected under the bilateral condition were indicated by a value of 1 for D_3 and values of 0 for D_1 and D_2 . Note that because a dummy code is included for each of the CI conditions, no intercept is included in the Level 2 models. By including the dummy codes at Level 2, the separate growth curve parameters under the different CI conditions can be estimated.

At Level 3, the coefficients from Level 2 (β) are viewed as outcomes that reflect individual differences across participants (j).

$$\begin{aligned}\beta_{01j} &= \gamma_{010} + \gamma_{011} \mathbf{X}_j + \mathbf{u}_{01j} \\ \beta_{02j} &= \gamma_{020} + \gamma_{021} \mathbf{X}_j + \mathbf{u}_{02j} \\ \beta_{03j} &= \gamma_{030} + \gamma_{031} \mathbf{X}_j + \mathbf{u}_{03j} \\ \beta_{11j} &= \gamma_{110} + \gamma_{111} \mathbf{X}_j + \mathbf{u}_{11j} \\ \beta_{12j} &= \gamma_{120} + \gamma_{121} \mathbf{X}_j + \mathbf{u}_{12j} \\ \beta_{13j} &= \gamma_{130} + \gamma_{131} \mathbf{X}_j + \mathbf{u}_{13j} \\ \beta_{21j} &= \gamma_{210} + \gamma_{211} \mathbf{X}_j + \mathbf{u}_{21j} \\ \beta_{22j} &= \gamma_{220} + \gamma_{221} \mathbf{X}_j + \mathbf{u}_{22j} \\ \beta_{23j} &= \gamma_{230} + \gamma_{231} \mathbf{X}_j + \mathbf{u}_{23j}\end{aligned}$$

The first three equations represent the intercepts under the three CI conditions and indicate that a particular participant's (j) intercept is a function of a grand mean across participants (e.g., γ_{010}) and a participant-level predictor (e.g., LOD, assumed to be grand-mean centered; γ_{011}). The second three equations represent the linear component of the growth curves and likewise represent these linear components separately for each CI condition and potentially varying as a function of individual differences. The last three equations represent the quadratic component of the growth curve. Contrast codes can then be used to compare particular coefficients. For example, a comparison of γ_{110} and γ_{120} tests whether the overall linear component of growth (at the point the data are centered) is different for the first-implanted ear and the second-implanted ear.

The HLM models were examined in two stages. An initial model included only the CI condition dummy variables at Level 2 and no moderators at Level 3. This model established the basic nature of change in performance over time, separately for each CI condition, for all participants. A second model was then tested that added a potential moderator to Level 3 to determine if the performance was additionally dependent on a characteristic of the participants (e.g., LOD in the second implanted ear). Note that the sample size prevents examining more than one predictor at Level 3.

Figure 1. Theoretical example of HLM curves and components

Examples of two theoretical HLM curves are shown (dotted and dashed lines) with the components indicated. Intercept is the expected performance at a point in time (the centering point) based on the HLM analysis of the group data. Three example intercepts are indicated with open circles along each curve (1, 2, 3 along the dashed line and a, b, c along the dotted line). Expected performance at the earliest point is much higher along the dashed line (1) than the dotted line (a). Linear Slope is the rate of change at a specific point in time (the centering point). That is, the slope of the tangent (gray lines) to the curve at the given time point. The linear slope at the intercept (b) is considerably steeper than the linear slope at the intercept (d). The rate of change is greater at the earlier time point. Curvilinearity is change in the linear component over time. The two example HLM curves differ in curvilinearity. The change over time is minimal for the dashed line and substantial for the dotted line. Each component and each condition has its own significance test that indicates if the parameter estimate is different from 0. For example, it is likely that the linear slope at (b) in Figure 1 would differ from 0 but the linear slope at (d) would not differ from 0. Comparisons of the components between CI conditions were conducted using chisquare tests.

Figure 2. Group mean speech recognition scores at the latest test interval

Group mean speech recognition scores in percent correct (panel A) and dB signal-to-noise ratio (SNR; panel B) at the latest test interval for the three cochlear implant conditions. Note that lower SNR scores indicate better performance. Scores are represented as white bars for the first implanted ear (CI1), gray bars for the second implanted ear (CI2) and black bars for bilateral cochlear implants. Error bars are one standard error. Significant differences are indicated with asterisk(s): * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Figure 3. Group mean results over time

Group mean results over time are indicated for the three cochlear implant (CI) conditions by test measure. The squares, diamonds and triangles represent group means at each test interval for the first CI (CI1), the second CI (CI2) and the bilateral conditions respectively. Error bars are one standard deviation. Significant differences are indicated in Table 4.

Figure 4. Scatter plots and correlations for speech recognition measures and cochlear implant conditions

Scatter plots and correlations for each speech recognition measure between second implanted ear (CI2) length of deafness and latest test interval scores for the three cochlear implant conditions: first implanted ear (CI1) in the first column, second implanted ear (CI2) in the second column, and bilateral cochlear implants in the third column. Correlations are indicated on each plot and significance indicated with asterisks (** $p < 0.01$; *** $p < 0.001$).

Figure 5. Group mean results over time plotted by length of deafness group

Group mean results over time for the three cochlear implant (CI) conditions are plotted separately for participants in the longer and shorter second implanted ear (CI2) length of deafness (LOD) groups. The longer CI2 LOD group is indicated with gray lines and symbols and includes participants with CI2 LOD > 30 years. The shorter CI2 LOD group is indicated with black lines and symbols and includes participants with CI2 LOD < 20 years. The squares, diamonds and triangles represent group means at each test interval for the first CI

(CI1), the second CI (CI2) and the bilateral conditions, respectively. Error bars are one standard deviation. Significant differences are indicated in Table 5.

Figure 6. Group mean RMS localization error in degrees

Panel A graphs the group mean RMS localization error in degrees at three test intervals (pre-bilateral in white, 6 months in gray and 12 months in black) for the first implanted ear (CI1), the second implanted ear (CI2) and bilateral cochlear implants. Panel B graphs the group mean RMS localization error in degrees at the 12-month interval for the longer and shorter second implanted ear (CI2) length of deafness (LOD) groups. Scores are represented as white bars for CI1, gray bars for CI2 and black bars for bilateral cochlear implants. Error

bars are one standard error. Significant differences are indicated with asterisks (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

Figure 7. Group mean ratings for the Speech, Spatial and Qualities of Hearing scale
Group mean ratings are plotted over time for the three domains of the Speech, Spatial and Qualities of Hearing scale (Speech, light gray diamonds; Spatial, medium gray squares; Quality, black diamonds). Error bars are one standard error. Significant changes from pre-bilateral are indicated with asterisks (** $p < 0.01$; *** $p < 0.001$) and from the 1-month interval with plus signs (+ $p < 0.05$; ++ $p < 0.01$). There were no significant differences between the 3–6 month and 9–12 month periods for any domain.

Table 1

Participant demographic and hearing history information

	Etiology	Ear	Age at Surgery		TBS	Age Onset (HL/SPHL)		LOD		HA Use	
			C11	C12		C11	C12	C11	C12	C11	C12
P1	Mondini	LE	47	64	17	0/9	0/9	38	55	39	0
P2	Noise	LE	55	58	3	34/42	34/42	13	16	20	23
P3	Autoimmune	RE	58	63	5	5/58	5/61	<1	2	28	10
P4	Familial	RE	39	45	6	6/30	6/38	9	7	30	29
P5	Possible Ototoxicity	RE	42	48	6	26/33	26/33	9	15	10	12
P6	Familial/Meniere's	RE	42	44	2	35/42	8/41	<1	3	7	8
P7	Meningitis	RE	46	47	1	1/1	1/1	45	46	39	0
P8	Unknown	RE	74	75	1	15/59	15/59	15	16	26	25
P9	Unknown	RE	50	51	1	0/20	0/20	30	31	2	2
P10	Autoimmune	LE	54	59	5	40/51	40/53	3	6	7	8
P11	Familial	RE	47	52	5	14/42	14/42	5	10	0	0
P12	Ototoxicity	RE	54	57	3	10/17	10/17	37	40	25	27
P13	Unknown	LE	39	53	14	0/4	0/4	35	49	30	0
P14	Maternal Rubella	RE	36	39	3	0/0	0/0	36	39	36	38
P15	Familial	RE	53	57	4	15/45	15/45	8	12	33	37
P16	Familial	RE	38	51	13	5/12	5/12	26	39	3	3
P17	Familial	RE	43	45	2	5/28	5/28	15	17	0	0
P18	Unknown	LE	56	57	1	30/39	30/39	17	18	21	23
P19	Unknown	RE	47	57	10	15/42	15/42	5	15	16	18
P20	Familial	RE	47	54	7	30/41	30/41	6	13	7	14
P21	Familial	LE	52	53	1	45/52	45/53	<1	<1	4	6
<hr/>											
		Mean	48.5	53.8	5.2	15.8/31.8	14.5/32.4	16.8	21.4	18.2	13.5
		SD	8.7	8.0	4.6	14.7/18.6	14.1/19.0	14.6	16.8	13.6	12.6

Note: All numeric information is in years. C11 = First cochlear implant; C12 = second cochlear implant; TBS = time between surgery; HL = hearing loss; SPHL = severe to profound hearing loss; HA = hearing aid; P = participant; LE = left ear; RE = right ear.

Table 2

Group mean hearing thresholds

	.25 Hz	.5 Hz	1k Hz	2k Hz	3k Hz	4k Hz	6k Hz	8k Hz
Unaided Pre-I (CI2)	80.0 (23.2)	92.4 (16.1)	106.4 (11.1)	111.3 (11.3)	117.1 (11.5)	119.8+ (11.2)	117.4+ (5.8)	109.8+ (1.1)
Aided SF thresholds Pre-I (CI2)	33.6 (16.2)	46.1 (13.7)	48.6 (12.7)	59.9 (10.1)	70.7+ (7.2)	73.3+ (4.4)	75.1+ (2.2)	
CI SF thresholds (CI1)	17.2 (4.7)	19.2 (4.6)	20.7 (4.1)	18.2 (5.6)	24.0 (6.2)	23.8 (5.4)	25.3 (12.3)	

Note: Standard deviations are indicated in parentheses; Hz = Hertz; Pre-I = Pre-implant; CI2 = second cochlear implant; SF = soundfield; CI1 = first cochlear implant

Table 3

Cochlear implant device information obtained at the six-month post-bilateral test interval

	First Cochlear Implant (CI1)					Second Cochlear Implant (CI2)				
	External	Internal	Strategy	Rate	#	External	Internal	Strategy	Rate	#
P1	Spectra	N22	Speak	250	17	Freedom	N24RE	ACE	1800	22
P2	Freedom	N24RE	ACE	1800	22	Freedom	N24RE	ACE	1800	22
P3	Freedom	N24	ACE	900	19	Freedom	N24RE	ACE	1800	22
P4	Esprit 3G	N24	ACE	1800	19	Freedom	N24RE	ACE	1800	22
P5	Freedom	N24RE	ACE	1200	20	Freedom	N24RE	ACE	1200	22
P6	Freedom	N24	ACE	1800	19	CP810	N512	ACE	500	22
P7	Freedom	N24RE	ACE	1200	22	Freedom	N24RE	ACE	900	22
P8	Freedom	N24RE	ACE	1800	20	Freedom	N24RE	ACE	1800	20
P9	Harmony	90K	HR120	2250	14	Harmony	90K	HR120	2250	14
P10	Freedom	N24RE	ACE	1200	20	CP810	N512	ACE	1200	22
P11	Harmony	CII	HR120	3712	13	Harmony	90K	HR120	3712	16
P12	Esprit 3G	N22	Speak	250	19	Freedom	N24RE	ACE	500	22
P13	Harmony	90K	HR120	2560	14	Harmony	90K	HR120	2560	11
P14	Freedom	N24	ACE	500	21	CP810	N512	ACE	500	21
P15	PSP	90K	HR120	2184	16	Harmony	90K	HR120	2184	16
P16	CP810	N512*	ACE	1200	10	CP810	N512	ACE	1800	22
P17	Freedom	N24RE	ACE	1200	22	Freedom	N24RE	ACE	1200	19
P18	Freedom	N24RE	ACE	1200	22	CP810	N512	ACE	1200	22
P19	Freedom	N24RE	ACE	1800	22	Freedom	N24RE	ACE	900	22
P20	Clarion	CII	HR120	3712	16	Harmony	90K	HR120	3712	14
P21	Freedom	N24RE	ACE	900	22	Freedom	N24RE	ACE	500	22

Note: # = number of active electrodes; P = participant; ACE = advanced combination encoder; HR = high resolution; PSP = platinum speech processor; N = Nucleus

* P16's original first ear cochlear implant was a Nucleus 22. After 12 years this device was explanted and P16's first ear was reimplanted with a System 5. All testing was completed with the System 5 and CP810.

Table 4

Hierarchical linear modeling summary of significant differences

Test	Component	CI1	CI2	Bilateral	CI1 vs. CI2	CI1 vs. Bil	CI2 vs. Bil
CNC	Curvilinearity		*	n/a	*	n/a	n/a
	Linear Slope		*P _{1,3,6,9,12}	n/a	*P _{1,3,6,9,12}	n/a	n/a
	Intercept	*P _{1,3,6,9,12}	*P _{1,3,6,9,12}	n/a	*P _{1,3}	n/a	n/a
HINT-N	Curvilinearity		*		*		*
	Linear Slope		*P _{1,3,6,12}	*P _{1,3,6}	*P _{1,3,6,12}		*P _{1,3,6,12}
	Intercept	*P _{1,3,6,9,12}	*P _{1,3,6,9,12}	*P _{1,3,6,9,12}	*P _{1,3,12}	*3,9,12	*P _{1,3,12}
TIMIT-N	Curvilinearity		*		*	*	*
	Linear Slope	* ₉	*P _{3,6}	* _{3,6}	*P _{3,6,12}		*P _{3,6}
	Intercept	*P _{3,6,9,12}	*P _{3,6,9,12}	*P _{3,6,9,12}	*P ₃	*3,6,9,12	*P _{3,6,9}
TIMIT-Q	Curvilinearity		*	*	*		*
	Linear Slope	*P _{1,3}	*P _{1,3,6,9,12}	*P _{1,3,6}	*P _{1,3,6,12}	* ₆	*P _{1,3,6,9,12}
	Intercept	*P _{1,3,6,9,12}	*P _{1,3,6,9,12}	*P _{1,3,6,9,12}	*P _{1,3,12}	*3,6,9,12	*P _{1,3,6,9,12}
R-Space	Curvilinearity		*		*		
	Linear Slope		*P _{1,3,6}	*P _{1,3,6}	*P _{1,3,6,12}		*P _{1,3}
	Intercept	*P _{1,3,6,9,12}	*P _{1,3,6,9,12}	*P _{1,3,6,9,12}	*P _{1,3}	*3,6,9	*P _{1,3,12}
BKB-SIN	Curvilinearity		*		*		*
	Linear Slope		*P _{3,6,12}	* ₆	*P _{3,6,12}		*P _{3,6,12}
	Intercept	*P _{3,6,12}	*P _{3,6,12}	*P _{3,6,12}	*P ₃	*3,6,12	*P _{3,12}

Note: CI1 = first cochlear implant, CI2 = second cochlear implant, Bil = bilateral, n/a = not applicable, P = pre-bilateral interval, 1–12 indicate post-bilateral intervals

*
p 0.005

Significant differences (from zero or between CI conditions) are indicated with an asterisk followed by the test intervals for which significant differences occurred. For example, on the HINT-N the first three significant findings columns indicate the quadratic component of the CI2 curve (but not CI1 or Bilateral) was significantly different from zero (straight). The three far right columns indicate that the CI2 quadratic curve component was significantly different from that of CI1 and Bilateral which were not significantly different from each other. CI2 and Bilateral linear slopes (rate of change) were significantly different from zero at P_{1, 3, 6, 12} and at P_{1, 3, 6} respectively. CI2 linear slope differed significantly from CI1 and Bilateral at P_{1, 3, 6} and 12. CI1 linear slope was not significantly different from zero at any interval and did not differ significantly from Bilateral at any interval. Significant differences for intercept are indicated in the same manner as for linear slope. Only significant post-hoc results following significant overall tests are indicated.

Table 5

Hierarchical linear modeling summary of significant findings including CI2 LOD as a moderator

Test	Component	Shorter CI2 LOD			Longer CI2 LOD			Shorter vs Longer CI2 LOD		
		CI1 vs. CI2	CI1 vs. Bil	CI2 vs. Bil	CI1 vs. CI2	CI1 vs. Bil	CI2 vs. Bil	CI1	CI2	Bil
CNC	Curvilinearity	*	n/a	n/a		n/a	n/a			n/a
	Linear Slope	*P,1,3,6,12	n/a	n/a	*P,1,3	n/a	n/a		*1,3,6	n/a
	Intercept	*P,1	n/a	n/a	*P,1	n/a	n/a	*1,3,6,9	*1,3,6,9,12	n/a
HINT-N	Curvilinearity	*		*					*	
	Linear Slope	*P,1,3,6,12		*P,1,3,6,12	*6				*P,1,3,12	
	Intercept	*P,1		*P,1,3	*P,1,3		*P,1,3,6,9,12	*1,3,6,9,12	*1,3,6,9,12	*1,3,6,9
TIMIT-N	Curvilinearity	*		*					*	
	Linear Slope	*P,3,6,12		*P,3,6,12					*P,3,6,12	
	Intercept	*P		*P,1					*3,6,9,12	*P,3,6,9,12
TIMIT-Q	Curvilinearity	*		*					*	
	Linear Slope	*P,1,3,6,12		*P,1,3,6,12					*P,1,3,6,12	
	Intercept	*P,1		*P,1,3				*1,3,6,9,12	*1,3,6,9,12	*P,1,3,6,9,12
R-Space	Curvilinearity	*		*					*	
	Linear Slope	*P,1,3		*P,1,3,6					*P,1,3	
	Intercept	*P,1		*P,1				*P,1,3,6,9	*1,3,6,9,12	*P,1,3,6,9,12
BKB-SIN	Curvilinearity	*		*					*	
	Linear Slope	*P,3,6,12		*P,3,6,12	*P,3,6				*P,3,6,12	
	Intercept	*P		*P,3	*P,3		*P,3,6,12	*3,6,12	*3,6,12	*3,6,12

Note: LOD = length of deafness, CI1 = first cochlear implant, CI2 = second cochlear implant, Bil = bilateral, n/a = not applicable, P = pre-bilateral interval, 1–12 indicate post-bilateral intervals, significant differences are indicated with an asterisk or asterisk followed by test intervals for which significant differences occurred.

* $p < 0.005$.

See Table 3 note for interpretation example. Only significant post-hoc results following significant overall tests are indicated.