



HAL
open science

Early Sentence Recognition in Adult Cochlear Implant Users

Chris James, Chadlia Karoui, Marie-Laurence Laborde, Benoit Lepage, Charles-Édouard Molinier, Marjorie Tartayre, Bernard Escudé, Olivier Deguine, Mathieu Marx, Bernard Fraysse

► **To cite this version:**

Chris James, Chadlia Karoui, Marie-Laurence Laborde, Benoit Lepage, Charles-Édouard Molinier, et al.. Early Sentence Recognition in Adult Cochlear Implant Users. *Ear and Hearing*, 2019, 40 (4), pp.905–917. 10.1097/aud.0000000000000670 . hal-02341936

HAL Id: hal-02341936

<https://hal.science/hal-02341936>

Submitted on 28 Apr 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Early Sentence Recognition in Adult Cochlear Implant Users

Chris J. James,^{1,2} Chadlia Karoui,^{1,3} Marie-Laurence Laborde,¹ Benoît Lepage,⁴ Charles-Édouard Molinier,¹ Marjorie Tartayre,¹ Bernard Escudé,⁵ Olivier Deguine,^{1,3} Mathieu Marx,^{1,3} and Bernard Fraysse¹

Objective: Normal-hearing subjects listening to acoustic simulations of cochlear implants (CI) can obtain sentence recognition scores near 100% in quiet and in 10 dB signal-to-noise ratio (SNR) noise with acute exposure. However, average sentence recognition scores for real CI listeners are generally lower, even after months of experience, and there is a high degree of heterogeneity. Our aim was to identify the relative importance and strength of factors that prevent CI listeners from achieving early, 1-mo scores as high as those for normal-hearing-listener acoustic simulations.

Design: Sentence recognition scores (100 words/list, 65 dB SPL) using CI alone were collected for all adult unilateral CI listeners implanted in our center over a 5-yr period. Sentence recognition scores in quiet and in 10 dB SNR 8-talker babble, collected from 1 to 12 mo, were reduced to a single dependent variable, the “initial” score, via logarithmic regression. “Initial” scores equated to an improved estimate of 1-mo scores, and integrated the time to rise above zero score for poorer performing subjects. Demographic, device, and medical data were collected for 118 subjects who met standard CI candidacy criteria. Computed tomography of the electrode array allowing determination of the insertion depth as an angle, and the presence or absence of scala dislocation was available for 96 subjects. Predictive factors for initial scores were selected using stepwise multiple linear regression. The relative importance of predictive factors was estimated as partial r^2 with a low bias method, and statistical significance tested with type II analysis of variance.

Results: The etiologies chronic otitis and autoimmune disease were associated with lower, widely variable sentence recognition scores in the long-term. More than 60% of CI listeners scored >50/100 in quiet at 1 mo. Congenital hearing loss was associated with significantly lower initial scores in quiet (r^2 0.23, $p < 0.001$), as was longer duration of hearing loss (r^2 0.12, $p < 0.001$, -0.76 pts per year). Initial scores were negatively correlated with insertion depth (r^2 0.09, $p < 0.001$, -0.1 pts per degree), with the highest initial scores being obtained for insertion depths of 300° to 400°. A much greater proportion of scala dislocations was found for perimodiolar arrays compared with straight arrays. Scores were negatively correlated with the proportion of the active electrode array found in scala vestibuli for Nucleus perimodiolar devices (r^2 0.14, $p < 0.01$, coefficient -25). Similar overall results were obtained for sentence recognition scores in noise (+10 dB SNR). The intercept value for the obtained regression functions indicated that CI listeners with the least limiting factors generally scored ~95/100 in quiet and ~90/100 in noise. In addition, CI listeners with insertion angles as low as 315° to 360° could obtain sentence recognition scores >80/100 even at 1 day after activation. Insertion depths of 360° were estimated to produce frequency-place mismatches of about one octave upward shift.

Conclusions: Patient-related factors etiology and duration of deafness together explained ~40% of the variance in early sentence recognition scores, and electrode position factors ~20%. CI listeners with insertion depths of about one turn obtained the highest early sentence recognition scores in quiet and in noise, and these were comparable with those reported in the literature for normal-hearing subjects listening to 8 to 12 channel vocoder simulations. Differences between device brands were largely explained by differences in insertion depths. This indicates that physiological frequency-place mismatches of about one octave are rapidly accommodated by CI users for understanding sentences, between 1 day to 1 mo postactivation, and that channel efficiency may be significantly poorer for more deeply positioned electrode contacts.

Key words: Cochlear implant, Frequency Allocation, Insertion depth, Patient-related factors, Sentence recognition.

(Ear & Hearing 2019;40:905–917)

INTRODUCTION

Cochlear implants (CI) can restore sensitivity to sound in deaf patients. The main aim for clinicians and manufacturers alike is to restore speech understanding in adult patients and allow the development of spoken language communication in children. In adult postlinguistically deaf patients, a primary outcome measure is the level of sentence recognition in quiet. This requires the complete integration of auditory information provided by the CI into the recipient’s existing linguistic processing capacities.

Speech recognition outcomes are known to be variable in CI recipients and depend on patient-related factors such as etiology of deafness, duration of deafness, and in some cases age and cognitive function (Blamey et al., 1996; Holden et al., 2013; Lazard et al., 2012; Lazard & Giraud, 2017). Outcomes in terms of sentence recognition scores are seen to improve over time from the first day of CI activation; however, while some CI listeners rapidly achieve high scores others may only obtain limited understanding of speech even after many months of experience. In the words of Holden et al. (2013), the highest performing CI listeners are those with the least limiting factors. Limiting factors may be patient related. However, device-related limiting factors may also play a role, as discussed below.

Normal-hearing (NH) subjects listening to acoustic vocoder simulations of CIs (e.g., Friesen et al., 2001) can achieve high sentence recognition scores even after only limited exposure. Parameters in CI simulations such as the number of channels, channel overlap, the type of carrier, and the mismatch in frequency-to-place mapping have been investigated, but scores for NH listeners remain consistently high for all but the most degraded conditions (e.g., <4 channels, considerable frequency mismatch). Even in some conditions that produce low scores in

¹Service ORL, CHU Toulouse, Toulouse, France; ²Cochlear France SAS, Toulouse, France; ³Centre de recherche Cerveau et Cognition, University Paul Sabatier, Toulouse, France; ⁴Service d’Épidémiologie, CHU Toulouse, Toulouse, France; and ⁵Radiologie, Clinique Pasteur, Toulouse, France.

acute testing, NH listeners can adapt to some distortions after relatively modest amounts of exposure or training (Fu & Galvin, 2007; Rosen et al., 1999).

In a landmark study by Friesen et al. (2001), the number of channels was varied for NH listeners and CI listeners to infer the number of effective channels that may be accessed via a CI. For NH listeners, average sentence recognition scores reached near 100% correct for 6–8 channels in quiet, and for 8–10 channels in noise [+10 dB signal-to-noise ratio (SNR)]. Average scores for CI listeners reached only 80% correct in quiet and 60% in noise for eight channels or greater. These findings implied that CI listeners cannot access more than about eight effective channels even when using a higher number of physical channels (e.g., all 16–22 electrodes). However, the authors did note that the best CI listeners achieved maximum scores similar to those of NH listeners while using similar numbers of physical channels.

Patient-Related Factors

Different durations of severe or profound deafness and therefore different exposures to sound before CI has been shown to explain some of the variability seen in speech recognition scores among patients (Blamey et al., 1996, 2013). Indeed, the use of hearing aids during a period of progressive hearing loss improves outcomes compared with nonuse for similar durations of deafness (Lazard et al., 2012). Once sensitivity to sound is restored using a CI, we would predict that recipients may take some time to accommodate to the new sound sensations, and to associate speech sounds processed via the CI with those they remember. Furthermore, learning to decode aural speech sounds may require a longer period for individuals who had limited hearing during childhood. Thus, sentence recognition scores early after CI activation may be low or zero and take some time to improve to a useful level. In addition, loss of cognitive function, due to aging, may slow the reacquisition of speech understanding, or limit it. (Schneider et al., 2010).

CI listeners' sentence recognition scores also vary according to the etiology of deafness (Blamey et al., 1996, 2012; Lazard et al., 2012): The physiological condition of the cochlea and its suitability for electrical stimulation may be significantly degraded, and this may also apply to the auditory nerve and higher centers. Leaving aside central processing deficits, such as those produced by auditory neuropathy spectrum disorder and acoustic neuromas, the cochlea structure itself may be damaged by physical trauma or specific disease such as meningitis and labyrinthitis. This may induce fibrosis, and in the extreme, considerable structural and neural damage (Schuknecht, 1974). Aberrant current paths may result, which distort consistent frequency-to-place percepts or simply degrade neural representation of frequency and temporal modulation (Garadat et al., 2012, 2013).

In the absence of substantial auditory deprivation, we might expect sentence recognition scores obtained by CI listeners early after activation to be similar to those measured for NH listeners. That is, if electrical stimulation channels in CI listeners worked equally well across the frequency range, similar to acoustic channels in vocoders. However, additional peripheral physiological factors that are common across CI listeners may limit performance to below that of NH listeners. These factors are generally assumed to produce fewer effective channels than

the number of physical electrodes. Some relevant aspects of peripheral hearing physiology that may be analyzed *in vivo* are addressed in the following sections.

Spiral Ganglion Morphology

The most parsimonious frequency band to electrode allocation in a CI would reproduce natural cochlear tonotopy. A normal human frequency-place function for the human spiral ganglion (SG) was derived by Stakhovskaya et al. (2007). The SG is considered the primary site of neural excitation produced by electrical stimulation of the cochlea (e.g., Kalkman et al., 2014). Tracing of dendritic processes has allowed conversion of the distance-to-frequency function for the Organ of Corti (Greenwood, 1990) to an angular function of frequency specifically for the SG. While in a typical human cochlea, the Organ of Corti and therefore the scala tympani (ST) extend to two and a half turns, Rosenthal's canal containing the SG extends to two turns or less (Ariyasu et al., 1989; Kawano et al., 1996; Stakhovskaya et al., 2007). Most of the compression occurs from the end of the first turn toward the low-frequency, apical end with increasing spatial density of SG neurons (Sridhar et al., 2006). In addition, Rosenthal's canal is only well defined in the first turn and ends in a terminal bulb at the level of the medial turn with disordered innervation to both the 2nd and 3rd turns of the Organ of Corti (Rask-Andersen et al., 2010). The absolute diameter of the SG is also substantially reduced in the 2nd turn (Figure 1, short dashed line taken from Stakhovskaya et al., 2007), contributing to the potential for reduced spatial selectivity for electric stimulation. There is some evidence from electrically evoked compound action potentials that electrode contacts in the 2nd turn of the ST produce channels that overlap considerably (Biesheuvel et al., 2016) and therefore reduce their efficiency in transmitting independent information. They can also produce pitch confusions (Kalkman et al., 2014; Kenway et al., 2015) such that speech recognition scores may be improved by deactivating the most apical contacts for longer electrode arrays (Gani et al., 2007 and for a review see Boyd, 2011).

Frequency-Place Mismatches

Frequency-place mismatches in CIs are influenced by two parameters: the physical position of the electrode array contacts and the frequency-to-electrode allocation used in the sound processor program. Using measurements from postoperative X-ray images in a clinical population, Landsberger et al. (2015) found an average upward basal shift of one octave relative to the SG function. Greater average mismatches were seen for low frequencies, with variation across devices. For a given frequency-to-electrode allocation, variations in frequency-place mismatches are produced by complex interactions between the design of the array (i.e., precurved perimodiolar or free-fitting straight), including the spacing of electrode contacts, the size of the cochlea (Escudé et al., 2006) and surgical technique (e.g., round window versus inferior cochleostomy opening of the cochlea, Briggs et al., 2006). The effects on speech recognition of mismatches between the place of stimulation associated with acoustic frequency and the actual mapping of frequency to electrode locations have been explored in normal-listener acoustic simulations. NH subjects listening to vocoded speech, where the synthesis bands are shifted upward in frequency relative to the analysis bands, initially exhibit reduced speech perception

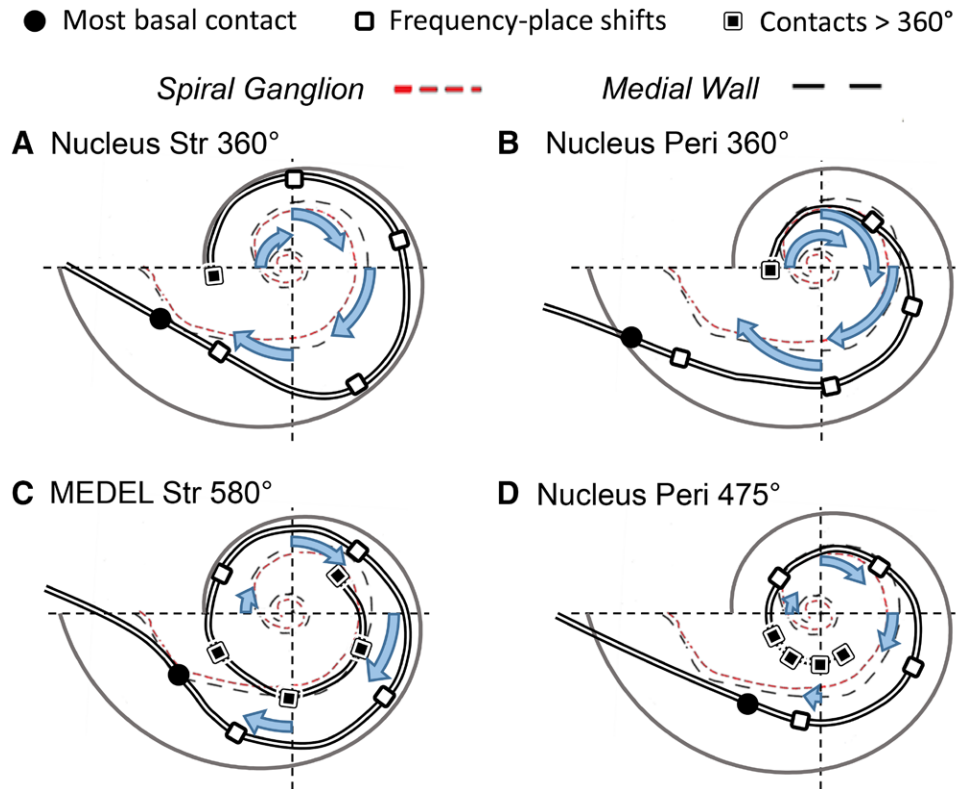


Figure 1. Four examples of electrode contact positions derived from postoperative CT imaging. Frequency-place shifts are indicated by the curved arrows, for a subset of electrode contacts for clarity; 90° corresponds to approximately one octave. Solid line lateral wall, dashed lines medial wall, and SG (to scale $\pm 15\%$ schematic from Fig. 3, Stakhovskaya et al., 2007).

compared with aligned bands. However, NH listeners are able to adapt to <1.5 octave basal shifts with prolonged exposure, within the order of tens of minutes, or with specific training (Faulkner et al., 2006; Fu & Galvin, 2003; Li et al., 2009; Rosen et al., 1999). Similarly, CI listeners are able to adapt to new frequency-to-electrode allocations over time, at least for consonant recognition and high-context (i.e., HINT) sentence recognition (Fu et al., 2002; McKay & Henshall, 2002). We may infer from these results that CI listeners may accommodate frequency-place mismatches within a relatively short time of having their sound processor activated, provided that channels transmit information effectively, and that there are no factors that may negatively affect their ability to process information. This type of short-term accommodation may be complemented by long-term re-normalization to pitch differences between electric hearing and residual acoustic hearing, that may be induced by the specific mapping of frequencies to electrode positions by the sound processor (McDermott et al., 2009; Tan et al., 2017).

In Figure 1, panels A to D, we illustrate frequency-place mismatches estimated for four CI recipients. Individual electrode contact positions were measured from ConeBeam computed tomography (CT) images using the cochlear view schema of Xu et al. (2000). The four arrows in each case indicate the degree of basal shift between a given frequency on the SG and the actual position of the electrode allocated to that frequency in the sound processor. Using the round window as the reference (0°), 90°, 180°, 270°, and 360° on the SG correspond to frequencies of approximately 6193, 3174, 1539 and 785 Hz (Stakhovskaya et al., 2007, Table 3). Basal shifts of between half and one octave, or a reduction in angle of 60–90° along the SG, are

seen in cases A, B, and C, with lower shifts seen for the more deeply inserted Nucleus perimodiolar electrode (most apical contact at 475°, panel D). The shifts for the MEDEL electrode (C) are about the same as for Nucleus straight electrode (A) despite a much greater angle for the most apical contact (580°). The default center frequency allocated to the most apical electrode in the Nucleus processor is ~250 Hz, and ~150 Hz in the MEDEL FS4/FSP processing strategies (Landsberger et al., 2015); this is a difference of 0.75 octaves. Further, center frequency spacings across the processor bandwidths are not necessarily comparable; for example, the spacings are not generally twice as large in the MEDEL processor as in the Nucleus processor, as might be expected from having roughly half as many channels in the 12-channel MEDEL system compared with the 22-channel Nucleus system. In fact, the default spacings are logarithmic in the MEDEL processor. The Nucleus processor uses a linear spacing up to approximately 1 kHz, followed by a logarithmic spacing for higher frequencies. The end result of these differences in sound processing, and particular electrode contact positions, is that the place-frequency mismatches are approximately equal for C and D in Figure 1 despite a difference of 105° in insertion depth.

Two examples are given in Figure 1 (B and D) for the same perimodiolar array type (Nucleus Contour Advance) with different insertion depths. Using the same frequency-to-electrode allocation, the mismatches would be different as indicated by the lengths of blue arrows. There can also be different frequency-place mismatches with approximately the same insertion depth: In panels A and B in Figure 1, the angle for the most apical electrode contact is approximately 360°. However, the

mismatches for the perimodiolar electrode (B) are nearly twice as large as those of the straight “lateral wall” electrode (A). This is due to differences in the design of the arrays such as the particular electrode contact spacings and the lateral versus medial position (note that both arrays have 22 electrode contacts and use the same default frequency-to-electrode allocation). Using the examples in Figure 1 as a guide, to obtain <1.5 octave basal shift the apical contact would need to be inserted to greater than 300° for Nucleus devices. For the MEDEL device, a deeper than 490° insertion would be required to obtain mismatches <1.5 octave.

The Effect of Electrode Insertion Depth on Speech Recognition Performance

If channel efficiency is reduced for electrode contacts >360°, then we expect to see reduced speech recognition performance for more deeply inserted electrodes. Indeed, lower speech recognition scores have been associated with greater insertion depths in several studies (Finley et al., 2008; Holden et al., 2013; Lazard et al., 2012).

However, several studies have reported the opposite effect with higher speech recognition scores associated with greater insertion depths: For example, in a study by Buchman et al. (2014), speech recognition scores were compared between two small groups of patients implanted with similar MEDEL electrode arrays of different active lengths of 26.4 mm (N = 7) and 20.9 mm (N = 6), resulting in mean apical insertion depths of 658° and 423°. Average sentence recognition scores 1 to 2 mo postactivation were ~30% points higher for the longer electrode group compared with the shorter electrode group. As well, O’Connell et al. (2016) found a positive correlation with word recognition scores for MEDEL CI listeners over insertion depths of 317° to 710°. In these two studies, the frequency-place shifts would range from much greater than +2 octaves, for the shallowest insertions, down to below +0.5 octaves for the deepest. In these studies, CI listeners with electrodes positioned at the shallowest angles may not have been able to adapt to the large basal shifts and hence had poorer speech recognition. Furthermore, in the study by O’Connell et al., it is not clear why insertion depths of only 360° to 450° were obtained for some subjects with standard arrays of 28 to 32 mm, which are designed to extend over two full turns of the cochlea. Thus, other surgical or anatomical factors may have had an influence on the performance of these cases. A study by Yukawa et al. (2004) also reported a positive correlation between speech recognition scores and insertion depth, this time for Nucleus CI listeners with a minimum depth of 211°. We note in the study by Yukawa et al. that there appeared to be a peak in word scores for angles 300 to 400°, with much poorer scores for very low insertion angles and the largest angles often producing poorer scores.

In summary, the positive effect of increased insertion depth seen in these three studies may have been due to the presence of extreme basal shifts for the lowest insertion depths. To better understand this, we may consider studies of within-subject experimental manipulation of active insertion depth for CI listeners. These studies have deactivated a number of apical electrodes and varied the frequency to electrode allocation. Başkent and Shannon (2005) measured speech recognition in MEDEL CI listeners as a function of

acute variations of insertion depth from deep insertion with 10 electrodes at 29 mm to shallow insertion with a single electrode at 7 mm. Speech recognition improved with deeper insertion, reaching an maximum at 19.2 to 21.6 mm, corresponding to ~360°, with no further improvement for greater simulated depths. In this condition, which used matched frequency-to-place channels, information was also progressively added as insertion depth increased. This suggests that channels >360° may have been very ineffective in conveying information and that CI listeners may potentially ignore these channels with experience.

Başkent and Shannon (2005) also included conditions where the entire frequency range was compressed across fewer activated channels. Speech recognition generally decreased compared with using the ≥360°, frequency-place matched conditions. Another acute study by Hochmair et al. (2003) had also tested a compressed condition using the eight most basal channels of the 12-channel MEDEL array, corresponding to ~360° insertion depth: Their compressed condition showed poorer speech recognition scores than when using the full length of the array. In their compressed condition, the upward frequency-place shift would have been >1.5 octaves, which is known to produce reduced speech recognition in acute vocoder experiments (e.g., Faulkner et al., 2006), and duplicated the result seen for similar compressed conditions in the study by Başkent and Shannon. In addition, vowel discrimination was lowest in the study by Hochmair et al. using the four most apical electrode contacts compared with using the middle or basal four contacts, supporting the hypothesis that channel efficiency is reduced toward the apex.

The aforementioned studies appear to indicate that there may be two opposite effects of insertion depth on the speech recognition scores for CI listeners: one positive, where increased insertion depth may reduce place-frequency mismatches to <1.5 octaves, and one negative where channel efficiency is significantly reduced for electrode positions >360°, possibly due to SG morphology. Either effect may reduce the performance of CI listeners to below that of NH listeners, as can the patient-related factors mentioned in previous sections.

Aims of the Study

As indicated in the Friesen et al. (2001) study, speech recognition scores for the best CI listeners are close to those for NH listeners in vocoder experiments, and it is important to identify the limiting factors that may prevent CI listeners from achieving the best level of performance (Holden et al., 2013). We examined the effect of etiology, auditory experience, type of device, and electrode position factors on sentence recognition in quiet and in noise. We analyzed the sentence recognition scores of adult CI listeners collected longitudinally over 12 months, as part of our standard clinical follow-up. To avoid selection bias, data were collected for all 118 adult patients implanted in our center between May 2009 and May 2014 who met the inclusion/exclusion criteria as indicated in the Methods section. Sentence recognition was tested in quiet and in 10 dB SNR multi-talker babble. The aim of the analysis was to establish the best level of sentence recognition that can be achieved by CI listeners early after activation and identify the relative importance and strength of factors associated with poorer performance.

MATERIALS AND METHODS

Population

We collected standard clinical data for all adult patients who were unilaterally implanted in our center over the 5-yr period. Those patients who underwent a revision surgery or received a second implant, either simultaneously or within the 12-mo follow-up period, were excluded. Also excluded were patients with significant cerebral trauma, with ossification preventing complete insertion of electrode arrays, and those who were not native French speakers. In addition, those patients participating in a CI program to treat single-sided deafness with tinnitus were excluded. Therefore, included patients met the standard criteria for cochlear implantation in France, with <50% correct word recognition in quiet with appropriately fit hearing aids, and at least severe levels of bilateral hearing loss.

Biographical data, device type, and electrode position data that were available from CT were collected from case notes for each patient. CT imaging data were acquired via two systems: A helical scanner with 0.67 mm slices reconstructed every 0.1 mm (Philips, collimation 20×0.625 , F.O.V. 160 mm, 140 kV 300 mAs, pitch 0.313 μm , high resolution 1024×1024 matrix, rotation 0.75, exposure 9.9 sec), and a flat panel “Cone Beam” volume tomograph producing 0.125 mm isometric voxels (New Tom, detector $200 \text{ mm} \times 25 \text{ mm}$, source distance 650 mm, F.O.V. $8 \text{ mm} \times 8 \text{ mm}$, 110 kV 30 mA, 360° rotation in 36 sec, exposure 9.0 sec). Both these systems produced 3D image sets with voxel spacing <0.2 mm and allowed visualization of the majority of individual electrode contacts in each case. Imaging had been performed for 96 CI recipients (Table 3) of the total 118 included.

Author B. E., an experienced neuroradiologist, made sagittal oblique reconstructions perpendicular to the plane of the basal turn according to the technique described by Marx et al., (2014). Then a series of mid-modiolar reconstructions and reconstructions in the plane of the ascending part of the basal turn were produced. Detecting dislocations from ST to scala vestibuli (SV) relied on visualizing the change in the trajectory of the electrode array with identification of the electrode in the inferior part of the basal turn for its proximal portion (i.e., ST), and in the superior part of the basal turn for its distal tip (SV).

Using a projection in the plane of the basal turn, the center of the modiolus to the round window was used as the reference 0° line to measure the insertion depth of electrodes (Xu et al., 2000). Using similar methods, the inter- and intrarater variability has been measured as within $\pm 10^\circ$ (e.g., Svračić et al., 2015). If dislocation occurred, the angle at the point of entry of the electrode into SV was determined. The proportion of electrode contacts in SV was determined for Nucleus perimodiolar electrodes.

All Nucleus devices had 22 intracochlear contacts/channels, Advanced Bionics (AB) sixteen and MEDEL twelve. The manufacturer’s latest sound processor and recommended sound coding parameters, as commercially available at the time, were used in all cases (ACE, HiRes120, FS4, respectively). Activation of CIs was performed according to the manufacturers’ instructions approximately 1 mo after surgery. In two $\frac{3}{4}$ hour sessions, over 2 days, psychophysical threshold (T) and comfort (C) levels for each electrode were determined, followed by fine-tuning, for example, by using a counted T level method for Nucleus users. Sound field thresholds were also checked.

In addition to counseling on the use of the CI system, subjects were given two $\frac{3}{4}$ hour sessions of aural rehabilitation. Where there was some difficulty finding comfortable sound processor stimulation levels, subjects were seen again for fitting 2 weeks later. Subjects received a further two to five $\frac{3}{4}$ hour aural rehabilitation sessions following activation. All subjects were seen at 1 mo after activation for sentence recognition testing followed by checking of stimulation levels. Aural rehabilitation varied across subjects after 1-mo postactivation. Subjects were asked about their sound processor use, with the majority reporting regular use. However, no data logging systems were included in sound processors at the time to verify subjective reports.

Sentence Test Scores

Sentence recognition testing was routinely performed at 1, 3, 6, 9, and 12-mo postactivation visits. Sentence testing was also performed for 25 subjects just 1 day after activation based on them performing well in rehabilitation sessions. Sentence recognition scores were obtained for the French MBAA2 lists each comprised of 15 “everyday” sentences of variable length; 3 to 15 words per sentence with a total of 100 to 103 words per list. The material was spoken by a female speaker with a neutral accent. The MBAA2 lists are used in every CI center in France, and closely resemble the English language CUNY sentence lists (Boothroyd et al., 1988). Lists were randomly selected per subject and per condition from the 34 test lists available. Several sentences from the two practice lists were used to familiarize the subject in each listening condition before testing.

The MBAA2 lists were scored by word with a maximum score of 100 words (common liaisons are counted as single words). Speech recorded on compact audio disks was presented in a soundproof booth at 65 dB SPL from a single loudspeaker placed 1.5 m in front of the subject. French eight-talker babble, recorded on the same disks at fixed SNRs, was presented from the same loudspeaker as a competing noise. At each visit, CI listeners were tested with one list in quiet and one list in noise at 10 dB SNR using their implant alone, with the contralateral ear plugged if there was residual hearing. The test–retest reliability of MBAA2 lists for CI listeners has previously been measured as eight points (Perrault, 2011).

Longitudinal Data Reduction

Sentence recognition scores obtained over time for each subject, in each test condition, quiet and noise, were reduced to an underlying single variable “Initial score” obtained from logarithmic regression: Four examples are shown in Figure 2. Logarithmic functions (i.e., $\text{Score} = A \times \log(\text{months}) + C$, with slope A and intercept C) fitted the longitudinal data better than straight lines and were more appropriate than S-curves, such as logits, because the earliest scores, at 1 mo or earlier, were often much greater than zero (Figure 2, S1) while others, especially in noise, did not reach ceiling level even at 12 mo (Figure 2, S2). Mathematically, the “Initial score” was the intercept of the score versus the logarithm of the number of months after activation (Figure 2, bold crosses). This equates to an improved estimate of the 1-month score ($\log(1) = 0$). Zero scores and scores after the first score >95 were not included in the logarithmic regression (e.g., Figure 2, series S1). The initial score was set equal to the 1-mo score if fewer than three points could thus be included.

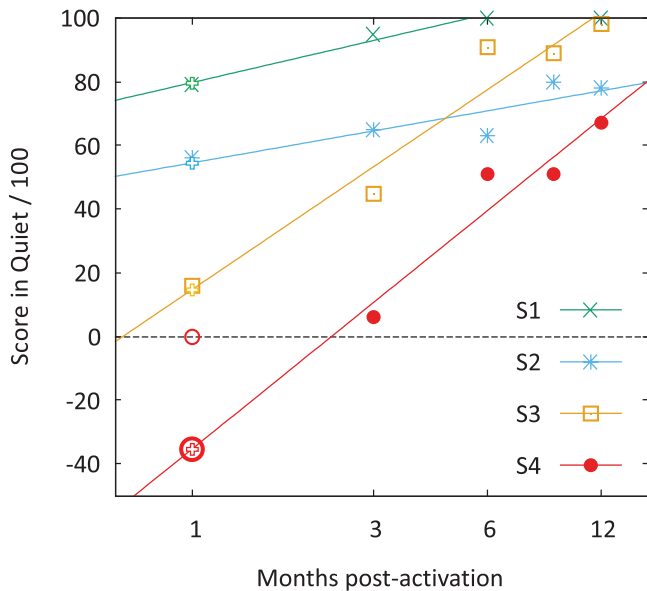


Figure 2. Example logarithmic regression fits (lines) to four series of longitudinally collected scores (points). Note that the horizontal scale is logarithmic. From top to bottom: S1, rapid early progression with scores later than the first score >95, at 6 mo, were not used in the regression; S2, slow progression over the entire follow-up period; S3, rapid progression; S4, zero score at 1 mo (open point). Initial scores (bold crosses) corresponded to where the regression line intercepted at 1 mo. Zero scores were not used in the logarithmic regressions: In the bottom series, S4, the initial score was less than zero, indicating very slow acquisition of sentence understanding (bottom series, bold circle/cross indicates derived initial score).

The initial score integrated the time to rise above zero score for poorer performing subjects, such that initial scores could be less than zero for patients with slow acquisition of speech understanding (Figure 2, series S4, bold circle/cross).

Multiple Regression Analyses

An exploratory approach, followed by stepwise multiple regression was used to assess the relationships between sentence recognition scores and predictive factors. The technique produces a linear analysis of covariance model (Chen & Peace, 2011; Verzani, 2005) that allows the combination of continuous (e.g., years of hearing loss, insertion depth angle, etc.) and categorical variables (e.g., etiology) as factors. Factors were entered into the stepwise procedure with no-interactions between them (R Core Team, 2017, *step* and *lm* functions). Those factors that were maintained by the stepwise procedure were then tested for independent statistical significance using type II analysis of variance to avoid sequence-testing bias, due to potential covariance between predictive factors. Normal probability quantile-quantile plots were used to assess the validity of the regression models. The authors considered arcsine transformation of the scores (e.g., Studebaker, 1985); however, the distribution of residuals for regression models of initial scores was satisfactory and transformation did not provide any further improvement. The relative importance of factors was estimated as the partial r^2 obtained using the Lindeman, Merenda and Gold method, implemented in the *relaimpo* function described by Grömping (2006), which also removes sequence bias. When the partial r^2 values calculated in this way are added up, they give a value equal to the total r^2 for the multiple regression unlike when

TABLE 1. Summary Statistics for Age, and Duration of Severe to Profound Hearing Loss of the 118 CI Users Included in the Study

Measure/yr	Mean (SD)	1st		3rd		
		Min	Quartile	Median	Quartile	Max
Age	57.8 (16.1)	19	50	62	71	85
Duration of severe-to-profound HL	10.6 (12.6)	0	2	5	14	68

using conventional calculations for partial r^2 . These r^2 values can be interpreted as the proportion of the sample variance, which is explained (or converted to a percentage) and thus the relative importance of factors can be determined such that one factor has perhaps twice as much influence on the test measure as another.

Age and duration of deafness were entered into the regression analyzes both as continuous variables and as quartile categories (Table 1) along with the other factors given in Table 2. Models I included all factors except those for electrode position. Models II and III included electrode position factors.

RESULTS

Sentence recognition scores in quiet varied considerably at all intervals postactivation with an overall growth in scores with time and convergence toward ceiling scores at 9 to 12 mo (Figure 3). Across 118 CI listeners more than 60% scored >50/100 in quiet at 1-mo postactivation. There were a number who had very high scores at 1 mo while others scored at or near-zero even at 12 mo.

Twelve-Month Sentence Recognition Scores

Multiple regression analysis of 12-mo sentence recognition scores in quiet (according to model I) revealed Etiology ($r^2 = 0.21$, $p < 0.01$), CI Brand and Design ($r^2 = 0.08$, $p < 0.01$), and duration

TABLE 2. Summary of Factors Entered into the Stepwise Multiple Regression Analyses by Model

Factor	Model		
	I	II	III
Patient related			
Age at implantation in years	X	X	X
Age at implantation quartile	X	X	X
Etiology (14 classifications*)	X	X	X
Duration of severe-to-profound hearing loss in years	X	X	X
Duration of severe-to-profound hearing loss quartile	X	X	X
Brand and design of CI (see Table 3)	X	X	
Electrode position factors			
Insertion depth of apical electrode in degrees E_a		X	X
ST or translocated ST->SV or SV			X
Proportion of active electrode array in SV			X

*Etiologies were unknown, chronic otitis, congenital hearing loss, genetic hearing loss, autoimmune disease, infection, Meniere's disease, meningitis, miscellaneous, noise, otosclerosis, ototoxicity, sudden hearing loss, and trauma. Model III used data for Nucleus Perimodiolar devices only.

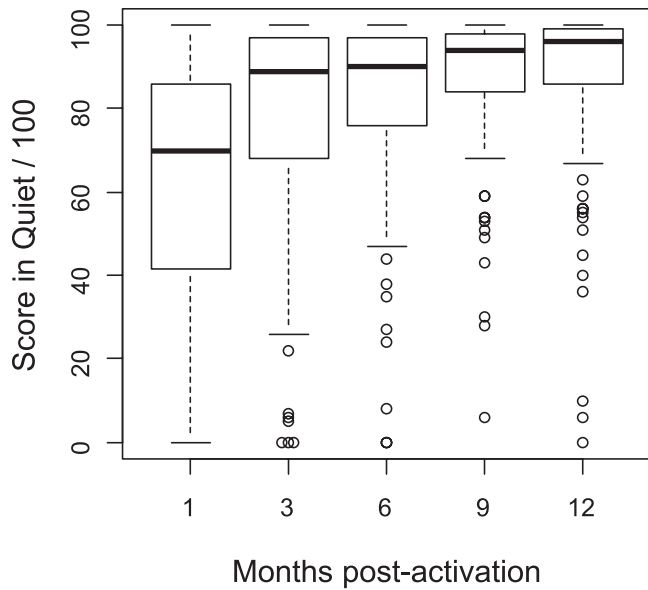


Figure 3. Exploratory analysis of the distribution of sentence scores in quiet vs follow-up visit for 118 patients: More than 60% of CI listeners had 1-mo scores >50 in quiet. There were a number of patients who had very high scores at 1 mo, while others continued to have near-zero scores even at 12 mo. Mid lines are medians, box limits 25th/75th and whisker limits 10th/90th percentiles; circles are outliers (some overlaps occurred).

of deafness ($r^2 = 0.09, p < 0.001, -0.46$ pts/yr) to be significant factors. Chronic Otitis and autoimmune disease groups were associated with significantly lower scores and considerable variability (Fig. 4, $***p < 0.001, *p < 0.05$, respectively), and therefore the 12 subjects in these two groups were removed from subsequent analyses.

Electrode Array Position and Early Sentence Recognition Scores

The insertion depth of the apical electrode contact varied significantly across Brand and Design (Table 3) (Kruskal-Wallis, $\chi^2 = 21.9, df = 3, p < 0.001$), with median angles for Nucleus devices being 150° less than those for AB and MEDEL devices. Most of the differences between average insertion depths could be attributed to the length and design of the electrode arrays (Landsberger et al., 2015). Based on the range of observed insertion depths, frequency-place mismatches would not have been greater than ~ 1.5 octaves upward shift for any Nucleus

device. However, the lowest angles seen for MEDEL devices (e.g., 360°) would have produced upward shifts >2 octaves, and the median insertion depth of 560° for MEDEL devices would represent a shift of ~ 0.5 octaves (i.e., similar to Fig. 1, bottom left). A range of shifts was seen across the small number of AB devices. Overall, basal ward shifts were estimated to be <1.5 octaves across the population, apart from four MEDEL CI listeners with apical electrodes positioned $\leq 450^\circ$.

Brand-design had statistically significant effect on initial scores in quiet and in noise when insertion depth was not included as a factor (models I, Tables 2 and 4), but was not selected by the stepwise procedure when insertion depth was included (model II). Increasing insertion depth was associated with significantly decreasing initial scores in quiet and in noise (Table 4 and Fig. 5) including all devices (models II), and for Nucleus Perimodiolar devices alone (models III).

A separate multiple regression analysis was performed for model II using raw 1-mo scores in quiet as the dependent variable, instead of initial scores. Similar statistically significant effects were still found for Etiology ($r^2 = 0.31, p < 0.01$) and duration of deafness ($r^2 = 0.05, p < 0.05$), and raw 1-mo scores were negatively correlated with insertion depth ($r^2 = 0.09, p < 0.01$, coefficient -0.09).

A large number of dislocations from ST to SV were seen only for the Nucleus Perimodiolar designs (Table 3). (We note that the small absolute number of AB devices makes it difficult to infer the likelihood of dislocation in the general population.) The proportion of the electrode array in SV was selected by the stepwise procedure over the binary factor of ST-SV or SV, versus complete ST: An increasing proportion of electrodes in SV was associated with a progressive reduction in initial scores (model III, Table 4 and Fig. 5 - crossed points). At the same time, the effect of insertion depth on initial scores remained statistically significant. This indicates that insertion depth and scala location had independent effects on scores. Holden et al. (2013) and Finley et al. (2008) also reported that larger proportions of electrode contacts in SV were associated with lower long-term speech recognition scores, in addition to a negative effect of increasing insertion depth.

The minimum insertion depths encountered here of $<360^\circ$ (for eight Nucleus CIs) would have produced basal ward shifts of slightly more than one octave. Given that the initial scores for these CI listeners were among the best, this indicates that a one octave frequency-place mismatch does not prevent a high level of sentence recognition with CI. Furthermore, increasing

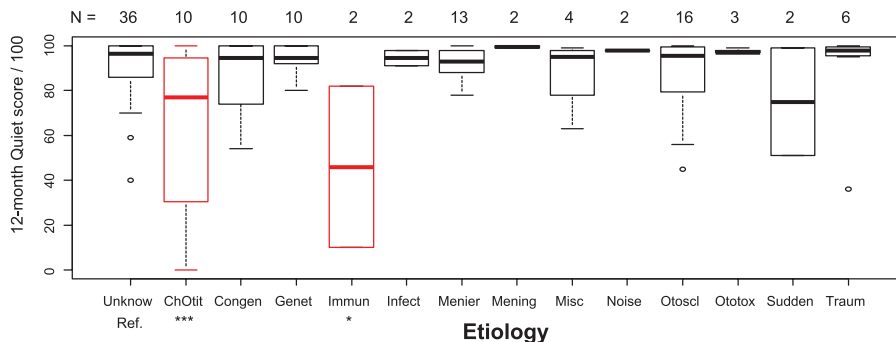


Figure 4. Distributions of sentence scores by Etiology for the 12-mo visit for 118 patients. Scores for Chronic Otitis and Immune disease groups were significantly different from the reference group with “Unknown” etiology. $***p < 0.001, *p < 0.05$ significantly different contrast coefficients from a multiple linear regression model.

TABLE 3. Numbers of Specific CI Devices by Device Brand and Design Category (Italics), and Results of Radiological Analysis: ST—Completely in Scala Tympani, ST-SV/SV—Dislocated from Scala Tympani to Scala Vestibuli or Completely in SV

Brand and Design	All Imaged		Median (Range) E_A	ST-SV / SV	
	<i>Nucleus perimodiolar:</i>	62	53	410°	33
CI24RE Contour Advance	43	49	(320°–560°)	30	19
CI512 Contour Advance	16				
CI24RE Modiolar Research	3				
<i>Nucleus straight:</i>	28	23	410°	21	2
CI24RE Standard	3	20	(315°–570°)	19	1
CI422 Slim Straight	25				
<i>AB straight:</i>	7	4	560°	2	2
HiRes 90k HiFocus 1j	7	4	(360°–630°)	2	2
<i>MEDEL straight:</i>	21	16	570°	15	1
Concerto / Sonata	16	13	(360°–720°)	12	1
Standard	3				
Concerto / Sonata Flex	2				
Concerto / Sonata EAS					
All	118	96	450°	71	25
	106	86	(315°–720°)	63	23

Numbers in italics exclude chronic otitis and autoimmune disease etiology groups. E_A – insertion depth of apical electrode contact.

the insertion depth past ~360° may be distorting the signal for CI listeners.

Optimal Performance: The Intercept Values Obtained from the Regression Models

The intercept values for models I, II, and III (Table 4) can be interpreted as the optimum initial score given no limiting factors

such as etiology, long duration of deafness, or disadvantageous electrode position. The intercept values for models II and III in Table 4 incorporate the minimum insertion depth angle, 315°, so that they can be compared with model I. Intercept values increased slightly between model I and II, with a further increase for model III, approaching or actually just exceeding 100/100 (standard error ~20) for model III_q. This indicated that near-perfect scoring occurred for CI listeners when factors were optimal. For example, increasing insertion depths were associated with a progressive reduction in initial scores by 0.10 to 0.19 points per degree across models, reducing initial scores by 18 to 25 points over 180° in quiet, and 23 to 34 points in noise. In Figure 5, we illustrate the effect of insertion depth on scores; residuals for initial scores (points) from model II_q (so taking into account etiology and duration of deafness) are plotted against insertion depth, along with the regression lines for models II_q and III_q.

Effect Sizes and the Overall Influence of Factors on Scores

Progressively more variance was explained from models I to III, with 67% and 60% explained for initial scores in quiet and in noise, using model III. The absolute effect of scala dislocation on sentence recognition scores was large (up to 25 in quiet and 35 points in noise), and similar to insertion depth. For comparison, the models indicate scores varied by ~6 to 15 points over the interquartile range of duration of severe to profound deafness. Across the models, only scores for congenital hearing loss were significantly lower than the reference “Unknown” etiology, with the 44 to 55 point differences producing the largest overall effect size, r^2 . As well, the Meniere’s group showed a tendency for lower scores across models, with scores in noise for model III being on average 41 points lower ($p < 0.01$) than

TABLE 4. Summary of Stepwise Linear Regression Analyses for Initial Scores in Quiet and in Noise: Model I—All Subjects Excluding Chronic Otitis and Autoimmune Disease; Model II—Remaining Subjects with Imaging Data; Model III—Remaining Subjects with Nucleus Perimodiolar Electrode and Imaging Data

Factors for Initial Scores	Quiet			10 dB SNR		
	I _{quiet}	II _{quiet}	III _{quiet}	I _{noise}	II _{noise}	III _{noise}
N	106	86	49	106	86	49
Intercept	88	91 [†]	103 [†]	71	78 [†]	98 [†]
Etiology—ref. “Unknown”	0.23[†]	0.34[†]	0.37[†]	0.16[§]	0.25[†]	0.31[§]
Congenital hearing loss	-43 [†]	-50 [†]	-54 [†]	-44 [†]	-50 [†]	-53 [†]
Meniere’s	+1 ^{NS}	-8 ^{NS}	-19 ^T	-5 ^{NS}	-21 ^T	-41 [†]
Brand-Design—ref. Nucleus Straight	0.08[†]	X		0.11[†]	X	
AB	-33 [†]			-61 [†]		
MEDEL	-29 [†]			-28 [†]		
Nucleus perimodiolar	-9 ^{NS}			-11 ^{NS}		
Duration of S-P deafness	0.12[†]	0.06[§]	0.05^{NS}	0.12[†]	0.08[†]	0.09^T
- per year	0.76	-0.67	-0.47	-1.11	-1.07	-0.77
Insertion depth Apical contact		0.09[†]	0.10[§]		0.08[†]	0.07[§]
- per degree (°)		-0.10	-0.14		-0.13	-0.19
Proportion of array in SV			0.14[†]			0.13[†]
- fraction 0–1			-25			-35
Total / Multiple R²	0.43[†]	0.49[†]	0.67[†]	0.39[†]	0.41[†]	0.60[†]
Adjusted R ²	0.33	0.40	0.55	0.29	0.30	0.46

Partial r^2 are in bold with significance levels from type II analysis of variance. Partial coefficients are in italics with significance levels.

^T $p < 0.10$, [†] $p < 0.01$, [‡] $p < 0.001$, [§] $p < 0.05$. NS, not significant.

[†]Intercept scores for models II and III were corrected for the minimum insertion depth to allow comparison with model I. “X” marks that the factor was entered into the analysis but rejected by the stepwise procedure, empty cells indicate the factor was not entered as summarized in Table 2.

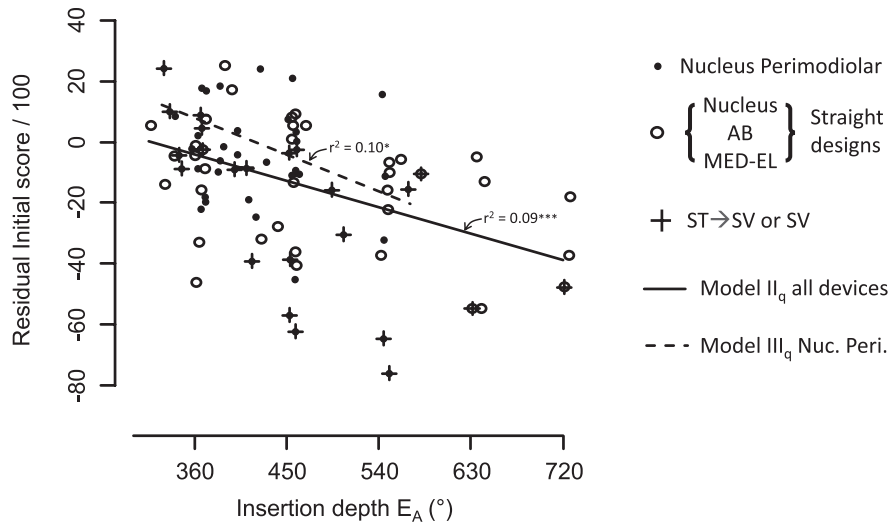


Figure 5. Plot of residuals for initial scores in quiet against insertion depth based on model II_{quiet} (Table 4). Regression lines are for all devices (N = 86, solid) and Nucleus Perimodiolar alone (N = 49, dashed). Crossed points indicate where the array was partially or totally located in SV. ****p* < 0.001, **p* < 0.05.

for the reference. Despite starting off nearly half-way down the scoring scale, both groups caught up by the 12-mo visit (Fig. 4).

Very Early Sentence Recognition: Scores at 1-day Postactivation

Sentence recognition scores were collected for 25 CI listeners, just 1 day after activation of their sound processor: 15 were tested in quiet, and 10 in quiet and in noise, giving a total of 35 data points. Due to the potential for selection bias, we cannot make a general statement about the distribution of sentence

recognition scores across all CI listeners. However, we performed within-subject comparisons of the actual scores measured after 1 day with extrapolations based upon the logarithmic growth in scores from 1 to 12 mo (e.g., Figure 2). Figure 6 gives the extrapolated scores plotted against the actual score, with insertion depths indicated to the upper left of each point where available. Points above the diagonal line indicate early improvement in scores faster than expected or, in other words, a more rapid, “steep” learning curve from 1 day to 1 mo, compared with the progression after 1 month.

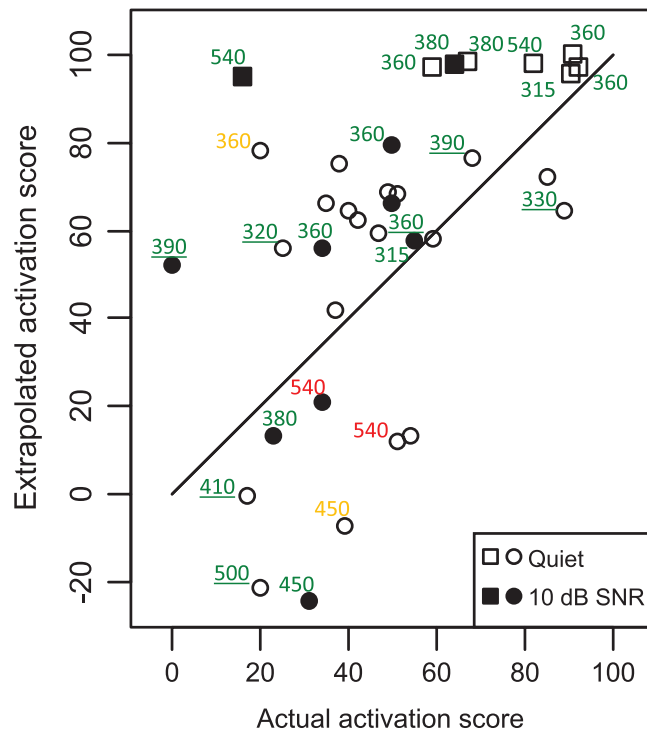


Figure 6. Predicted vs actual scores at 1-day postactivation. The predicted scores were obtained by extrapolation from the regression of 1 to 12 mo scores against the logarithm of the delay after activation (circles). Where too few longitudinal points were available for extrapolation/linear regression (see text), the raw 1-mo score is indicated (squares). Numbers next to points indicate insertion depth angles; underlining indicates ST-SV/SV position. Open points are for scores in quiet, filled points scores in 10 dB SNR.

We note a broad range in insertion depth across most sectors, except the lower left quadrant. The total exposure time for these CI listeners would have been of the order of 8 to 16 hours. Thus, accommodation to basal shifts, which were generally the rule, can be very rapid. In the lower left quadrant of Figure 6, we see insertion angles exceeding 400° . In this quadrant, the actual scores as well as extrapolated scores are low, indicating some hindrance to short-term, as well as to long-term learning. These data collected very early after activation strengthen the result seen for the 1-mo and initial scores in that they indicate that frequency-place mismatches do not appear to be a factor limiting performance, and that greater insertion depths (generally resulting in smaller frequency-place mismatches) slow the acquisition of sentence recognition in CI patients.

DISCUSSION

In the present study, we aimed to identify the relative importance and strength of factors that prevent CI listeners from achieving early, 1-mo sentence recognition scores as high as those for NH listener, acoustic simulations. The highest French MBAA2 sentence scores obtained at 1-mo postactivation, indicated by the intercept values obtained from the multiple regression (Table 4), are comparable with maximum HINT sentence scores obtained by NH subjects listening acutely to acoustic simulations with 8 to 10 channels in quiet and 10 to 12 channels in 10 dB SNR noise (Friesen et al., 2001). The HINT sentences are composed of 5 to 7 words with relatively simple structure and vocabulary, whereas the MBAA2 sentences are more variable length “everyday” sentences with perhaps more linguistic and semantic difficulty, similar to the English language CUNY sentences. Thus, we would expect slightly higher performance with the HINT sentences than MBAA2 sentences, all other things being equal. Therefore, the best 1-mo MBAA2 sentence recognition scores seen here for CI listeners would indicate levels of performance at least as high as those for the NH vocoder conditions cited above.

At least some of our CI listeners achieved optimal sentence recognition scores even at 1 day after activation, or in many cases within 1 month of activation. The short-term results of CI listeners are more appropriately compared with the results of vocoder experiments, which usually only allow limited exposure to the stimuli (of the order of tens of minutes maximum). In some cases, CI listeners’ scores rose quickly from 1 day to 1 mo after activation, compared with longer term growth rates over 1 to 12 mo (Fig. 6). In others, scores either started low and remained low, such was generally true for etiologies associated with labyrinthitis (chronic otitis or autoimmune disease, Fig. 2), or increased relatively slowly over 12 mo as for congenital hearing loss (Table 4 and Fig. 4, and also Fig. 2, square points from a single subject). In the labyrinthitis cases, the cochlea and supporting neural structure may be sufficiently damaged to significantly limit the efficiency of stimulation channels, and these limitations cannot be overcome with time and experience. Linguistic and phonetic experience, and more generally sound processing experience, would be significantly reduced with congenital hearing loss so that language and sound processing capabilities may have to be learned, rather than just relearned. Therefore, in these cases, sentence recognition scores may take a considerably longer time to reach functional levels compared with CI listeners who only encountered hearing loss in adult life

and were implanted relatively soon after profound hearing loss was diagnosed.

Proportions of Variance Explained by Factors

Parametric multivariate analyses is useful to understand the absolute differences in sentence recognition scores between NH-listener acoustic simulations and CI listeners rather than analyzing rank order. In addition, it allows estimation of the proportion of the total variance contributed by factors that may limit performance, using a reduced bias r^2 estimate. Subject-related factors etiology and duration of deafness together explained ~40% of the variance for initial scores in quiet, and 30 to 40% in noise (partial r^2 values, Table 4). Device type or electrode position parameters explained up to a total of 20% of the variance or were only half as important as patient-related factors. This implies, for studies looking for the effects of electrode position, that care should be taken to control for stronger factors such as etiology. A good example is the presence of labyrinthitis, such as chronic otitis and autoimmune disease, which often severely limited sentence recognition scores in the long-term (Figure 4). We note that in the present study, the variance in scores explained by the regression models was at a minimum of ~40%, ranging up to >60%, which is higher than that reported in the studies conducted by Blamey et al. (20–30%) employing nonparametric analyses. This may be due to the single-center data and parametric technique employed in the present study, and using a single device type when considering data for Nucleus Perimodiolar users alone (i.e., regression models III). The large Holden et al. (2013) study, and the two very large, multicenter studies by Blamey and coauthors (Blamey et al., 1996, 2012; Lazard et al., 2012) involving 1000, and slightly more than 2000 subjects, respectively, have substantially contributed to our understanding of long-term outcomes for adult CI listeners, including patient-related factors such as auditory experience, cognitive function and etiology, as well as electrode position. Factors such as preoperative hearing, cognitive function, auditory attention, and verbal processing capacity may go some way to explaining the remaining ~40% of the variance (Heydebrand et al., 2007; Moberly et al., 2016). The results from the present study are generally in line with the results from the two large studies cited above with respect to the effects of patient-related factors, but provide some further insights.

The Effects of Etiology

Chronic otitis and autoimmune disease groups largely represented poor scoring at 12 mo (Fig. 4). These etiologies can generally be described as forms of labyrinthitis with varying levels of severity (Schuknecht, 1974), which can affect labyrinth structure as well as neural tissue. We hypothesize that the physical damage would produce varying current paths, or a reduction in the amount of responsive neural substrate. Poor overall results for Meningitis and Trauma were not observed in the present study, perhaps due to the exclusion of cases with partial insertion, usually due to fibrous tissue or bone growth. Further research to identify and quantify poor channels should allow us a better understanding of the electro-neural interface, especially in poor-performing groups, and may indicate methods for improving performance (Bierer & Litvak, 2016; Garadat et al., 2012; Long et al., 2014; Pfungst et al., 2015).

Removing cases that may involve significant cochlear trauma allowed us to model the growth of sentence recognition scores over time on an individual basis. The regression of scores against the logarithm of postactivation delay generally produced only small RMS errors, certainly within test–retest reliability. Initial scores, that is, the intercept of the individual log functions ($\log(1) = 0$), ranged from negative values to at or near ceiling values. Negative initial scores indicated that subjects took a number of months to be able to recognize any words in sentences. This technique was particularly useful for analyzing scores in noise where CI listeners more often required at least 3 mo to achieve nonzero scores. The congenital hearing loss group started approximately halfway down the initial score scale compared with other etiology groups (Table 4), with some suggestion that Meniere’s was also associated with overall lower initial scores, particularly in noise (model III_{noise}, Table 4). We consider that the congenital hearing loss group’s low initial scores indicate language processing impairment due to long-term auditory deprivation. We saw that reduced speech recognition scores were associated with longer durations of hearing loss, to the degree of less than one point per year in quiet, and more than one point per year in noise. In the present study, we saw no significant effect of age, even though one-quarter of CI listeners were older than 70 and would tend toward some cognitive decline that may be detrimental to understanding spoken language (Schneider et al., 2010). We also found no effect of age on early scores in 10 dB SNR multi-talker babble. A recent study by Holden et al. (2016) indicated a negative correlation between scores in noise and age, for a group of subjects with on average 5 years’ experience using a CI. Cognitive decline associated with aging may, therefore, influence CI listeners’ ability to improve scores in noise over longer time frames. At 12 mo, the scores for the congenital HL group were not significantly different from the group average despite being substantially lower (~50 pts) than for other groups at 1 month (Table 4). It is unclear at this stage whether long-term performance for congenital HL patients may remain limited by these factors for more difficult material, or in higher levels of noise.

The Effect of Electrode Position

A significant, negative correlation between insertion depth and initial score was found across all devices as well as for Nucleus Perimodiolar devices alone. Therefore, the intercept values indicate optimal performance (Table 4) and correspond to initial scores for the lowest angles encountered in the data set. The effects of insertion depth seen in models II largely explained the differences seen in initial scores when only considering device brand (models I). The association of increasing insertion depth with poorer speech recognition scores with CI has been observed previously (Finley et al., 2008; Holden et al., 2013; Lazard et al., 2012). As the basal ward shifts in this population would not have generally exceeded ~1.5 octaves, the frequency-place mismatch would not have significantly impacted performance according to the results of vocoder experiments where subjects had been given extended listening experience (Li et al., 2009). The proportion of scala dislocations seen with Nucleus Perimodiolar electrodes was significantly higher than for straight electrodes (~40% versus ~12%), and a separate analysis for Nucleus Perimodiolar electrodes revealed that scala dislocation was associated with a reduction in initial scores, and that this was separate effect from the effect of insertion depth.

These results have a direct bearing on surgical technique and electrode design; first, that insertion depths should not exceed approximately 360° and, second, that scala dislocation must be avoided. Preformed, perimodiolar electrodes are generally more prone to scala dislocation, especially when surgical technique is not optimal, but also new perimodiolar designs should aim to reduce or remove their occurrence (Aschendorff et al., 2017). The use of 300° to 360° as an optimal insertion depth for electric hearing is serendipitous for the application of CIs in residual hearing cases, in that, shallower insertion depths are generally associated with better, and longer lasting hearing preservation (Jurawitz et al., 2014; Skarzynski et al., 2014)

A negative correlation between insertion depth and sentence recognition scores appears to support the hypothesis of reduced channel effectiveness for positions greater than 360°, which could be due to the tight coiling and bulb like form of the SG in the terminal part of Rosenthal’s canal, at the level of the second turn. The effect may depend on individual cochlear morphology, for example, how tightly wound are the scalae or the SG (for an excellent histologic exhibition of SG morphology we recommend the article by Rask-Andersen et al., 2010, which is available on the PubMed Central system as PMC2821077). Early speech recognition performance may rely more heavily on a full set of efficient channels such that it takes time for CI listeners to learn to interpret, or even learn to ignore, certain channels where information is mixed, as suggested by Başkent and Shannon (2005).

Perimodiolar placement, or reduced distance between the electrode contacts and the modiolus, has been associated with higher long-term word scores (Esquia Medina et al., 2013; Holden et al., 2013). However, in the present study, we observed no significant difference between perimodiolar designs and straight lateral wall designs, taking other factors into account. The morphology and neural distribution in the SG may also explain the lack of benefit observed in speech recognition scores when attempts have been made to increase spatial selectivity; for example, by moving electrode contacts closer to the modiolus, or by current focusing using multipolar stimulation to cancel out the flanks of the current field generated by each contact (e.g., Kalkman et al., 2015). As shown in Figure 1, the less tightly rolled basal turn of the cochlea already presents a relatively favorable stimulation target even for contacts placed at the lateral wall (Kalkman et al., 2014); however, for the second turn, the small distance across the diameter of the SG and bulb-like structure would tend to produce cross-turn stimulation for both lateral and medial positioned contacts (indeed, the actual medial-lateral distances within the ST are also reduced). In addition, approximately 80% of the length of the SG is found in the first turn, containing 60% of nerve cells compared with 20% and 40%, respectively, for the second turn (Sridhar et al., 2006). Thus, cell density in the second turn is three times that in the first turn. Generally, in the first turn, the spread of current required to give equal loudness between different current focusing strategies would be similar; however, in the second turn, the potential to limit flanking currents may be offset by the penetration of currents further into the center of the SG such that cross-turn stimulation could occur, and remove the benefit of current focusing (Kalkman et al., 2015). Thus, current focusing or sound coding strategies that are aimed at improving frequency selectivity for CI listeners may be more successful if stimulation is limited to locations <360°, and if the cochlea is in a healthy physiological state. Alternatively, the lack of a significant difference between

Nucleus straight and perimodiolar electrode designs may just be due to the difficulty of the sentence recognition task: Only ~10 effective channels would be required to produce near-perfect scoring even at 10 dB SNR, and we can suppose that both designs can provide at least this number for the best CI listeners. We currently plan to reduce long-term scores for fixed SNRs to speech recognition thresholds in noise (SNR50) to further understand CI listeners' performance in higher levels of noise, and also elucidate the question whether initially poorer performers can catch up with those who rapidly achieve high scores.

Based on the results of this study of 118 unilateral CI listeners, the best solution for CI listeners would be placement of the deepest, most apical electrode contact at 300° to 360°. Further work is required to understand if limiting active insertion depth by selectively deactivating apical electrode contacts >360° may improve performance early after activation, as has been seen for some studies in the long-term (Gani et al., 2007; Kenway et al., 2015). Any such attempt should take into account the potentially limiting effects of large frequency-place mismatches. We note here that the current results were obtained with the default sound coding strategies and frequency allocations. Future work should investigate different sound coding methods, such as current focusing, and investigate frequency allocations that may reflect more natural frequency-to-place matches, and could thus change the results for deeper insertions.

In addition, further physiological work is required to understand the variability of individual cochlear morphology in CI listeners, either using high-resolution imaging or other measures of “cochlear health” (Pfungst et al., 2015). It is important to note that, the results of this study indicate that the relative level of performance of CI listeners can be estimated very early on, and this can be used to customize rehabilitation programs, as well as identify unexpected poor performance. Finally, the relationship of early sentence recognition scores of CI listeners to long-term performance, especially in noise, should be further elucidated.

CONCLUSIONS

The patient-related factors etiology and duration of deafness together explained ~40% of the variance in early sentence recognition scores, for this population of 118, unilaterally implanted CI users. Device type or electrode position parameters explained up to a total of 20% of the variance, and so were only half as important as patient-related factors. Thus, patient-related factors should be accounted for when examining electrode position factors. CI listeners with insertion depths of ~360° obtained the highest early sentence recognition scores in quiet and in noise, and the scores were comparable with those found in the literature for normal-hearing listeners listening to 8 to 10 channel acoustic simulations. This indicates that physiological frequency-place mismatches of about one octave are rapidly accommodated by CI users for sentence understanding, between 1 day to 1 mo postactivation, and that channel efficiency may be significantly poorer for more deeply positioned electrode contacts.

ACKNOWLEDGEMENTS

Authors C. J. J., C. K., M. M., and B. F. designed the study and drafted the report; C. J. J., C. K., and B. L. verified and analyzed the data; M.-L. L., M. T., and C.-E. M. managed CI patients, collected the data, and interpreted

medical files; B. E. assured the CT image analyses; O. D. approved the article. The authors heartily thank the section editor Michelle Hughes and two anonymous reviewers for their great assistance in improving this article.

Portions of this work were previously presented at conferences including the Conference for Implantable Auditory Prostheses, Lake Tahoe, CA; July 16–21 2017.

C. J. J. is also an employee of Cochlear France. C. K. received partial doctoral funding from Cochlear France as part of the program “Conventions industrielles de formation par la recherche” (CIFRE). For the remaining authors, no conflicts of interest declared. The views expressed herein are not necessarily those of the Cochlear company.

Address for correspondence: Chris J. James, Hôpital Pierre-Paul Riquet, Place du Docteur Baylac, TSA 40031, 31059 Toulouse cedex 9, France. E-mail: chris.j.james@wanadoo.fr

Received December 15, 2017; accepted August 6, 2018.

REFERENCES

- Ariyasu, L., Galey, F. R., Hilsinger, R. Jr, et al. (1989). Computer-generated three-dimensional reconstruction of the cochlea. *Otolaryngol Head Neck Surg*, *100*, 87–91.
- Aschendorff, A., Briggs, R., Brademann, G., et al. (2017). Clinical investigation of the nucleus slim modiolar electrode. *Audiol Neurootol*, *22*, 169–179.
- Başkent, D., & Shannon, R. V. (2005). Interactions between cochlear implant electrode insertion depth and frequency-place mapping. *J Acoust Soc Am*, *117*(3 Pt 1), 1405–1416.
- Bierer, J. A., & Litvak, L. (2016). Reducing channel interaction through cochlear implant programming may improve speech perception: Current focusing and channel deactivation. *Trends Hear*, *20*, 1–12.
- Biesheuvel, J. D., Briaire, J. J., Frijns, J. H. (2016). A novel algorithm to derive spread of excitation based on deconvolution. *Ear Hear*, *37*, 572–581.
- Blamey, P. J., Arndt, P., Bergeron, F., et al. (1996). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants. *Audiol Neurootol*, *1*(5), 293–306.
- Blamey, P., Artieres, F., Başkent, D., et al. (2013). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants: an update with 2251 patients. *Audiol Neurootol*, *18*, 36–47.
- Boothroyd, A., Hnath-Chisolm, T., Hanin, L., & Kishon-Rabin, L. (1988). Voice fundamental frequency as an auditory supplement to the speechreading of sentences. *Ear Hear*, *9*(6), 306–12.
- Boyd, P. J. (2011). Potential benefits from deeply inserted cochlear implant electrodes. *Ear Hear*, *32*, 411–427.
- Briggs, R. J. S., Tykocinski, M., Xu, J., et al. (2006). Comparison of round window and cochleostomy approaches with a prototype hearing preservation electrode. *Audiol Neurootol*, *11*, 42–48.
- Buchman, C. A., Dillon, M. T., King, E. R., et al. (2014). Influence of cochlear implant insertion depth on performance: A prospective randomized trial. *Otol Neurotol*, *35*, 1773–1779.
- Chen, D., & Peace, K. (2011). Treatment comparisons in clinical trials with covariates. In *Clinical Trial Data Analysis Using R* (1st ed., pp. 57–84). Boca Raton, FL: CRC Press.
- Escudé, B., James, C. J., Deguine, O., et al. (2006). The size of the cochlea and predictions of insertion depth angles for cochlear implant electrodes. *Audiol Neurootol*, *11 Suppl 1*(suppl 1), 27–33.
- Esquia Medina, G. N., Borel, S., Nguyen, Y., et al. (2013). Is electrode-modiolus distance a prognostic factor for hearing performances after cochlear implant surgery? *Audiol Neurootol*, *18*, 406–413.
- Faulkner, A., Rosen, S., Norman, C. (2006). The right information may matter more than frequency-place alignment: Simulations of frequency-aligned and upward shifting cochlear implant processors for a shallow electrode array insertion. *Ear Hear*, *27*, 139–152.
- Finley, C. C., Holden, T. A., Holden, L. K., et al. (2008). Role of electrode placement as a contributor to variability in cochlear implant outcomes. *Otol Neurotol*, *29*, 920–928.
- Friesen, L. M., Shannon, R. V., Baskent, D., et al. (2001). Speech recognition in noise as a function of the number of spectral channels: Comparison of acoustic hearing and cochlear implants. *J Acoust Soc Am*, *110*(2), 1150–63.

- Fu, Q. J., & Galvin, J. J. 3rd. (2003). The effects of short-term training for spectrally mismatched noise-band speech. *J Acoust Soc Am*, *113*, 1065–1072.
- Fu, Q. J., & Galvin, J. J. 3rd. (2007). Perceptual learning and auditory training in cochlear implant recipients. *Trends Amplif*, *11*, 193–205.
- Fu, Q. J., Shannon, R. V., Galvin, J. J. 3rd. (2002). Perceptual learning following changes in the frequency-to-electrode assignment with the Nucleus-22 cochlear implant. *J Acoust Soc Am*, *112*, 1664–1674.
- Gani, M., Valentini, G., Sigrist, A., et al. (2007). Implications of deep electrode insertion on cochlear implant fitting. *J Assoc Res Otolaryngol*, *8*, 69–83.
- Garadat, S. N., Zwolan, T. A., Pfungst, B. E. (2012). Across-site patterns of modulation detection: Relation to speech recognition. *J Acoust Soc Am*, *131*, 4030–4041.
- Garadat, S. N., Zwolan, T. A., Pfungst, B. E. (2013). Using temporal modulation sensitivity to select stimulation sites for processor MAPs in cochlear implant listeners. *Audiol Neurootol*, *18*, 247–260.
- Greenwood, D. D. (1990). A cochlear frequency-position function for several species—29 years later. *J Acoust Soc Am*, *87*(6), 2592–2605.
- Grömping, U. (2006). Relative importance for linear regression in R: The package relaimpo. *J Stat Softw*, *17*(1), 1–27.
- Heydebrand, G., Hale, S., Potts, L., et al. (2007). Cognitive predictors of improvements in adults' spoken word recognition six months after cochlear implant activation. *Audiol Neurootol*, *12*, 254–264.
- Hochmair, I., Arnold, W., Nopp, P., et al. (2003). Deep electrode insertion in cochlear implants: apical morphology, electrodes and speech perception results. *Acta Otolaryngol*, *123*, 612–617.
- Holden, L. K., Finley, C. C., Firszt, J. B., et al. (2013). Factors affecting open-set word recognition in adults with cochlear implants. *Ear Hear*, *34*, 342–360.
- Holden, L. K., Firszt, J. B., Reeder, R. M., et al. (2016). Factors affecting outcomes in cochlear implant recipients implanted with a perimodiolar electrode array located in Scala Tympani. *Otol Neurotol*, *37*, 1662–1668.
- Jurawitz, M. C., Büchner, A., Harpel, T., et al. (2014). Hearing preservation outcomes with different cochlear implant electrodes: Nucleus® Hybrid™-L24 and Nucleus Freedom™ CI422. *Audiol Neurootol*, *19*, 293–309.
- Kalkman, R. K., Briare, J. J., Dekker, D. M., et al. (2014). Place pitch versus electrode location in a realistic computational model of the implanted human cochlea. *Hear Res*, *315*, 10–24.
- Kalkman, R. K., Briare, J. J., Frijns, J. H. (2015). Current focussing in cochlear implants: An analysis of neural recruitment in a computational model. *Hear Res*, *322*, 89–98.
- Kawano, A., Seldon, H. L., Clark, G. M. (1996). Computer-aided three-dimensional reconstruction in human cochlear maps: Measurement of the lengths of organ of Corti, outer wall, inner wall, and Rosenthal's canal. *Ann Otol Rhinol Laryngol*, *105*, 701–709.
- Kenway, B., Tam, Y. C., Vanat, Z., et al. (2015). Pitch discrimination: An independent factor in cochlear implant performance outcomes. *Otol Neurootol*, *36*, 1472–1479.
- Landsberger, D. M., Svrakic, M., Roland, J. T. Jr, et al. (2015). The relationship between insertion angles, default frequency allocations, and spiral ganglion place pitch in cochlear implants. *Ear Hear*, *36*, e207–e213.
- Lazard, D. S., & Giraud, A. L. (2017). Faster phonological processing and right occipito-temporal coupling in deaf adults signal poor cochlear implant outcome. *Nat Commun*, *8*, 14872.
- Lazard, D. S., Vincent, C., Venail, F., et al. (2012). Pre-, per- and postoperative factors affecting performance of postlinguistically deaf adults using cochlear implants: A new conceptual model over time. *PLoS One*, *7*, e48739.
- Li, T., Galvin, J. J. 3rd, Fu, Q. J. (2009). Interactions between unsupervised learning and the degree of spectral mismatch on short-term perceptual adaptation to spectrally shifted speech. *Ear Hear*, *30*, 238–249.
- Long, C. J., Holden, T. A., McClelland, G. H., et al. (2014). Examining the electro-neural interface of cochlear implant users using psychophysics, CT scans, and speech understanding. *J Assoc Res Otolaryngol*, *15*, 293–304.
- Marx, M., Risi, F., Escudé, B., et al. (2014). Reliability of cone beam computed tomography in scalar localization of the electrode array: A radio histological study. *Eur Arch Otorhinolaryngol*, *271*, 673–679.
- McDermott, H., Sucher, C., & Simpson, A. (2009). Electro-acoustic stimulation. Acoustic and electric pitch comparisons. *Audiol Neurootol*, *14 Suppl 1*, 2–7.
- McKay, C. M., & Henshall, K. R. (2002). Frequency-to-electrode allocation and speech perception with cochlear implants. *J Acoust Soc Am*, *111*(2), 1036–44.
- Moberly, A. C., Lowenstein, J.H., & Nittrouer, S. (2016). Word recognition variability with cochlear implants: The degradation of phonemic sensitivity. *Otol Neurootol*, *14*–26.
- O'Connell, B. P., Hunter, J. B., Gifford, R. H., et al. (2016). Electrode location and audiologic performance after cochlear implantation: A comparative study between nucleus CI422 and CI512 electrode arrays. *Otol Neurootol*, *37*, 1032–1035.
- Perrault, M. (2011). *Matrix test : Une harmonisation européenne des procédures de mesures audiologiques chez les implantés cochléaires*. University of Montpellier 1.
- Pfungst, B. E., Zhou, N., Colesa, D. J., et al. (2015). Importance of cochlear health for implant function. *Hear Res*, *322*, 77–88.
- R Core Team. (2017). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved November 30th, 2017 from <https://www.r-project.org/>.
- Rask-Andersen, H., Liu, W., Linthicum, F. (2010). Ganglion cell and 'dendrite' populations in electric acoustic stimulation ears. *Adv Otorhinolaryngol*, *67*, 14–27.
- Rosen, S., Faulkner, A., Wilkinson, L. (1999). Adaptation by normal listeners to upward spectral shifts of speech: Implications for cochlear implants. *J Acoust Soc Am*, *106*, 3629–3636.
- Schneider, B.A., Pichora-Fuller, K., Daneman, M. (2010). Effects of senescent changes in audition and cognition on spoken language comprehension. In S. Gordon-Salant, R. Frisina, A. Popper, & R. Fay (Eds.), *The Aging Auditory System* (pp. 167–210). New York, NY: Springer.
- Schuknecht, H. (1974). *Pathology of the Ear*. Cambridge, MA: Harvard University Press.
- Skarzynski, H., Lorens, A., Matusiak, M., et al. (2014). Cochlear implantation with the nucleus slim straight electrode in subjects with residual low-frequency hearing. *Ear Hear*, *35*, e33–e43.
- Sridhar, D., Stakhovskaya, O., & Leake, P. A. (2006). A frequency-position function for the human cochlear spiral ganglion. *Audiol Neurootol*, *11 Suppl 1*, 16–20.
- Stakhovskaya, O., Sridhar, D., Bonham, B. H., et al. (2007). Frequency map for the human cochlear spiral ganglion: Implications for cochlear implants. *J Assoc Res Otolaryngol*, *8*, 220–233.
- Studebaker, G. A. (1985). A "rationalized" arcsine transform. *J Speech Hear Res*, *28*(3), 455–62.
- Svrakic, M., Friedmann, D. R., Berman, P. M., et al. (2015). Measurement of cochlear implant electrode position from intraoperative post-insertion skull radiographs: A validation study. *Otol Neurootol*, *36*, 1486–1491.
- Tan, C. T., Martin, B., Svirsky, M. A. (2017). Pitch matching between electrical stimulation of a cochlear implant and acoustic stimuli presented to a contralateral ear with residual hearing. *J Am Acad Audiol*, *28*, 187–199.
- Verzani, J. (2005). Analysis of variance. In *Using R for Introductory Statistics* (1st ed., pp. 313–341). Boca Raton, FL: CRC Press.
- Xu, J., Xu, S. A., Cohen, L. T., et al (2000). Cochlear view: Postoperative radiography for cochlear implantation. *Am J Otol*, *21*(1), 49–56.
- Yukawa, K., Cohen, L., Blamey, P., et al. (2004). Effects of insertion depth of cochlear implant electrodes upon speech perception. *Audiol Neurootol*, *9*, 163–172.