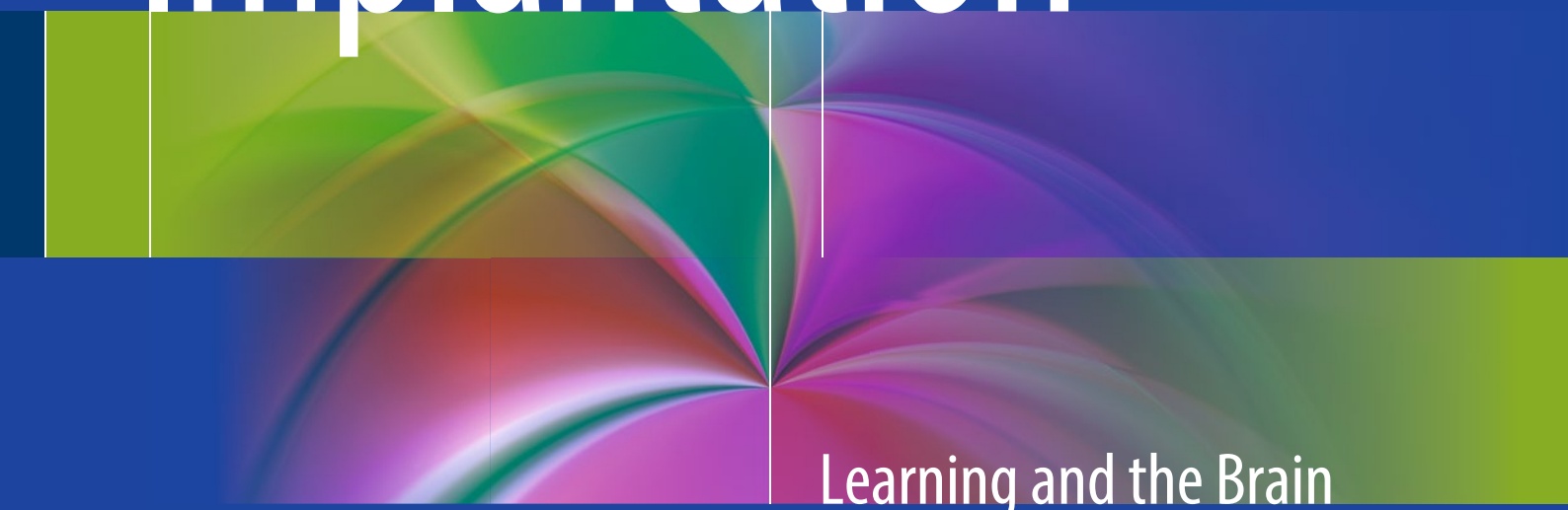
Nancy M. Young
Karen Iler Kirk
Editors

Pediatric Cochlear Implantation



Learning and the Brain

Springer

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In memory of John K. Niparko, M.D., a renowned clinician–scientist and leader in cochlear implantation, who cared deeply about improving the lives of children.

Preface: Cochlear Implants in Children—A Personal Perspective

The cochlear implant is the most successful of all neural prostheses, both in terms of the degree to which it can restore function and in the number of people who have received this device worldwide. Children implanted at a young age can now acquire speech recognition, speech production, language, and reading abilities that previously were not possible for the vast majority of hard-of-hearing or deaf children. The effectiveness of the cochlear implant also has transformed the education of these children. The majority of children with cochlear implants now are educated in oral classrooms that emphasize the use of spoken language and listening skills; inclusion of children with cochlear implants in mainstream classrooms with their typically hearing peers is increasingly common. Classrooms with instruction in Total Communication (i.e., the combined use of manually coded and spoken English) now are integrating listening and spoken language development into the curriculum more than ever before. This change has likely been driven in part by research demonstrating that children using manually coded (signed) English may experience a doubling of the rate of language acquisition after implantation. These expanded educational options have in turn contributed to enhanced language and literacy outcomes. A generation of hard-of-hearing and deaf children is graduating high school, enrolling in postgraduate education, and finding employment to an extent never before seen. To observe these changes unfold over our careers has been most rewarding.

Our goal is for this book to serve as a resource for a broad audience of clinicians and clinical researchers regarding current and emerging best practice in pediatric cochlear implantation. We hope to inspire research in new areas of importance, especially the role of cognitive processing skills in cochlear implant outcomes. We were fortunate to enlist participation from a highly experienced and distinguished group of coauthors. We are very grateful to them for their willingness to share their knowledge and the considerable time they devoted to this project.

Our lead chapter is by Blake Wilson and coauthors Michael F. Dorman, René H. Gifford, and David McAlpine. Wilson's pioneering work in signal processing enabled development of the modern cochlear implant. Over more than 30 years, his work at the Research Triangle Institute in North Carolina has transformed this neuroprosthesis and the lives of many children. In contrast to early implant devices, modern cochlear implant systems utilizing speech processing based on his work have enabled most recipients to understand speech through listening alone and even to use a cell phone. In recognition of his significant contribution to the development of cochlear implants, Wilson was one of several scientists awarded the Lasker-Debakey clinical medical research award in 2013 and the Fritz J. and Delores H. Russ Prize in bioengineering in 2015. The former is commonly referred to as the American Nobel and the latter as the Nobel of engineering. These high honors have brought much recognition to our field. Cochlear implantation is now recognized as the first successful electronic device to replace a human sensory end organ and as one of the major medical advances of the twentieth century. Wilson points out that the brain may be the most important determinant of cochlear implant outcomes. He advocates for the use of a "top down" or "cognitive neuroscience" approach to improve the effectiveness of this and other neural prostheses.

Part II of the book focuses upon clinical management. Rene Gifford gives us a comprehensive description of the interdisciplinary evaluation of pediatric candidates and the significant evolution of candidacy beyond those children with bilateral profound deafness. Tina Tan, an

infectious disease specialist and an expert in pneumococcal disease, provides an overview of the risk of infectious disease in implanted children. She explains the rationale for the Center for Disease Control's current vaccination guidelines that are designed to reduce bacterial meningitis due to pneumococcal disease and Haemophilus influenzae type b. These recommendations now include annual influenza vaccination to reduce the risk of otitis media which may lead to bacterial meningitis. Sharon Cushing, Susan Blaser, and Blake Papsin discuss medical and radiological aspects of unusual cases. They provide us with their medical approach and intraoperative techniques for children with conditions that often precluded cochlear implantation in the past. Pearls they share also include a practical approach to pediatric vestibular assessment and the relationship between poor vestibular function and increased risk of internal device failure. Brandon Isaacson and Peter Roland provide a state-of-the-art overview of surgical considerations including hearing preservation techniques and specialized approaches to address unusual surgical anatomy. Holly Teagle's chapter highlights the important role audiologists play in maximizing cochlear implant outcomes. She describes a sophisticated and logical approach to speech processor programming and postimplant follow-up. Teagle also emphasizes the child, family, and educational factors that come into play when optimizing device programming for individual children. Terry Zwolan and Casey Stach have contributed a chapter on diagnosis and management of device problems that limit use or benefit and may result in reimplantation. They describe the process of recognizing and managing "soft" failures including the important role of imaging, monitoring of auditory progress and electrophysiological measures to identify this challenging problem. The role of electrophysiological testing in clinical management is elucidated by Karen Gordon. Gordon makes a compelling case for more widespread use of electrophysiological measures as part of the test battery to aid in programming and monitoring of progress over time.

Outcomes after implantation are the focus of Part III. Karen Iler Kirk and Michael Hudgins provide insight into the assessment of spoken word recognition abilities in infants and children, review long-term cochlear implant outcomes in children, and highlight factors that have been shown to influence speech and language development in children with cochlear implants. Ruth Litovsky explains the differences between true binaural hearing and the bilateral hearing permitted by current implant technology. She describes measurable gains in speech recognition in noise and in sound localization obtained by bilaterally implanted children, despite receiving degraded binaural cues. Litovsky attributes these findings to the brain's ability to integrate the uncoordinated information received from two implants. Susan Nittrouer and Amanda Caldwell-Tarr review language and literacy of implanted children, including the results of their own ongoing longitudinal investigations. They observed dramatic initial improvements in language and literacy following implantation. However, over time the cochlear implant users in their study developed language and literacy skills that fell within the lower end of the normal range for children with normal hearing. The authors propose that changes in cochlear implant design as well as effective postimplant behavioral intervention may be necessary to ameliorate this situation. Alexandra L. Quittner, Ivette Cejas, Jennifer Barnard, and John Niparko share important research findings regarding psychosocial development gleaned from the Childhood Development after Cochlear Implantation (CDaCI) study, the first longitudinal multicenter national cohort study to systematically evaluate early cochlear implant outcomes in children. Their research demonstrates that, despite the many areas of great improvement, implanted children often face challenges in psychosocial and social-emotional functioning. They suggest a family-centered management approach, as well as proactive screening of young children for delays in cognition, behavioral development, and social-emotional function and health-related quality of life.

In the early days of pediatric cochlear implantation, often only children thought to be "ideal" candidates were eligible to receive an implant. Today cochlear implantation is the accepted treatment for deafness. Therefore it is only natural that a growing number of children with a broad range of co-occurring complicating conditions that may slow progress or reduce expecta-

tions for spoken language development are being evaluated for cochlear implantation. These children are the focus of Part IV. An overview of many of these conditions, the range of benefits obtained, and increased need for communication between the implant team and others serving these children is provided by Nancy Young, Elizabeth Tournis, and Constance Weil. The goal of their chapter is to encourage a redefinition of implant candidacy and a better understanding of the potential impact of hearing in the lives of these children and their families beyond what typically is measured in current clinical practice. Children with cochlear nerve deficiency are a very special population who present a management challenge. The literature demonstrates that this problem is more common than previously recognized. An overview of diagnosis and management options is provided by Claire Iseli, Oliver Adunka, and Craig Buchman. The authors describe the incidence and clinical presentation of children with cochlear nerve deficiency and consider audiological and radiological assessments used to diagnosis this condition. They also describe functional electrophysiological assessments that may help to improve preoperative and intraoperative prediction of cochlear implant benefit in these children. Their contribution is followed by a discussion of auditory brainstem implantation (ABI) for congenital deafness by Robert Shannon, Lilliana Colletti, and Vittorrio Colletti, pioneers in this area. The authors report that pediatric ABI users demonstrate a broader range of speech recognition skills, including open-set word recognition, and they consider the role of neuroplasticity in pediatric ABI outcomes. And finally, the new frontier of cochlear implantation to address single-sided deafness is described by David Friedmann, Susan Waltzman, and J. Thomas Roland. Because single-sided deafness can be congenital, acquired, or result from a progressive hearing loss, they highlight the need for careful monitoring in children with unilateral hearing loss. The authors describe the negative impact of single-sided deafness on language and educational outcomes in children. Finally, they consider the relative merits of various treatment options for single-sided deafness, including cochlear implantation.

What factors beyond the implant affect learning and how outcomes may be maximized are addressed by multiple authors in Part V. Motivated by a desire to understand individual differences in cochlear implant outcomes, David Pisoni and collaborators from the Speech Research Laboratory within the Department of Psychological and Brain Sciences at Indiana University have conducted pioneering research into the relationship of cognitive processing and working memory to spoken word recognition, speech perception, and language skills in pediatric implant recipients. This work has led to the development of novel interventions to improve spoken language processing. Angela AuBuchon, David Pisoni, and William Kronenberger explore neurocognitive processes underlying verbal working memory; they suggest that prelingually deaf cochlear implant users appear to be at risk for slow and inefficient phonological recoding and verbal rehearsal processes because of the early atypical auditory and language environments in which their verbal working memory systems develop. Kronenberger and Pisoni describe neurocognitive training procedures that have been used to improve working memory in children with normal hearing and children with cochlear implants. Speech perception training is explored by Patrick Wong and Erin Ingvalson. They recommend an individualized approach which selects training targets based on a child's ability to perceive the acoustic properties of speech. Wong and Ingvalson propose that training outcomes can be enhanced through the use of an adaptive strategy that matches the listener's skill set throughout the training paradigm. Susan Nittrouer provides a chapter on intervention to improve language and literacy skills in children with cochlear implants. Based on empirical evidence, she recommends that children receive intensive support for language learning throughout childhood. She presents a set of organizing principles that underlie an integrated approach to language intervention. Nittrouer also makes recommendations to enhance the effectiveness of intervention such as the use of audiovisual speech signals to strengthen the child's internal representations of speech, and bimodal cochlear implant use (i.e., the use of a hearing aid on the contralateral nonimplanted ear) in unilaterally implanted children. Kate Gfeller considers the importance of music in children's daily lives and describes the limitations of cochlear implant signal processing in conveying the structural properties of music. Gfeller provides a comprehensive summary of

research concerning pediatric cochlear implant users' perception of music and the role of music training paradigms in improving music perception and enjoyment. Finally, she explores music training's potential to impact speech and language development and describes principles for the application of music-based training for children with cochlear implants.

Two chapters on educational management comprise Part VI. Marybeth Lartz and Tracy Meehan provide a comprehensive overview of the therapy needs of children with cochlear implants who are younger than 3 years of age and are enrolled in early intervention programs. They describe a framework for designing and delivering intervention for children across a range of chronological ages and language levels. They also provide strategies to enhance listening, language, and literacy skills that can be used with parents and their children before and after cochlear implantation. Finally Nancy Mellon and her colleagues at the River School in Washington DC, a superb inclusion program integrating children with implants and typically hearing children, provide an excellent overview of building auditory skills, spoken language, academic, and socioemotional skills within the classroom.

This book reflects the remarkable progress that has been made in the interdisciplinary field of cochlear implantation, yet so much still remains to be done. Variability is a hallmark of cochlear implant outcomes, and not every child reaches his or her maximum potential. Current cochlear implant technology provides a crude signal, at best, in comparison to normal hearing. Even cochlear implant recipients with the best results may have difficulty in challenging situations such as when background noise or competing speakers are present. Other reasons for poorer performance include further degradation of the auditory signal due to suboptimal programming or lack of identification of a "soft" failure, inadequate or ineffective therapy, and less than adequate school services to support auditory and spoken language development. In addition, access to cochlear implantation remains a serious problem even in developed countries. Many parents of newly diagnosed deaf children remain unaware of the effectiveness of cochlear implantation. Candidates may not be recognized or referred early in life for candidacy evaluation. Financial barriers may prevent or delay implantation of one or both ears. Children with medical complexity, especially those with conditions associated with cognitive impairment, may not be viewed as viable candidates. For children in less developed countries, access to cochlear implantation is far more limited and may be the exception for deaf children. Much work remains for the next generation of clinicians and investigators.

Numerous studies of speech perception, spoken language, and literacy of early implanted children have yet to reveal the reason for differences in low- and high-performing children on standard measures of performance. Differences in cognitive processing and learning likely underlie the variability in outcomes after implantation. In other words, the brain is as important as the ear. Using this framework, the redesign of cochlear implant systems and implementation of novel therapies may enable more rapid progress and improved outcomes after implantation. Methods of evaluation that provide insight into each child's cognitive strengths and weaknesses may permit development of customized therapy to preemptively address the needs of those children likely to have poorer outcomes. These are just some of the areas of future research that we hope the readers of this book will embrace.

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Nancy M. Young, M.D.
Development of a multidisciplinary program capable of meeting the diverse needs of children with hearing loss and their families would not have been possible without the many individuals who deeply believe in our mission of helping children achieve their full potential. I gratefully acknowledge the Buehler Family Foundation, the Lillian S Wells Foundation, and the Foundation for Hearing and Speech Rehabilitation for their crucial support. I also wish to thank our implant team members, past and present, and the community-based professionals with whom we collaborate for all they have taught me. I am profoundly grateful to the children and families I serve. They continue to provide me with an invaluable education in humility and a reminder of the struggles that families endure and often overcome.

An important influence early in my career was Alfred E. Mann. Observing first hand his relentless drive and faith in his own vision to alleviate human suffering by translating scientific discovery into clinical interventions remains a source of inspiration. I am also indebted to the many clinicians and researchers in our multidisciplinary field who have generously shared their knowledge. I am fortunate that many have become good friends. One such colleague is Karen Iler Kirk, Ph.D., to whom I am forever grateful for her wisdom and friendship.

My husband Mitchell Marinello, despite his own demanding career, has been unswerving in his support. I am truly blessed to have found such a wonderful husband and father to our three daughters.

Karen Iler Kirk, Ph.D.
I owe a debt of gratitude to William F. House, M.D., who gave me the opportunity to work with his cochlear implant team in 1981, near the beginning of cochlear implantation in children. My work at the House Ear Institute in Los Angeles inspired me to pursue further graduate study, choose an academic career, and conduct research in cochlear implant outcomes. I have been privileged be a part of this pioneering research field and to see the transformative effect this revolutionary technology has had on children and families. Many families gave generously of their time through participation in research to further our understanding of speech and language development following cochlear implantation. I am most grateful to them.

None of this would have been possible without the love and support of my family. My husband, Gerald Kirk, M.D., has been an equal partner in our home and family life, thus allowing me to pursue my career goals. I also want to acknowledge my wonderful children: Andrew and his wife Shawna, Brian and Sarah. I am so proud that they are compassionate, productive young adults who want to make a difference in the world. Finally, I want to thank my dear friend and collaborator, Nancy M. Young, M.D., for having the vision and drive to bring this book to fruition. It wouldn't have been possible without her.

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Part I

Introduction

Cochlear Implant Design Considerations

1

Blake S. Wilson, Michael F. Dorman, René H. Gifford, and David McAlpine

Abbreviations

AB	Arthur Boothroyd (as in the AB words)
AzBio	Arizona Biomedical Institute (as in the AzBio sentences)
BKB	Bamford-Kowal-Bench (as in the BKB sentences)
BPF	Band-pass filter
CI	Cochlear implant
CIS	Continuous interleaved sampling
CNC	Consonant-nucleus-consonant (as in the CNC words)
CUNY	City University of New York (as in the CUNY sentences)
EAS	Electric and acoustic stimulation (as in combined EAS)
F0	Fundamental frequency
HINT	Hearing in Noise Test (as in the HINT sentences)
HSM	Hochmair-Schulz-Moser (as in the HSM sentences)
LPF	Low-pass filter
PTA	Pure tone average
RF	Radio frequency
RM ANOVA	Repeated-measures analysis of the variance
S/N	Speech-to-noise ratio
SEM	Standard error of the mean

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Introduction

The performance of the present-day cochlear implants (CIs) is made possible with (1) multiple and perceptually separable sites of stimulation in the cochlea; (2) good use of those sites with processing strategies aimed at representing in a clear way most of the information that can be perceived with CIs; and (3) the remarkable ability of the brain to make good use of a sparse and otherwise unnatural input from the periphery. When all of the parts come together, the results can be surprisingly good. For example, the great majority of patients today can understand everyday speech in quiet with the CI alone, in the absence of any visual cues. Indeed, most patients today use their cell and landline phones routinely. This restoration of function is a long trip from total or nearly total deafness. As the esteemed Professor Dr. Jan Helms put it (Helms 2009), "From my perspective, cochlear implants are the most significant medical development in the second half of the twentieth century, as they replace an entire sensory organ."

In this chapter, we describe (1) the designs of the present-day unilateral CIs; (2) the performance of those CIs; (3) stimulation that might be added to a unilateral CI to improve performance; and (4) other possibilities for improving performance. Additional information about the performance of the current CI systems is presented in Chap. 9, and information about the designs and performance of prior systems is presented in Wilson (2004, 2006, 2015), Wilson and Dorman (2008, 2009), and Zeng et al. (2008).

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Design and Performance of the Present-Day Cochlear Implants

Components shared by all CI systems now in widespread use are shown in Fig. 1.1. The components include an external sound processor, an external transmitting coil, an implanted receiver/stimulator, a cable from the receiver/stimulator to the implanted electrodes, and the array of the electrodes that are inserted into the scala tympani at the time of surgery. In the illustrated device, the array has 12 sites of stimulation along its length. Other arrays have 16 or 22 sites, although more sites than 8 may not confer further benefits, at least with the present designs and placements of electrodes, and at least with the present processing strategies (see Fig. 1.7 and the accompanying text in the section on "Performance of Unilateral Cochlear Implants"). The other major component in the systems, the user's brain, is not shown in Fig. 1.1. All components are important and must work together to produce good outcomes.

Electrodes

Multiple sites of stimulation and multiple channels of sound processing are needed to maximize performance with CIs. Prior to the 1990s, some developers of CI systems believed that a single site of stimulation and a single channel of processing could be, or might be, just as effective as multiple sites and multiple channels (e.g., House and Urban 1973; Hochmair-Desoyer et al. 1981). However, results from studies conducted at the University of Iowa (e.g., Gantz et al. 1988), along with results from the first prospective, randomized trial of CI devices (Cohen et al. 1993), demonstrated that the multisite and multichannel systems at the times of the studies were better than the contemporaneous single-site and single-channel systems.

As indicated previously, increasing the number of sites up to about eight can produce significant improvements in speech reception. In addition, monopolar stimulation, with currents passed between each intracochlear electrode and a

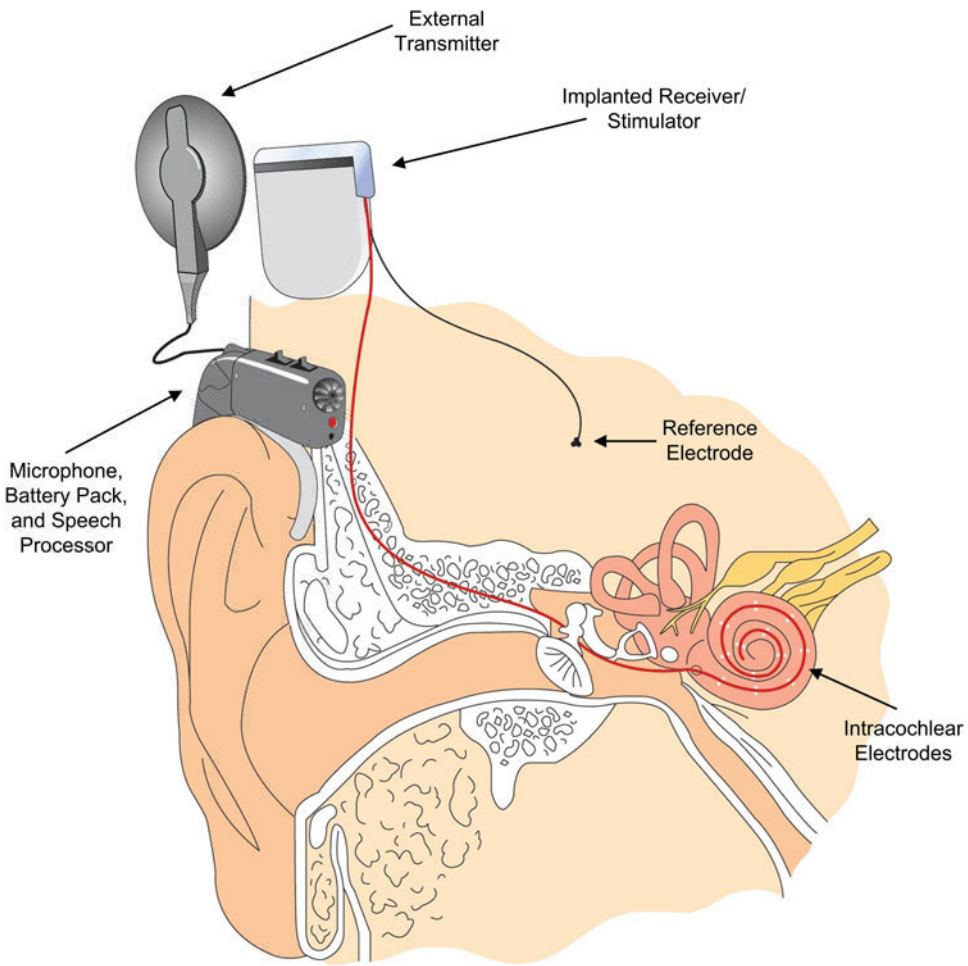

Fig. 1.1 Components of cochlear implant systems (diagram courtesy of MED-EL GmbH of Innsbruck, Austria)

remote reference electrode outside of the cochlea (see Fig. 1.1), is at least as effective as other modes of stimulation, e.g., bipolar stimulation in which currents are passed between intracochlear electrodes, from one electrode to the other in a pair of electrodes. This finding was surprising in that the other modes were thought to produce sharper (more spatially distinct) patterns of electrical stimulation than monopolar stimulation (e.g., Wilson 2004). (Whether the patterns are in fact sharper with the other modes is now an open question; see the two opposing points of view expressed in Kwon and van den Honert 2006, versus Nelson et al. 2011.) However, speech reception scores are at least as good with monopolar stimulation compared to the other modes, and some patients describe monopolar stimulation as sounding more natural than the other modes. Fortunately too, monopolar stimulation requires less battery power than the other modes, and produces much more uniform stimulus magnitudes required for threshold and comfortably loud percepts compared to the other modes. This latter result facilitates the fitting of the device; monopolar stimulation is used in all modern CIs.

Processing Strategies

The external sound processor implements a processing strategy—or a choice among strategies—for transforming the sound input into a set of instructions that are transmitted to the implanted receiver/stimulator via the transcutaneous link that includes the external transmitting coil and the receiving antenna in the implanted receiver/stimulator. Radio-frequency (RF) transmission is used and the instructions are encoded in the RF carrier through some form of modulation. The instructions are decoded upon receipt at the receiver/stimulator using active electronics in that part of the device, and the decoded (recovered) instructions are used to generate the stimuli that are directed to the intracochlear and reference electrodes via cables. (See also the cable for the reference electrode in Fig. 1.1.) Power for the implanted electronics and the stimuli is generated in the receiver/stimulator by rectifying and then smoothing (low-pass filtering) the overall RF signal received by the antenna.

A simple but effective processing strategy for CIs is illustrated in Fig. 1.2. This is the "continuous interleaved sampling" (CIS) strategy that produced a breakthrough in the performance of CIs in the early 1990s (e.g., Wilson et al. 1991; Fayad et al. 2008) and is used to this day as a processing option in all of the devices manufactured by the three largest companies in the field, which together have more than 99 % of the world market. CIS gets its name from the continuous sampling of band energies and presenting that information in an interleaved sequence of stimulation across the utilized intracochlear electrodes in the implant. Multiple other strategies use this same basic approach, with additions to or variations in the processing, as described for example in Wilson and Dorman (2012).

The overarching goal of the design was to represent in the clearest possible way most or all of the information that could be perceived with CIs. That information included the "place" and "temporal" codes for the frequencies of components within sounds, and the amplitude or charge of electrical stimuli for the intensities of the components.

Coding Frequency by Place of Stimulation

For most patients, stimulation of electrodes near the basal end of the cochlea elicits percepts with relatively high pitches and stimulation of electrodes at progressively more apical locations elicits percepts with progressively lower pitches. This representation based on the site of stimulation is the place code for frequencies, a topographic organization that is maintained throughout the ascending auditory pathways all the way up to and including the A1 area of the auditory cortex. Some patients are able to discriminate among a high number of electrodes when the electrodes are stimulated in isolation and at the same pulse rate or sinusoidal frequency. For example, some patients can discriminate among the 22 sites of stimulation provided with the implant devices manufactured by Cochlear Ltd. (Nelson et al. 1995; Zwolan et al. 1997), although results for most patients demonstrate poorer discrimination and no patient tested to date has more than about eight effective sites when the electrodes are stimulated in a speech processor context with rapid sequencing of stimuli among the utilized electrodes. Thus, having more than about eight sites may be "overkill" and we shall return to this point in the sections on "Performance of Unilateral Cochlear Implants" and "Possibilities for Improvements."

Coding Frequency by Rate or Frequency of Stimulation

In addition to the place code for frequencies, stimulation at different rates (for pulses) or frequencies (for sinusoidal or "analog" stimuli) at any one of the multiple sites can produce different pitches up to a maximum rate or frequency beyond which further increases in pitch are not produced. This maximum rate or frequency is called the "pitch saturation limit" for CIs and typically approximates 300 pulses/s or 300 Hz (e.g., Zeng 2002). However, the limit can be higher for exceptional patients, up to or a bit beyond 1000 pulses/s or 1000 Hz for at least one of each patient's electrodes (Hochmair-Desoyer et al. 1983; Townshend et al. 1987; Wilson et al. 1997b). Frequencies in the modulations of pulse trains also have the same limits; for example, the great majority of patients can perceive different frequencies in the modulation waveforms as different pitches up to about 300 Hz but not higher. Discrimination among rates or frequencies below the pitch saturation limit is progressively

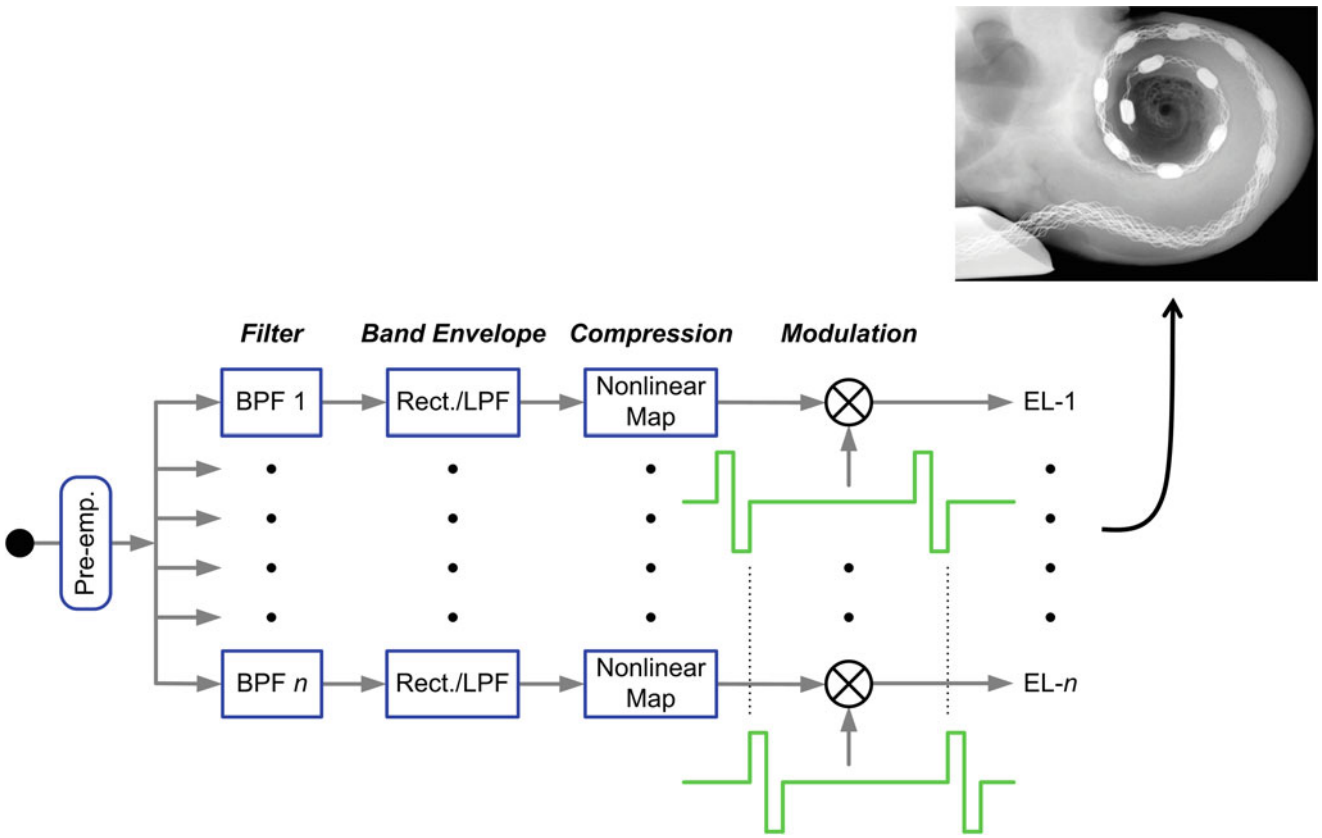

Fig. 1.2 Block diagram of the continuous interleaved sampling (CIS) processing strategy. The diagram is explained in the text. Abbreviations: *Pre-emp.* pre-emphasis filter, *BPF* band-pass filter, *Rect.* rectifier, *LPF* low-pass filter, *EL* electrode. The *circles* with "x" *marks* within them are multiplier blocks, and the *green traces* beneath those blocks are stimulus waveforms (the diagram is adapted from Wilson et al. (1991) and is used here in its modified form with the permission of the Nature Publishing Group; the *inset* is from Hüttenbrink et al. (2002) and is reproduced here with the permission of Lippincott Williams & Wilkins)

worse as the limit is approached and even for low rates or frequencies the discrimination for implant patients is typically ten times worse than the frequency difference limens for subjects with normal hearing (e.g., Zeng 2002). Variation in the rates or frequencies that can produce different pitches for CI users is the temporal code for frequencies; the code is a coarse, but nonetheless useful, representation of frequencies below the pitch saturation limit.

Coding Signal Amplitude

Matching of loudnesses between electric and acoustic stimuli for implant patients who have partial or normal hearing contralateral to the implant has demonstrated the same growths in loudness with (1) equal dB (ratio) increases in intensity on the hearing side or (2) linear increases on the implant side (Eddington et al. 1978; Zeng and Shannon 1992; Dorman et al. 1993). This finding indicates that the growth of loudness in normal hearing can be approximated with a logarithmic mapping (compression) function for electric stimuli, i.e., a logarithmic transformation of acoustic intensities to electric intensities.

The number of discriminable steps in intensity for electrically elicited hearing using balanced biphasic pulses as the stimuli can range from about 7 to about 45 among subjects and electrodes within subjects (Nelson et al. 1996), with an average of about 25 across the subjects and their tested electrodes (Nelson et al. 1996; Chua et al. 2011). These numbers are lower, but not dramatically lower, than the average number of discriminable steps in intensity for listeners with normal hearing, about 83 steps (Nelson et al. 1996).

Design of CIS

In CIS, frequencies of components in the input sound are represented with both the place and temporal codes, and the energies of those components are represented with stimulus intensities. As indicated in Fig. 1.2, multiple channels of processing are used and the output from each channel is directed to a corresponding electrode in the cochlea. Each channel includes a band-pass filter (BPF), an energy (or "envelope") detector, a nonlinear mapping function, and a multiplier, which multiplies (modulates) a train of balanced biphasic pulses with the output of the nonlinear mapping function.

The energy detector illustrated in the figure includes a rectifier (Rect.) followed by a low-pass filter (LPF). Other types of energy detectors can be used, e.g., a Hilbert transform, but the illustrated one is simpler than the alternatives and functions similarly.

The only difference among the channels is the frequency response of the BPFs. The frequency responses range from low to high along a logarithmic scale, which approximates the mapping of frequencies along the cochlear partition in normal hearing. For a six-channel processor, for example, the overall range of frequencies might be from 300 to 6000 Hz and for that range the corner or "break" frequencies of the BPFs would be 300–494, 494–814, 814–1342, 1342–2210, 2210–3642, and 3642–6000 Hz. (The range of frequencies between each pairing of the corner frequencies is the "pass band" for each BPF.) The modulated pulse train for the channel with the lowest center frequency for the bandpass filters is directed to the apicalmost among the utilized electrodes in the implant; the train for the channel with the highest center frequency is directed to the basalmost among the utilized electrodes; and the trains for the channels with intermediate center frequencies are directed to the utilized electrodes at intermediate positions in the implant. This representation approximates the place coding of frequencies in normal hearing, in which high frequencies produce maximal displacements of the basilar membrane at basal positions along its length, and lower frequencies produce maximal displacements at more apical positions.

Within channels, the effective "cutoff" frequency for the energy detectors is set by the frequency response of the LPF. The upper end of the frequency response typically is between 200 and 400 Hz and most commonly at 400 Hz. With that latter setting, frequencies as high as 400 Hz and a bit beyond may be included in the derived energy signal for each channel, and that range of frequencies encompasses and slightly exceeds the pitch saturation limit for most (nearly all) patients. Thus, the temporal information that can be perceived by CI users as a variety of pitches is represented in the energy signal. Representing higher frequencies in this way most likely would be fruitless for all but an exceedingly small fraction of patients, and might well present conflicting cues for the great majority of patients.

The nonlinear mapping function in each channel is used to map the wide dynamic range of the energy signals, which can be as high as about 70 dB, onto the much narrower dynamic range of electrically evoked hearing, which for short-duration pulses usually is between 5 and 20 dB. The mapping is a logarithmic (or sometimes a power law) transformation of the energy variations into pulse amplitude (or pulse charge) variations. This transformation preserves a normal growth of loudness across the dynamic ranges of the energy variations and the derived pulse amplitudes (or charges), as described previously. The mapping also preserves the maximum number of discriminable steps within the dynamic ranges, for each patient and electrodes within patients. (The values of the parameters for the mapping function for each electrode for a patient are derived mathematically from measurements of the currents or charges needed to produce threshold and comfortably loud percepts, and thus the function is customized for each of the utilized electrodes in the implant.)

The modulated pulses for the different channels and corresponding electrodes are interlaced in time so that stimulation at any one electrode is not accompanied by simultaneous or overlapping stimulation at any other electrode in the implant. This interleaving of pulses across electrodes eliminates a principal component of "channel" or electrode interactions due to the direct summation of the electric fields from the different (simultaneously stimulated) electrodes. This direct summation component is much larger than other components of interaction that are produced by neural refractory and temporal summation effects, which are present even with nonsimultaneous stimulation (e.g., Favre and Pelizzone 1993). Without the interleaving, the high levels of interaction (or "cross talk") among electrodes would (1) produce spurious cues that are not related to the signal at the input to the sound processor and (2) greatly degrade the independence of the represented channel outputs.

For an undistorted representation of the temporal variations in the modulation waveforms, the pulse rate for each channel and corresponding electrode must be at least four times higher than the highest frequency in the waveform for the channel (Busby et al. 1993; Wilson et al. 1997a). This fact became known as the "4× oversampling rule" for CIs. Thus, in a typical implementation of CIS the cutoff frequency for the energy detectors might be 400 Hz and the pulse rate for each channel and corresponding electrode might be around 1600/s or higher. (Such high pulse rates cannot be supported by all transcutaneous links and receiver/stimulators, so in those cases at least the pulse rate must be reduced.)

Most fortunately, the typical cutoff frequencies for the energy detectors also include most or all of the range of fundamental frequencies (F0s) in human speech. Thus, the represented modulation waveforms may convey information about the overall energy in a band, F0s for periodic sounds, and the random fluctuations in energy that are characteristic of aperiodic sounds. (Whether other representations of F0s and periodic/aperiodic distinctions might be more salient is not clear at this point and is a topic of current research.) This within-channel information may be especially helpful for perceiving different voices as such; distinguishing interrogative versus declarative intent by a speaker; and discriminating among voiced, unvoiced, and mixed voiced plus unvoiced consonants in speech. In addition, the information could enable perception of F0s and periodic versus aperiodic components in other sounds such as music.

With CIS, frequencies above about 300 Hz are represented with the site(s) of stimulation, and frequencies below about 300 Hz are represented with the temporal variations in the modulation waveforms. Intensities of energies within bands are represented with the modulated pulse amplitudes. The pulses for the different channels are presented from one electrode to the next until all of the utilized electrodes are stimulated. This cycle of stimulation across electrodes is repeated continuously and at a high rate so that energy variations up to the pitch saturation limit for most patients are represented at each of the electrodes. The pulse rate for all electrodes is the same. No assumptions are made in the design about sounds in the environment or in particular how speech is produced or perceived.

Prior processing strategies either (1) extracted specific features from the input and represented those features only in the stimuli directed to the intracochlear electrodes or (2) presented stimuli simultaneously or with substantial overlaps at the electrodes. In addition, prior strategies using nonsimultaneous pulses as the stimuli presented the pulses at relatively low rates. CIS produced a large jump up in performance compared to the prior strategies and is the basis for many of the strategies that were developed subsequently. CIS remains as the principal strategy against which other strategies are compared.

A more detailed description of CIS and how it departed from the past is presented in Wilson (2015). And considerable further information about the prior and subsequent strategies is presented in Wilson (2004, 2006), and in Wilson and Dorman (2008, 2009, 2012).

CIS exemplifies the design principles that are used in all of the current CI systems. Those principles include (1) representing at least most of the information that can be perceived according to place, frequency, and intensity of stimulation; (2) minimizing electrode interactions; and (3) using appropriate mapping functions and other aspects of processing to minimize perceptual distortions.

Performance of Unilateral Cochlear Implants

Snapshots of the performance of unilateral CIs as of the mid-1990s and today are presented in Fig. 1.3. The two left panels show results from a multicenter study in Europe to evaluate the COMBI 40 implant device (Helms et al. 1997) and the two right panels show results for all postlingually deafened adults who were implanted at the Vanderbilt University Medical Center, USA, from the beginning of 2011 through early 2014 using a variety of the devices now in widespread use (data provided by author RHG). The columns in each panel show scores (circles) for different times after the initial fitting of the device for each subject in the Helms et al. study or for each implanted ear in the Vanderbilt dataset. All of the subjects in the Helms et al. study were implanted unilaterally, and most of the subjects in the Vanderbilt cohort were implanted unilaterally as well, but the rest received bilateral CIs, either sequentially or simultaneously. For those latter subjects, each ear was tested separately and thus data are shown for ears rather than subjects in the right panels. The subjects who participated in the Helms et al. study also were postlingually deafened adults. Selection criteria for those subjects included (but were not limited to) a patent scala tympani as demonstrated in preoperative radiologic scans; at least relatively normal gross anatomy of the cochlea as also demonstrated in the scans; no prior CI; no middle- or outer-ear pathologies that could impede cochlear implantation; a duration of profound hearing loss less than or equal to 50 % of a candidate's lifetime; and "general health good enough to allow testing at scheduled intervals." In contrast, the Vanderbilt cohort included all adults with postlingual onsets implanted there from 2011 through early 2014, many of whom would not have met one or more of the selection criteria for the Helms et al. study. On the other hand, the patients in the Vanderbilt cohort had more residual hearing on average than the subjects in the Helms et al. study, as the audiological restrictions for implant candidacy had been relaxed in multiple steps from the mid-1990s onward.

The tests in the Helms et al. study and at Vanderbilt included measures of word and sentence recognition. Scores for the sentence tests are shown in the top panels in Fig. 1.3, and scores for word tests in the bottom panels. The Hochmair-Schulz-Moser (HSM) sentences (Hochmair-Desoyer et al. 1997), or their equivalents in languages other than German, were used in the Helms et al. study, and the Arizona Biomedical Institute (AzBio) sentences (Spahr et al. 2012) were used at Vanderbilt. The AzBio sentences include multiple talkers and fewer contextual cues than the HSM sentences, and thus are far more difficult than those or other "everyday" sentences uttered by a single talker (Gifford et al. 2008; Spahr et al. 2012). For the word tests, the Freiburger monosyllabic words (Hahlbrock 1953, 1970) or their equivalents for languages other than German were used in the Helms et al. study, and the monosyllabic consonant-nucleus-consonant (CNC) words (Peterson and Lehiste 1962) were used at Vanderbilt. All tests at Vanderbilt were conducted in English. The word tests were comparable in difficulty for the different languages in the Helms et al. study, and between the Helms et al. study and the Vanderbilt measures. In particular, none of the tests included contextual cues and all of the tests used the CNC structure and single talkers. All 55 subjects who participated in the Helms et al. study were tested at all intervals after the initial fitting and thus the number of data points in each column in each of the left panels is 55. Most of the presented data are from Helms et al. (1997), and the remaining data were collected after that publication and provided by Jan Helms (the supplemental

data are reported in Wilson 2006). A total of 267 ears were tested at Vanderbilt, and different numbers of ears were tested at the different intervals, depending on patient availability and when the ear was implanted (of course, recent implants could preclude tests at the later intervals). One of the columns in the right panels includes 183 scores, and the other columns include fewer scores. The numbers of scores vary across the columns in each panel and between like columns in the two panels. The mean of the scores in each column in each panel of Fig. 1.3 is shown with the horizontal red line. CIS was used for the COMBI 40 device, and a variety of processing strategies including CIS were used for the various devices implanted at Vanderbilt, which included devices manufactured by Cochlear Ltd., Advanced Bionics LLC, and MED-EL GmbH. All tests were conducted with hearing alone and without feedback as to correct or incorrect responses. The test items were unknown to the subjects prior to testing. Direct-input or live-voice presentations were used in the Helms et al. study for the word and sentence tests, respectively, whereas free-field presentations in audiometric booths were used at Vanderbilt for all tests. The level of the presentations at Vanderbilt was 60 dBA at the subject's

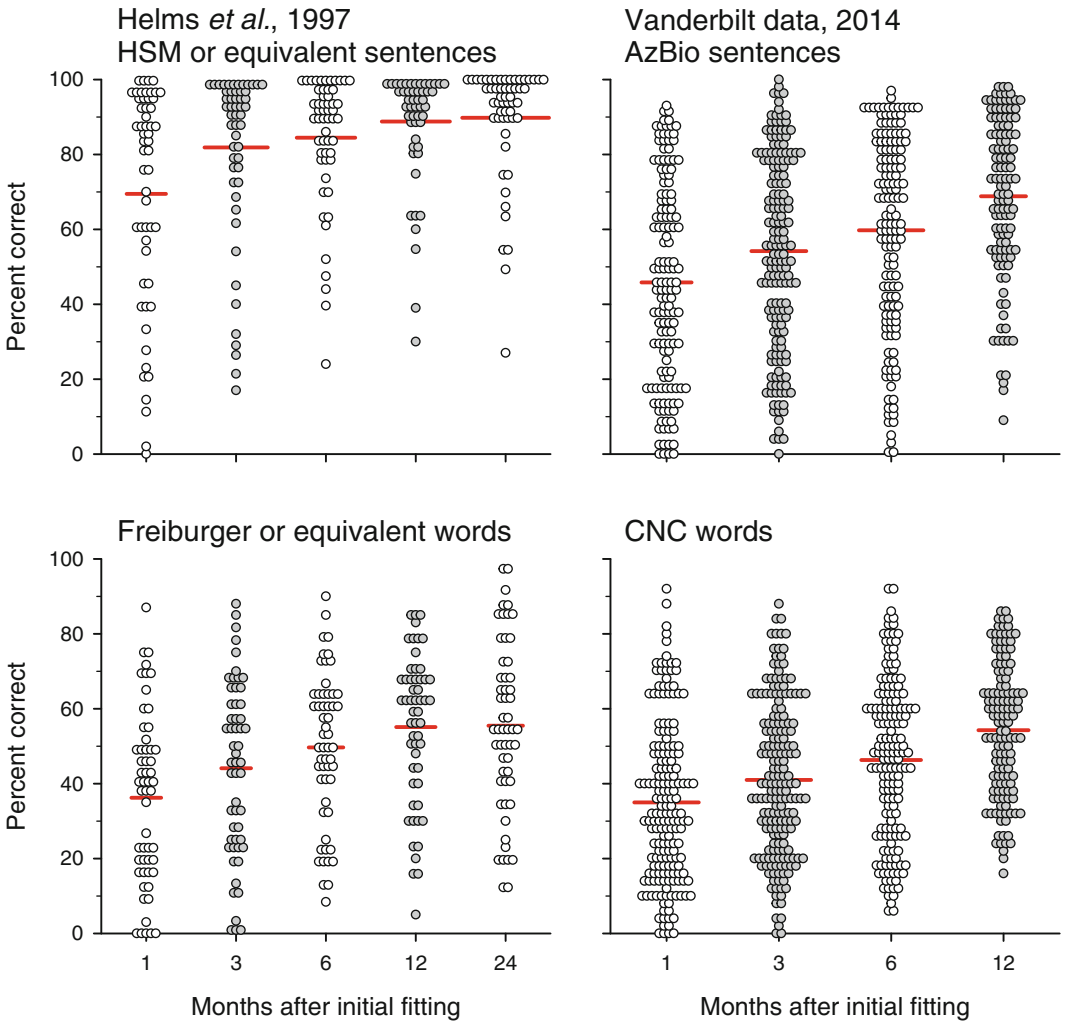

Fig. 1.3 Speech reception scores (*circles*) for cochlear implant (CI) subjects. Data from a multicenter study in Europe by Helms et al. (1997) are presented in the *left panels*, and data collected between 2011 and the first part of 2014 at the Vanderbilt University Medical Center in the USA are presented in the *right panels*. Tests for Helms et al. subjects included recognition of the Hochmair-Schulz-Moser (HSM) sentences or their equivalents in languages other than German, and recognition of the monosyllabic Freiburger words or their equivalents in languages other than German. Tests for the Vanderbilt subjects included recognition of the Arizona Biomedical Institute (AzBio) sentences and recognition of the monosyllabic consonant-nucleus-consonant (CNC) words. The *columns* within the panels show scores for different times after the initial fitting of the device. All tests were conducted with hearing alone and without feedback as to correct or incorrect responses. The Helms et al. subjects used the COMBI 40 CI device and its implementation of the continuous interleaved sampling (CIS) processing strategy, and the Vanderbilt subjects used a variety of the latest devices and strategies. All of the subjects were adults with postlingual onsets of severe or profound hearing loss. The *red horizontal lines* show the means of the scores at each of the test intervals for each of the tests. Many of the scores are displaced slightly along the abscissa and binned into small intervals along the ordinate to aid in the reading of each panel

location, and a "conversational level" was used for the sentence presentations in the Helms et al. study, which typically approximates 60 dBA.

In both sets of data, scores for both the word and sentence tests improve over time, out to 3–12 months after the initial fitting of the device. Scores for the sentence tests are substantially higher than the scores for the word tests; this finding is not surprising given that the word tests do not include the contextual cues available in the sentence tests. Scores for the sentence tests become progressively more clustered near the top with increasing time after the initial fitting out to 1 year for the Helms et al. data and some slight clustering is observed in the Vanderbilt data at the 6- and 12-month intervals only. As might be expected, scores for the AzBio sentences are substantially lower than the scores for the HSM or equivalent sentences. Indeed, the latter scores show clear ceiling effects, whereas ceiling effects are not obviously encountered with the AzBio sentence tests. At the 2-year interval for the HSM or equivalent sentence tests, the mean score is about 90 % correct and the median score is 95 % correct. This high level of performance is completely consistent with high levels of everyday communications. In fact, most CI recipients today have little or no difficulty in using the telephone for communications even with unfamiliar persons or unknown and varying topics. Scores for the other tests are consistent with everyday communications as well; the lower scores for those tests simply reflect their greater difficulty.

An especially interesting aspect of the data in Fig. 1.3 is the time course of improvements for each of the tests. This aspect is easier to see in Fig. 1.4, which shows the means and standard errors of the means (SEMs) for the cases in which both sentence and word scores are available at all of the test intervals. Those cases include the 55 subjects in the Helms et al. study (data in the left panels of Fig. 1.3) and 29 of the ears that were tested at Vanderbilt (subset of the data in the right panels of Fig. 1.3). In addition, means and SEMs are shown in Fig. 1.4 for the additional intervals included in the Helms et al. study for the sentence tests, for the same 55 subjects.

One-way, repeated-measures analyses of the variance (RM ANOVAs) indicate highly significant improvements in the mean scores over time for the recognition of both sentences and words for the Helms et al. subjects and for both sentences and words for the ears tested at all intervals at Vanderbilt ($p < 0.001$ in all cases). Results from *post hoc* pairwise comparisons using the Holm-Sidak method are presented in Table 1.1. In broad terms, significant improvements in the scores for each of the tests are observed out to 3–12 months after the initial fitting of the device for each subject or ear. Asymptotic scores are reached earlier with the HSM or equivalent sentences than for the other tests, most likely due to ceiling effects. (The onset of ceiling effects can be seen in the narrowing of the error bars in Fig. 1.4 starting at the 3-month interval.) Six to 12 months (or perhaps more in the Vanderbilt data) are required to reach asymptotic performance with the more difficult tests. A clear plateau in performance starting at 12 months is seen in the scores from the word tests in the Helms et al. data.

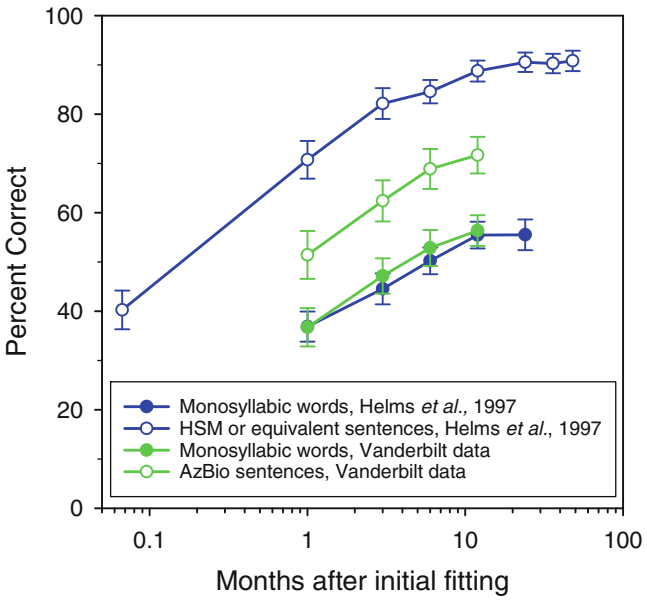

Fig. 1.4 Means and standard errors of the means (SEMs) for the recognition of words (*closed symbols*) and sentences (*open symbols*). The data are from (1) the 55 subjects tested at all of the indicated times after the initial fitting of the cochlear implant in the study by Helms et al. (1997) and (2) the 29 ears tested with both words and sentences at all of the indicated times at Vanderbilt. Details about the tests are provided in the text. Note that the time scale is logarithmic

These long time courses of improvements (on average) are consistent with changes in brain function (e.g., Moore and Shannon 2009; Lazard et al. 2012), but not with changes at the periphery, which are far more rapid. For example, any fibrous encapsulation of the electrode array is usually complete within several weeks of implantation and reductions in electrode impedances typically asymptote within minutes or hours following initial stimulation. Those or other short-term changes are not correlated with the improvements in speech reception.

Scores for the AzBio test are intermediate to the scores for the word tests on the one hand, and the scores for the HSM or equivalent sentence tests on the other hand. In addition, the scores for the AzBio test do not exhibit ceiling effects for the population (although some scores are above 90 % correct and the distribution of scores is slightly skewed toward the top at the 6- and 12-month intervals, as shown in Fig. 1.3). These facts make the AzBio test more useful than easier sentence tests for discriminating possible differences among devices, subjects, processing strategies, and different amounts of experience with a CI. Also, the AzBio test more closely approximates real-world situations than the monosyllabic

Table 1.1 Results from *post hoc* comparisons using the Holm-Sidak method, following significant repeated-measures ANOVAs for each of the tests in Fig. 1.4

Data set	Test	Results
Helms et al.	Sentences	Scores at the intervals between and including 1–48 months are > the score at the 2-day interval; scores at the intervals between and including 3–48 months are > the score at the 1-month interval
	Words	Scores at the intervals between and including 6–24 months are > the score at the 1-month interval; scores at the 12- and 24-month intervals are > the score at the 3-month interval; the score at the 3-month interval is > the score at the 1-month interval
Vanderbilt	Sentences	All pairwise comparisons are significantly different except for the scores at the 12- and 6-month intervals
	Words	All pairwise comparisons are significantly different except for the scores at the 12- and 6-month intervals

The criterion for significance for the *post hoc* comparisons was $p < 0.05$

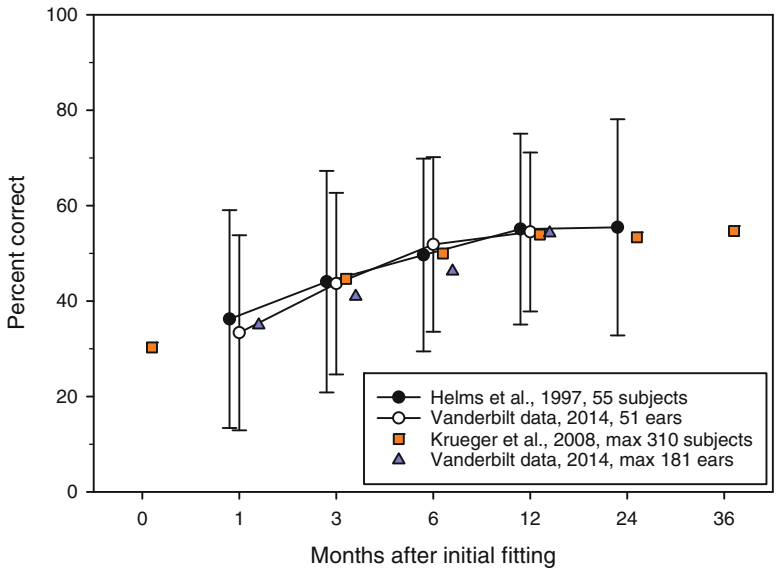

Fig. 1.5 Means of percent correct scores for the recognition of monosyllabic words by cochlear implant subjects. The sources of the data are indicated in the legend. Standard deviations are shown for (1) the 55 subjects in the Helms et al. study who took the test at all five intervals after the initial fitting of the device and (2) the 51 ears tested at all four intervals at Vanderbilt. Some of the symbols are offset slightly along the abscissa to aid in the reading of the figure (the figure is adapted from Wilson (2015), and is used here with the permission of Elsevier BV)

word tests, and thus might be a better measure of everyday performance. Author RHG and colleagues have therefore advocated the use of the AzBio test, instead of easier tests, in standard clinical practice (e.g., Gifford et al. 2008).

A striking finding shown in Fig. 1.4 is the complete overlap in scores for like intervals from the word tests conducted at Vanderbilt and the word tests conducted in the Helms et al. study (two sets of filled symbols in the figure). That is, no improvement in the recognition of monosyllabic words was observed between the mid-1990s, when the Helms et al. data were collected, and 2011–2014, when the Vanderbilt data were collected, despite (1) the introductions of new processing strategies and electrode designs; (2) greater numbers of processing channels and associated sites of stimulation; and (3) substantial relaxations in the audiological restrictions for implant candidacy during the intervening period. This observation is a little sobering and frustrating of course, given the tremendous efforts by our teams and many others to improve performance in the period. The COMBI 40 device, with its eight sites of stimulation in the cochlea and its use of CIS, has yet to be surpassed, at least according to these data and with the caveat that some of the experimental conditions were different between the Helms et al. study and the Vanderbilt measures.

We would like to emphasize here that the data presented in Figs. 1.3 and 1.4 are from large populations of sequentially implanted patients that include all adults with postlingual onsets who received their implants as part of a large clinical trial (the Helms et al. study) or from a large clinical center (Vanderbilt) and who were all treated and tested uniformly. The subjects from such populations represent the broad clinical experience and include CI users with relatively poor outcomes even with the best medical care and the best of the available devices. Higher scores have been reported (e.g., Blamey et al. 2013; Holden et al. 2013; Gifford et al. 2014a), but those scores were obtained with more highly restricted populations and sometimes with different tests and test conditions within the populations. The figures provide an accurate and fully representative picture of where we were as a field in the mid-1990s and recently, from 2011 through early 2014.

The similarities in performance across the years shown in Fig. 1.4 are even more evident in Fig. 1.5, which shows data

for the recognition of monosyllabic words from three sources and at various points in time. The data include the scores for the 55 subjects who participated in the Helms et al. study, and the scores for the 51 ears that were tested at all intervals at Vanderbilt, for the recognition of monosyllabic words. Means and standard deviations are shown. In addition, the means of the scores for all ears tested at Vanderbilt at each of the intervals are shown with the purple triangles, and the means for subsets of the 310 subjects in Group 5 in a retrospective chart study by Krueger et al. (2008) are shown with the orange squares. (Group 5 included the subjects using the latest devices and processing strategies as of 2008; the subjects in Groups 1–4 used earlier devices and processing strategies.) A maximum of 310 subjects were tested at each of the indicated intervals in the Krueger et al. study, and a maximum of 183 ears were tested at any one interval at Vanderbilt. As mentioned previously, the Freiburger or equivalent tests were used in the Helms et al. study and the CNC word test was used at Vanderbilt. The subjects in the Krueger et al. study were all implanted at the Medizinische Hochschule Hannover in Hannover, Germany, and the Freiburger word test was used exclusively for those subjects. All of the subjects from the various studies were adults when they received their implant(s) and had postlingual onsets of severe or profound hearing loss. In addition, malformations of the cochlea or a handicap or handicaps in addition to hearing loss were among the exclusion criteria in the Krueger et al. study. The mode and level of presentations of the test items were not specified in the paper by Krueger et al. The Helms et al. data were collected in the mid-1990s, the Kruger et al. data in the mid-to-late 2000s, and the Vanderbilt data from 2011 to early 2014. With the noted exceptions, the Krueger et al. data also include scores from every single adult patient with a postlingual onset implanted at a large clinic (in fact, the world's largest CI clinic) over a span of years, ending in the year 2008 in this case.

The result from a one-way RM ANOVA for the Helms et al. data was mentioned previously, and a one-way RM ANOVA for the larger set of ears for the monosyllabic word test only in the Vanderbilt data also was highly significant ($p < 0.001$). *Post hoc* comparisons using the Holm-Sidak method for the latter data again showed that the mean score at any one interval is significantly different from the scores at the other intervals, except for the scores at the 6- and 12-month intervals.

The scores for these two sets of data completely overlap, at all of the common intervals. In addition, the standard deviations are the same for the two sets of data.

Further, the mean scores for all of the ears tested at each interval at Vanderbilt, and the mean scores for subsets of subjects in Group 5 tested at each of the intervals in Hannover, closely approximate each other and the mean scores for the 51 ears tested at all intervals at Vanderbilt and for the 55 subjects tested at all intervals in the Helms et al. study. In all sets of data, scores increase out to 6–12 months after the initial fitting of the device, and the score for 12 months and beyond is around 55 % correct. That latter score has become the "gold standard" for present CI devices and processing strategies, at least for unilateral CIs and large groups of unselected subjects.

Of course, experimental conditions varied somewhat among the studies, and one or more of the differences may have affected the results. However, the correspondence in the data across the studies is remarkable and the available results do not indicate any improvements in isolated word recognition performance from the mid-1990s through the beginning of 2014.

Although the mean scores for the recognition of monosyllabic words often approximate 55 % correct for experienced users of unilateral CIs only, the variability in scores is high, as shown by the high standard deviations in Fig. 1.5 and the nearly uniform distributions of the individual scores for those tests in Fig. 1.3. In the Helms et al. data, for instance, the individual scores at the 24-month interval range from about 10 % correct to nearly 100 % correct. One of the principal remaining questions in implant research is why the range is so large, and a related question is how to bring up the lower end of the range.

With that said, performance for some patients is spectacular. Some examples can been seen in Fig. 1.3 and a further example is presented in Fig. 1.6, which shows scores for a CI subject (subject HR4) versus scores for six undergraduate students at Arizona State University with clinically normal hearing (the data are from Wilson and Dorman 2007). The tests included recognition of the CNC words; recognition of the City University of New York (CUNY) sentences; recognition of the Hearing in Noise Test (HINT) sentences (here presented without noise); recognition of the AzBio sentences; identification of 20 English consonants in a /e/-consonant-/e/ context; identification of 13 American English vowels in a /b/-vowel-/t/ context; and recognition of separate lists of the CUNY and AzBio sentences presented in competition with a four-talker babble at the speech-to-babble ratio of +10 dB for both tests and at +5 dB for the AzBio test. The sentences and words were unknown to the subjects prior to the tests and the presentations of the consonants and vowels were randomized. No feedback was given as to correct or incorrect responses and all tests were conducted with hearing alone. The CI subject used an implant device manufactured by Advanced Bionics LLC and its implementation of the CIS strategy. For this subject, 16 channels of processing and corresponding sites of stimulation were used, and the pulse rate at each site was 1449/s.

The scores for the CI subject (HR4) are statistically indistinguishable from the means of the scores for the subjects with normal hearing for all of the tests except for the AzBio

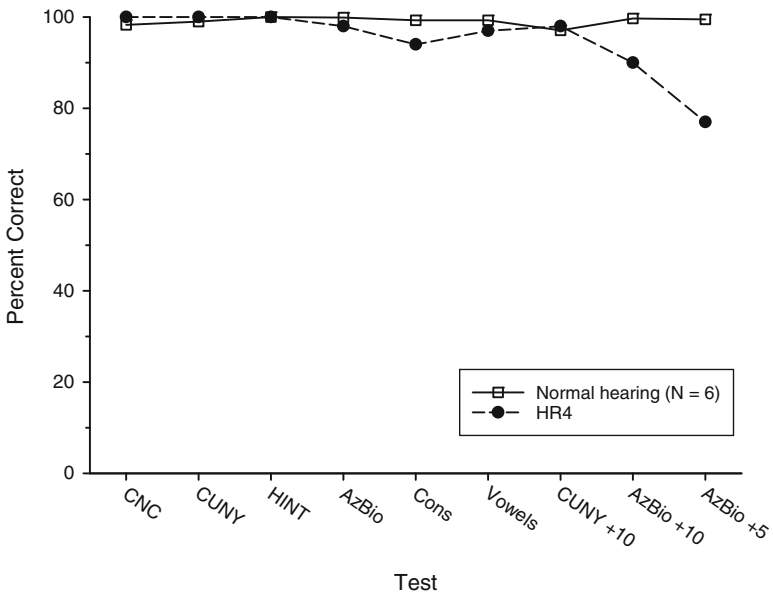

Fig. 1.6 Scores for cochlear implant subject HR4 (*closed circles*) and six subjects with normal hearing (*open squares*) for a battery of speech reception tests. The tests are identified in the text. Means are shown for the subjects with normal hearing; the maximum standard error of the means was 1.1 %. The +10 and +5 labels denote the speech-to-babble ratios of +10 and +5 dB, respectively (the data are from Wilson and Dorman (2007), and the figure is adapted from Wilson (2015), and is used here with the permission of Elsevier BV)

sentences presented in competition with the multitalker babble. The CI subject achieved a perfect score in the monosyllabic word test, and that subject scored at or near the ceiling for most of the other tests, including tests such as the AzBio sentences in quiet that are far more difficult than the sentence tests administered in standard clinical practice.

HR4 and other similarly performing subjects were postlingually deafened and had been profoundly deaf before receiving their CIs. After the CIs and some experience with them, the speech reception scores achieved by these subjects with their restored hearing alone are in the normal ranges according to the standard clinical measures.

This is not to say however that these subjects have normal hearing. As seen for example in Fig. 1.6, the top performers still have difficulties in listening to speech presented in competition with noise. That is a serious problem, because real-world environments such as restaurants and workplaces are notoriously noisy, with typical speech-to-noise ratios (S/Ns) on the order of zero to +5 dB (Pearsons et al. 1977). In addition, and what is not shown in Fig. 1.6, is the great concentration that must be exerted by the CI subjects in achieving their high scores. In contrast, subjects with normal hearing achieve the scores without obvious conscious effort. Furthermore, even the top-performing CI subjects have trouble in fully perceiving sounds that are more complex than speech, such as most music. Full perception of those sounds may require a finer grained representation of frequencies than is possible with the present-day unilateral CIs.

Nonetheless, the high levels of speech reception shown in Fig. 1.6 and elsewhere are impressive. Indeed, they are an existence proof that the peripheral representation is adequate for reception of difficult speech items—and for reception of speech presented in adverse situations—for some patients. That such a sparse representation could be adequate is both surprising and fortunate.

The Number of Electrodes Does Not Equal the Number of Perceptual Channels

The top and average performances of the present-day unilateral CIs are all the more surprising when one appreciates that no more than eight effective channels are available to the users of those CIs, even if the users have a higher number of discriminable electrodes. This fact is illustrated in Fig. 1.7, which shows speech reception scores with different numbers of processing channels and corresponding sites of stimulation in the cochlea. The top panel shows results from one of author BSW's prior laboratories at the Research Triangle Institute in North Carolina, USA, for a subject using a Cochlear Ltd. implant with 22 sites of stimulation in the scala tympani, and the bottom panel shows results from a laboratory within the Manchester Cochlear Implant Programme in the UK, for 11 subjects using MED-EL COMBI 40+ implants with 12 sites of stimulation in the scala tympani (data from Garnham et al. 2002). The tests for the subject in the top panel were identification of 24 English consonants in a /a/-consonant-/a/ context, presented in quiet and in competition with speech-spectrum noise at the S/N of +5 dB (additional details about the tests and results from additional subjects are presented in Lawson et al. 1996; Wilson 1997). The tests for the subjects in the bottom panel were recognition of the Bamford-Kowal-Bench (BKB) sentences; identification of 16 English consonants also in a /a/-

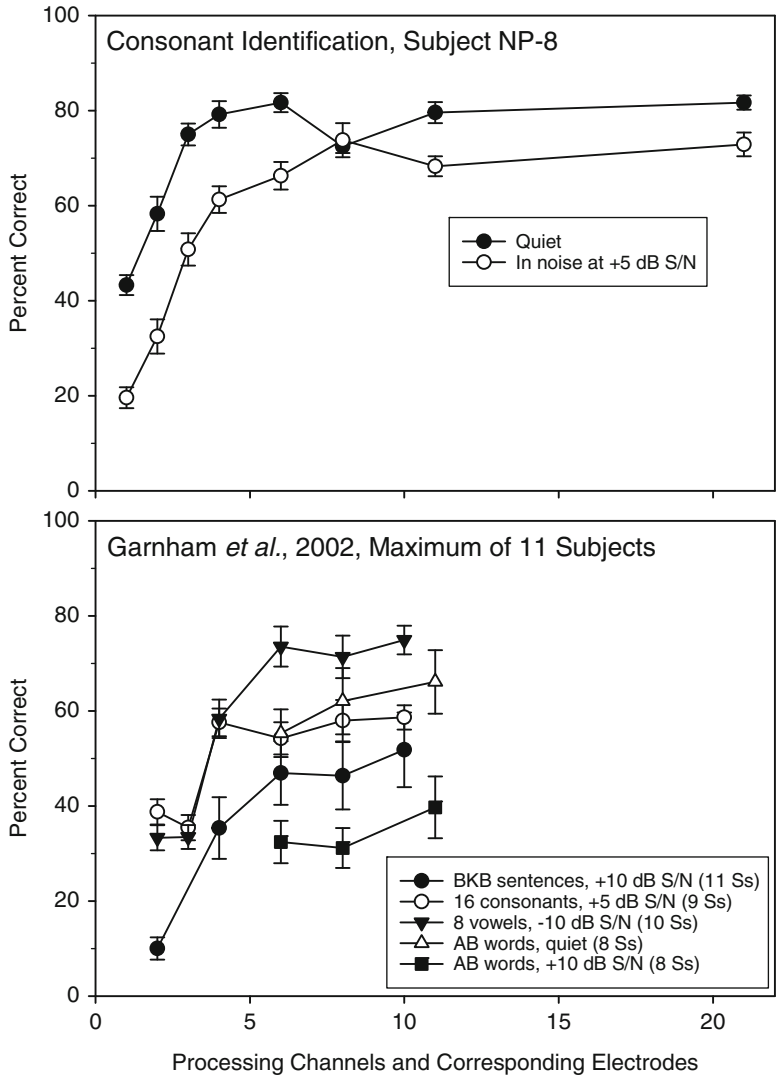

Fig. 1.7 Speech reception scores for different numbers of processing channels and corresponding electrodes. The continuous interleaved sampling (CIS) processing strategy was used. Means and standard errors of the means are shown. The data presented in the *top panel* are from one of author BSW's prior laboratories and the experimental conditions are described briefly in the text and more completely in Lawson et al. (1996) and Wilson (1997). The data presented in the *bottom panel* are from Garnham et al. (2002). The tests are identified in the text, and additional abbreviations in the figure are S/N for speech-to-noise ratio and Ss for subjects (the figure is from Wilson and Dorman (2008), and is reproduced here with the permission of Elsevier BV)

consonant-/a/ context; identification of 8 British vowels in a /b/-vowel-/d/ context; and recognition of the Arthur Boothroyd (AB) monosyllabic words. Many of the speech items were presented in competition with pink noise at the S/Ns indicated in the legend for the figure. A maximum of 11 subjects took each test. All 22 of the intracochlear sites could be discriminated by the subject in the top panel when the sites were stimulated in isolation, one after the other with pauses in between. Users of the MED-EL implants (such as the subjects for the tests in the bottom panel) usually can discriminate a high proportion if not all of their intracochlear sites, also when stimulated in isolation. (The center-to-center distance between adjacent sites in the COMBI 40+ and some other MED-EL implants is 2.4 mm, whereas the distance for the Cochlear Ltd. implants is 0.75 mm; the greater separation in the MED-EL implants generally leads to higher discrimination among the sites.) All tests were conducted with hearing alone and without prior knowledge of the test items or feedback as to correct or incorrect responses. CIS was used for all subjects. Means and SEMs are shown in the figure.

The results from both sets of tests demonstrate asymptotes in performance as the number of processing channels and corresponding electrodes is increased beyond 3, 4, or 6, depending on the test. This limitation is present despite the fact that many patients—including the subjects in the two studies in Fig. 1.7—can discriminate more electrodes when stimulated in isolation, compared with the number of effective channels in a speech processor context, when all of the utilized electrodes are stimulated in rapid sequences. Possibly, temporal interactions among electrodes, such as might be produced with neural refractory or temporal summation effects, impose limits on the maximum number of effective channels with the present-day processing strategies, electrode designs, and electrode placements. An increase in the number of effective channels also could lead to a breakthrough in the design and performance of unilateral CIs.

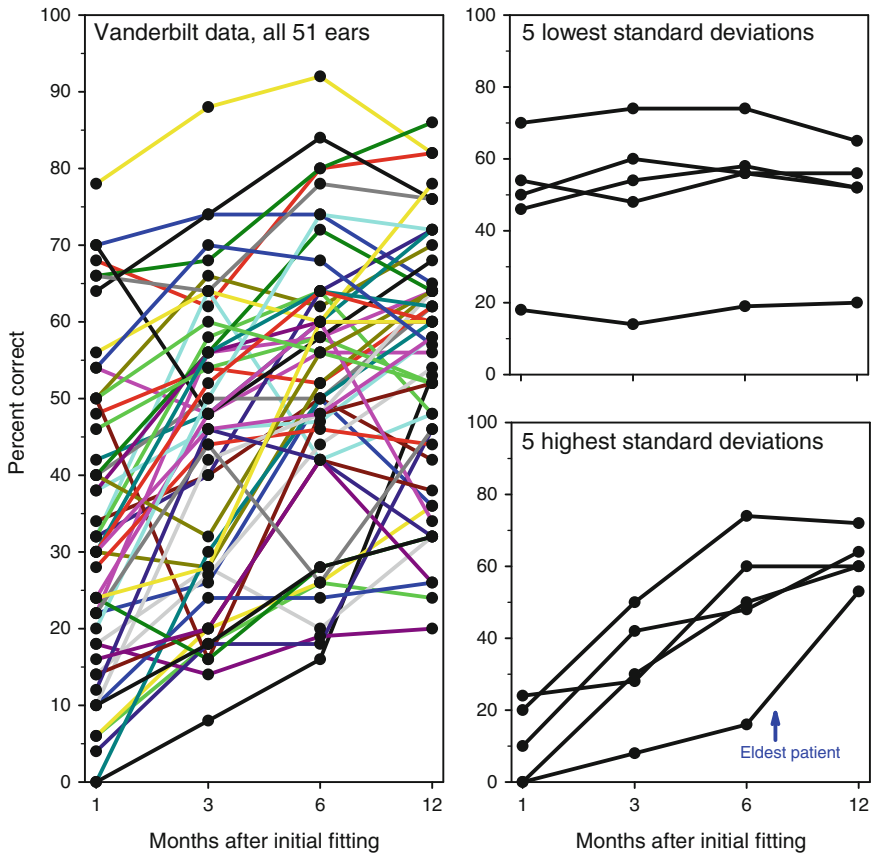

Fig. 1.8 Scores for the recognition of monosyllabic words for (1) the 51 ears tested at all four intervals at Vanderbilt (*left panel*); (2) the 5 among the 51 ears with the lowest standard deviations for the scores across the intervals (*upper right panel*); and (3) the 5 among the 51 ears with the highest standard deviations (*lower right panel*). The data are from 46 patients, 5 of whom were implanted bilaterally. The scores for the ear implanted the latest in life among the patients are identified in the *lower right panel*. That ear was implanted at age 83.6 for the patient, and that was the only ear implanted for the patient. The ear implanted the earliest in life among the 46 patients was implanted at age 27.7 for the patient

Results from the studies in Fig. 1.7 are mirrored by the results from multiple other studies, in which the CIS and other strategies were used, and in which a variety of implant devices were used (Lawson et al. 1996; Fishman et al. 1997; Wilson 1997; Kiefer et al. 2000; Friesen et al. 2001). The findings are always the same; that is, no more than about eight channels are effective for any subject, device, test, or processing strategy. And in many cases, the number is lower than eight.

Thus, the representation provided by the present-day unilateral CIs is even sparser than the number of intracochlear electrodes. In addition, many aspects of the intricate processing in the normal cochlea are not included in the processing or in the neural representations provided by those CIs. (Many of these missing aspects are listed and described in Wilson and Dorman 2007.) The brain can somehow utilize this seemingly impoverished input, and that ability enables the performance of the present-day devices.

Variability in Performance

A final important aspect of the speech reception data for unilateral CIs is the variability among subjects in improvements in scores during the initial 6–12 months of implant use. Although the mean scores for populations of subjects improve in that period (Figs. 1.3, 1.4, and 1.5), not all subjects show improvements. This fact is illustrated in Fig. 1.8, which presents in the left panel recognition of monosyllabic words for all 51 ears that were tested at all intervals at Vanderbilt (the mean scores are shown with the open circles in Fig. 1.5) and in the right panels the sets of scores with the five lowest (upper panel) and five highest (lower panel) standard deviations across the intervals. The high variability in improvements over time is evident in the left panel, and patterns of scores showing no improvements and large improvements are evident in the right panels. The upper right panel shows patterns for the lower tenth of the population in terms of improvements over time, and the lower right panel shows patterns for the upper tenth. A one-way RM ANOVA for the data in the upper right panel is not significant, whereas a one-way RM ANOVA for the data in the lower right panel is highly significant ($p < 0.001$). A further remaining question in implant research is why results for some patients demonstrate large improvements during the first 6–12 months of implant use but results for other patients do not. The age of the patient does not appear to be a limiting factor, as the results for the ear tested for the eldest patient in the group demonstrated some of the largest improvements over time. In addition, the starting point (the scores at 1 month after the initial fitting) does not seem to predict whether scores will stay flat with time, as those points range from about 18 % correct to about 70 % cor-