Springer Handbook of Auditory Research

Gerald R. Popelka
Brian C. J. Moore
Richard R. Fay
Arthur N. Popper *Editors*

Hearing Aids

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Richard R. Fay, Woods Hole, MA, USA
Arthur N. Popper, College Park, MD, USA

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Editors
Gerald R. Popelka
Otolaryngology–Head and Neck Surgery
Stanford University
Stanford, CA, USA

Brian C.J. Moore
Department of Experimental Psychology
University of Cambridge
Cambridge, UK

Richard R. Fay
Marine Biological Laboratory
Woods Hole, MA, USA

Arthur N. Popper
Department of Biology
University of Maryland
College Park, MD, USA

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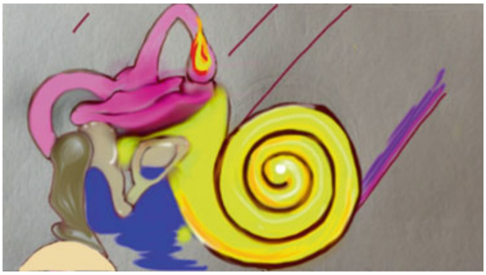
Series Preface



The following preface is the one that we published in Volume 1 of the *Springer Handbook of Auditory Research* back in 1992. As anyone reading the original preface, or the many users of the series, will note, we have far exceeded our original expectation of eight volumes. Indeed, with books published to date, and those in the pipeline, we are now set for more than 50 volumes in *SHAR*, and we are still open to new and exciting ideas for additional books.

We are very proud that there seems to be consensus, at least among our friends and colleagues, that *SHAR* has become an important and influential part of the auditory literature. While we have worked hard to develop and maintain the quality and value of *SHAR*, the real value of the books is very much because of the numerous authors who have given their time to write outstanding chapters and to our many coeditors who have provided the intellectual leadership to the individual volumes. We have worked with a remarkable and wonderful group of people, many of whom have become great personal friends of both of us. We also continue to work with a spectacular group of editors at Springer. Indeed, several of our past editors have moved on in the publishing world to become senior executives. To our delight, this includes the current president of Springer US, Dr. William Curtis.

But the truth is that the series would and could not be possible without the support of our families, and we want to take this opportunity to dedicate all of the *SHAR* books, past and future, to them. Our wives, Catherine Fay and Helen Popper, and our children, Michelle Popper Levit, Melissa Popper Levinsohn, Christian Fay, and Amanda Fay, have been immensely patient as we developed and worked on this series. We thank them, and state, without doubt, that this series could not have happened without them. We also dedicate the future of *SHAR* to our next generation of (potential) auditory researchers—our grandchildren—Ethan and Sophie Levinsohn; Emma Levit; and Nathaniel, Evan, and Stella Fay.

Preface 1992

The *Springer Handbook of Auditory Research* presents a series of comprehensive and synthetic reviews of the fundamental topics in modern auditory research. The volumes are aimed at all individuals with interests in hearing research including advanced graduate students, postdoctoral researchers, and clinical investigators. The volumes are intended to introduce new investigators to important aspects of hearing science and to help established investigators to better understand the fundamental theories and data in fields of hearing that they may not normally follow closely.

Each volume presents a particular topic comprehensively, and each serves as a synthetic overview and guide to the literature. As such, the chapters present neither exhaustive data reviews nor original research that has not yet appeared in peer-reviewed journals. The volumes focus on topics that have developed a solid data and conceptual foundation rather than on those for which a literature is only beginning to develop. New research areas will be covered on a timely basis in the series as they begin to mature.

Each volume in the series consists of a few substantial chapters on a particular topic. In some cases, the topics will be ones of traditional interest for which there is a substantial body of data and theory, such as auditory neuroanatomy (Vol. 1) and neurophysiology (Vol. 2). Other volumes in the series deal with topics that have begun to mature more recently, such as development, plasticity, and computational models of neural processing. In many cases, the series editors are joined by a coeditor having special expertise in the topic of the volume.

Richard R. Fay, Woods Hole, MA, USA
Arthur N. Popper, College Park, MD, USA

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Volume Preface

Hearing loss is a major health condition that affects a very large portion of the general population. All people with hearing loss as measured by the audiogram potentially would benefit from a conventional acoustic hearing aid that amplifies sounds to compensate for the decrease in hearing sensitivity, although many such people do not regularly use hearing aids. This volume provides an overview of current key issues in hearing aid research from the perspective of many different disciplines. The volume offers insight into the scientific knowledge, current technology, and future technology that can help improve hearing aids. The book should prove useful to people with a wide range of backgrounds, including engineers, basic scientists, ENT specialists, and audiologists, as few people have expertise over the whole range of the individual disciplines that are relevant.

Chapter 1 by Moore and Popelka provides an overview of this volume as well as a discussion of general principles associated with hearing aids. In Chap. 2, Curan and Curan consider the incidence and causes of hearing loss. Chapter 3, by Killion, Van Halteren, Stenfelt, and Warren, describes the transducers used in hearing aids: these are the microphones that are used to pick up sounds and the receivers that are used to generate the sound after processing by the hearing aid circuitry. In Chap. 4, Launer, Zakis, and Moore describe the signal processing that is used in digital hearing aids to restore audibility while maintaining comfortable loudness, reducing the effects of background sounds, and increasing sound quality and listening comfort.

Chapter 5, by Mecklenburger and Groth, describes ways in which signals can be transmitted wirelessly from external devices (remote microphones, conventional and mobile telephones, televisions, stereos, computers, tablets) to hearing aids and between bilaterally fitted hearing aids. In Chap. 6, Souza describes the effects of hearing loss and of hearing aids on the perception of speech. Chapter 7, by Akeroyd and Whitmer, describes the influence of hearing loss and hearing aids on spatial perception, synthesizing material from a large number of published studies. In Chap. 8, Zakis describes the effect of hearing aids on the perception of music and considers the characteristics required of microphones, amplifiers, signal processors, and receivers to provide a relatively undistorted, high-fidelity, noise-free representation of musical signals.

Chapter 9, by Munro and Mueller, is concerned mainly with methods for fitting hearing aids and methods for verifying that the fitting is correct in terms of the sound delivered to the tympanic membrane. In Chap. 10, Whitmer, Wright-Whyte, Holman, and Akeroyd focus on validation of the performance of hearing aids, especially via the use of questionnaires. They also review the very large number of questionnaires that have been developed for the purpose of validation of hearing aid performance and describe the great variety of domains that have been addressed. Finally, Chap. 11, by Popelka and Moore, describes possible future directions for hearing aids and hearing aid research.

Much of the material in earlier *SHAR* volumes that provide basic science of hearing leads to this volume, where the authors describe the most common intervention for hearing loss. Hearing aids and other assistive devices have been discussed in *Speech Processing in the Auditory System* (Vol. 18, edited by Greenberg, Ainsworth, Popper, and Fay in 2004), *Cochlear Implants: Auditory Prostheses and Electric Hearing* (Vol. 20, edited by Zeng, Popper, and Fay in 2004), and *Auditory Prostheses: New Horizons* (Vol. 39, edited by Zeng, Popper, and Fay in 2011), as well as *The Middle Ear: Science, Otosurgery, and Technology* (Vol. 46, edited by Puria, Fay, and Popper in 2013).

Gerald R. Popelka, Stanford, CA, USA
Brian C.J. Moore, Cambridge, UK
Richard R. Fay, Woods Hole, MA, USA
Arthur N. Popper, College Park, MD, USA

Contents

Contributors

Michael A. Akeroyd MRC Institute of Hearing Research, School of Medicine, University of Nottingham Medical School, Nottingham, UK

MRC Institute of Hearing Research, University Park, Nottingham, UK

Gary Curhan Channing Division of Network Medicine, Brigham and Women's Hospital, Boston, MA, USA

Sharon Curhan Channing Division of Network Medicine, Brigham and Women's Hospital, Boston, MA, USA

Torben Groth GN ReSound Group, Glenview, IL, USA

Aart Van Halteren Sonion Nederland BV, Hoofddorp, The Netherlands

Jack A. Holman MRC/CSO Institute of Hearing Research – Scottish Section, Glasgow Royal Infirmary, Glasgow, UK

Mead C. Killion Etymotic Research, Inc, Elk Grove Village, IL, USA

Stefan Launer Phonak AG, Stäfa, Switzerland

University of Queensland, Brisbane, QLD, Australia

Jill Mecklenburger GN ReSound Group, Glenview, IL, USA

Brian C.J. Moore Department of Experimental Psychology, University of Cambridge, Cambridge, UK

H. Gustav Mueller Department of Hearing and Speech Science, Vanderbilt University, Nashville, TN, USA

Kevin J. Munro Manchester Centre for Audiology and Deafness, University of Manchester, Manchester, UK

Gerald R. Popelka Otolaryngology–Head and Neck Surgery, Stanford University, Stanford, CA, USA

Pamela Souza Department of Communication Sciences and Disorders and Knowles Hearing Center, Northwestern University, Evanston, IL, USA

Stefan Stenfelt Department of Clinical and Experimental Medicine, Linköping University, Linköping, Sweden

Daniel M. Warren Specialty Components–Acoustics, Knowles, Itasca, IL, USA

William M. Whitmer MRC/CSO Institute of Hearing Research – Scottish Section, Glasgow Royal Infirmary, Glasgow, UK

Kay F. Wright-Whyte MRC/CSO Institute of Hearing Research – Scottish Section, Glasgow Royal Infirmary, Glasgow, UK

Justin A. Zakis Cirrus Logic (Dynamic Hearing) Pty. Ltd, Cremorne, VIC, Australia

Chapter 1
Introduction to Hearing Aids

Brian C.J. Moore and Gerald R. Popelka

Abstract This chapter describes the background to the volume and introduces the range of disciplines that are involved in the development and evaluation of hearing aids. It then describes some basic aspects of hearing aids, such as the different styles of hearing aids and requirements for batteries. The chapter then gives an overview and brief summary of the remaining chapters in the volume, describing the components that are used in hearing aids; the needs of users; the signal processing that is used in hearing aids for listening to speech, music, and environmental sounds; wireless accessories and wireless communication between hearing aids; the fitting of hearing aids; the benefits of bilateral fittings; the verification of fittings; and evaluation of effectiveness.

Keywords Batteries • Epidemiology • Fitting methods • Hearing aids • Hearing impairment • Microphones • Music perception • Real-ear measurements • Receivers • Signal processing • Spatial perception • Speech perception • Validation questionnaires • Wireless connectivity

1.1 Introduction

Hearing loss is a major health condition that affects a very large portion of the general population and has a very wide range of etiologies. Most auditory pathologies result in a decrease in hearing sensitivity, although there has been increasing interest recently in "hidden hearing loss," in which hearing difficulties may be experienced without any abnormality in the audiogram (Kujawa and Liberman 2009; Füllgrabe et al. 2015). Actual hearing restoration is possible with certain surgical or

B.C.J. Moore (✉)
Department of Experimental Psychology, University of Cambridge,
Downing Street, Cambridge CB2 3EB, UK
e-mail: bcjm@cam.ac.uk

G.R. Popelka
Otolaryngology–Head and Neck Surgery, Stanford University,
801 Welch Road, Stanford, CA 94305, USA
e-mail: gpopelka@stanford.edu

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pharmaceutical interventions in a small minority of cases. Partial functional hearing restoration is possible with other surgical interventions, and the promise of hearing restoration resulting from biological and pharmaceutical interventions is on the distant horizon (Oshima et al. 2010; Rivolta 2013). However, these hearing restoration interventions apply to a very small portion of the entire hearing-impaired population and/or have yet to be developed. All people with a nontreatable hearing loss as measured by the audiogram potentially would benefit from a conventional acoustic hearing aid that amplifies sounds to compensate for the decrease in hearing sensitivity, although in practice many such people do not use hearing aids; see Chap. 2 by Curhan and Curhan.

As described in Chap. 2, the largest proportion of hearing impairment in the population is due to permanent sensorineural hearing loss associated with the aging process. The prevalence of age-related permanent sensorineural hearing loss is increasing because of the increase in longevity and the rise in the population in many countries associated with the increased birth rates that occurred after World War II. For the next generation, well over 1 billion people in the world will have age-related, permanent sensorineural hearing loss for which acoustic hearing aids are the only option.

Hearing aids are extremely complicated electroacoustic devices that must operate in hostile environments, both physically (heat, cold, humidity, water, electric and magnetic fields, wind) and acoustically (very large range of input sound levels and frequencies), with many inherent restrictions, including limited power supply, the need to be very small, and the proximity of the microphone to the receiver (the name for the loudspeaker that actually generates the amplified sound). It should be no surprise that these devices require a large cadre of professionals from a wide variety of wholly independent disciplines to conceive of, design, manufacturer, test, distribute, fit, adjust, and evaluate hearing aids. These professionals include physicians, audiologists, engineers, psychologists, psychoacousticians, acousticians, experts in ergonomics, and many others from an equally wide range of institutions varying from clinical facilities; small, medium, and large companies; charities; various government institutions; and universities. This multidisciplinary nature of hearing aids is one of the most challenging aspects of hearing aid research. Very few scientific educational degree programs provide a systematic introduction to all of the complex issues relating to hearing aids, resulting in challenges and obstacles that limit or prevent effective research. Few if any individuals are knowledgeable about all of the factors relevant to hearing aids. However, effective research is the key to the conduct of high-impact studies that ultimately result in significant clinical advances and improved patient outcomes.

This volume provides an overview of current key issues in hearing aid research from the perspective of many different disciplines, not only those of the key funding agencies but also those of the scientists and clinicians who are currently involved in hearing aid research. The volume offers insights into experience with hearing aids, factors affecting the candidacy for and efficacy of hearing aids, perceptual factors, current technology and future technology, and the interaction of these variables.

These insights can make scientists and clinicians aware of the important issues over the entire range of the individual disciplines that are relevant, paving the way for future research to improve hearing aids.

This book should be regarded as complementing existing books on hearing aids. The book *Digital Hearing Aids* by Kates (2008) has a particular focus on the signal processing that is performed in hearing aids, and, for the technically minded, provides a good understanding of the operation of multichannel compression, noise reduction, and acoustic feedback reduction. The book *Hearing Aids* by Dillon (2012) and the series *Modern Hearing Aids* (Bentler and Mueller 2013; Mueller et al. 2013) are aimed more at clinicians and include many practical tips and recommendations.

1.2 Population

Chapter 2 reviews the incidence of hearing loss and the many factors that can contribute to the development of hearing loss. The authors point out that hearing loss affects about 20 % of individuals in at least one ear—a higher prevalence than any other sensory disorder. Remarkably, only about 20 % of people who could potentially benefit from hearing aids actually use them. The etiology of hearing impairment reflects the cumulative and interacting influences of many factors, including aging, genetics, epigenetics, environment (e.g., exposure to noise at work or during leisure activities, or exposure to industrial solvents), health, diet, and lifestyle. This makes it difficult to determine the specific factors contributing to hearing loss in any given individual as well as the anatomical and physiological changes associated with the hearing loss. Work is ongoing to identify risk factors for hearing impairment. This may lead to a better understanding of the cellular and molecular mechanisms associated with acquired hearing impairment and could contribute to efforts toward prevention; early detection; delay of progression; and medical, pharmaceutical, surgical, and biological interventions to restore hearing.

1.3 Technical Aspects of Hearing Aids

1.3.1 Components of Hearing Aids

Most modern hearing aids contain the following components (see Chap. 4 by Launer, Zakis, and Moore and Chap. 8 by Zakis for block diagrams):

1. One or more microphones to pick up the external sound (described in detail in Chap. 3 by Killion, Van Halteren, Stenfelt, and Warren).

2. A preamplifier for each microphone to increase the electrical signal magnitude combined with a low-pass filter to limit the highest frequency that is present. Usually, this has a cutoff frequency of 9 kHz or lower.
3. An analog-to-digital converter for each amplified microphone signal. This converts the continuously varying voltage to a series of numbers representing the voltage at discrete regularly spaced times. The number of samples per second is called the sampling rate. This must be two or more times greater than the cutoff frequency of the low-pass filter described in (2) (Kates 2008). Typically, there might be 20,000 samples per second, allowing the representation of frequencies up to about 9,000 Hz. The voltage of each sample is usually represented with 16-bit precision, which means that the largest voltage that can be represented is 65,536 (2^{16}) times the smallest voltage that can be represented. This corresponds to a dynamic range of about 96 dB.
4. A digital signal processor, essentially a miniature computer, that performs operations such as frequency-dependent amplification, amplitude compression and limiting, noise reduction, cancellation of acoustic feedback (the squealing resulting from the receiver output getting back to the microphones of the aid), and directional processing (described in detail in Chap. 4).
5. A receiver, which is a device for converting the output of the signal processor to sound. Sometimes this is accomplished via a digital-to-analog converter, but in many hearing aids the digital output of the processor is converted directly into sound by the receiver (see Chap. 3).
6. A battery for powering the circuitry and the receiver.
7. A casing in which most of the aforementioned components are housed, often customized to fit into the convoluted external ear and ear canal.

1.3.2 Styles of Hearing Aids

Hearing aids are made in several different styles, as illustrated in Fig. 1.1. One style employs a single case that contains all of the components and is referred to as either in-the-ear (ITE) if the case is visible in the concha (the bowl of the pinna; Fig. 1.1a) or completely-in-the-canal (CIC) if the case is small enough to fit completely in the ear canal (Fig. 1.1b). Some CIC aids can fit more deeply into the ear canal than shown in Fig. 1.1b and are essentially invisible. The most prevalent style currently is the behind-the-ear (BTE) aid (Fig. 1.1c) in which most of the components are housed in a small case that fits behind the pinna and the microphones are positioned just above the pinna (Kochkin 2010). The receiver can be mounted in the BTE case with the sound delivered to the ear canal by an acoustic tube fitted into a custom-made earmold or held in place via a soft "dome." Alternatively, the receiver may be placed in the ear canal, held in place via a dome, and connected via a very thin wire to the BTE part. This BTE style is referred to as receiver in the canal (RIC) or receiver in the ear (RITE) and is illustrated in Fig. 1.1d.

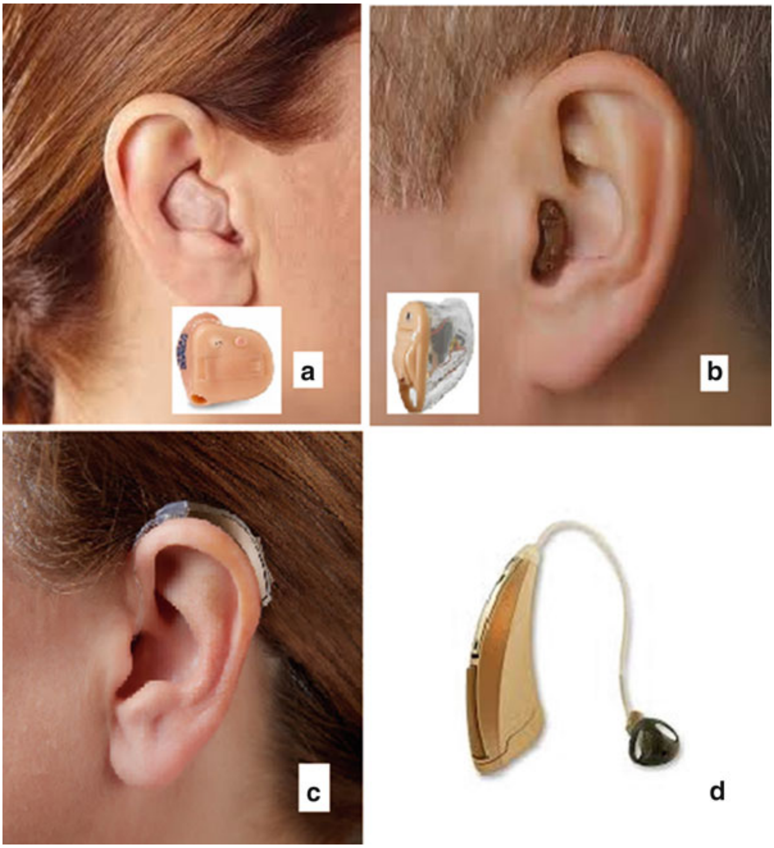

Fig. 1.1 Illustration of some styles of hearing aids. (**a**) In the ear. (**b**) Completely in the canal. (**c**) Behind the ear. (**d**) Behind the ear with receiver in the canal and open dome

1.3.3 Closed and Open Fittings

The earmold or dome can be sealed into the ear canal; this is called a closed fitting. A closed fitting may be required when the hearing loss is severe or profound and considerable gain is needed. The seal prevents intense amplified sound in the ear canal from being perceived by others and it also helps to control or limit acoustic feedback. However, for people with mild or moderate hearing loss at low frequencies, a closed fitting can give rise to the "occlusion effect," whereby the user's own voice sounds loud and boomy (Killion et al. 1988). This happens because the sound of the user's voice is transmitted into the ear canal via the bones of the head and cannot escape because of the blocked ear canal (Stone et al. 2014). An earmold or dome with a large vent or opening (Fig. 1.1d), called an open fitting, can reduce or avoid the occlusion effect and allow much of the external sound to enter the ear canal unamplified for frequency regions where amplification is not required. Open fittings have become very popular in recent years because they are physically comfortable, may be less visible than the large ITE styles, and do not require a custom earmold to be made, so a person can be fitted with a hearing aid on his or her first visit to the clinic. In some cases, an open fitting may prevent exacerbation of certain medical conditions in the external ear canal.

1.3.4 Batteries

Hearing aid batteries need to be small but to have sufficient capacity to power both the circuitry (preamplifier, analog-to-digital converter, signal processor, and for some aids the wireless receiver and transmitter) and the receiver. Most hearing aid batteries are disposable, have a single-cell structure, and generate approximately 1.5 V when “fresh.” Hearing aids are designed to work properly when the voltage drops to a value as low as 1.1 or 1.0 V. Many hearing aids generate an audible warning via the receiver when the battery is running low but before it is completely depleted to alert the user of the need to change the battery. Common battery sizes for hearing aids are 675 (the largest, mainly used in large BTE devices), 312, 13, and 10 (the smallest, used mainly in very small BTE devices or ITE devices). A small-to-medium battery, such as the 312, typically has a capacity of 180 mAh, so that it can generate, for example, a current of 1 mA for 180 h, corresponding to an operational life of 6–10 days.

The most common type of hearing aid battery is the disposable zinc–air battery, which generates power by oxidizing zinc using oxygen from the air. Zinc–air batteries have high energy densities and are relatively inexpensive to produce. The high energy density is possible because the oxygen used in the reaction comes from the air and does not need to be part of the battery cell. New zinc–air batteries are supplied with a small tabbed seal that covers an opening in the cell casing. This tabbed seal prevents activation of the oxidation process so the battery can be stored for up to 3 years. When the tab is removed, air enters the casing and the battery becomes fully activated within several seconds or tens of seconds. The battery then starts to run down whether or not it is actually used in a hearing aid. The output voltage remains quite stable until the cell approaches exhaustion, which occurs between 1 and 10 days of use. The high range of durations of use occurs because of the large range of battery capacities and the large range of power requirements of hearing aids. Hearing aids that transmit and receive electromagnetic signals, as described in Chaps. 4 and 5 (by Mecklenburger and Groth), tend to consume more power than those that do not. The short-term demand for current is also higher for hearing aids that transmit and receive electromagnetic signals than for those that do not, which means that, for the former, the battery must have a low internal resistance. Some other factors that affect battery life are discussed in Chap. 8. In a survey, 18 % of hearing aid users were dissatisfied with the operational life of their hearing aid batteries (Kochkin 2010).

Some hearing aid users, especially older individuals and those with limited manual dexterity, find it difficult to change the battery on a hearing aid; it is a fiddly job, and it is easy to drop the battery and lose it. One solution to this problem is the use of rechargeable batteries. Typically, when a hearing aid is supplied with a rechargeable battery, the battery cannot be removed from the hearing aid and is recharged by placing the aid in a small inductive charging station. This is usually found to be easy, even by those with limited manual dexterity. The batteries typically last for about 20 h and require 2–4 h to be recharged. Most users recharge the battery overnight.

It is possible to buy rechargeable batteries for use as an alternative to zinc–air batteries. These have to be removed from the hearing aid for charging so they do not solve problems associated with limited manual dexterity. The main advantage is a saving in cost. Although a rechargeable battery costs more than a disposable zinc–air battery and a separate charger has to be purchased, the rechargeable battery can be used and recharged many times so there is eventually a cost saving. Most rechargeable batteries intended for conventional hearing aids use nickel–metal–hydride technology and are housed in a stainless steel casing the size of a conventional disposable battery. Rechargeable batteries are generally more environmentally friendly than disposable batteries.

1.3.5 Transducers

Chapter 3 describes the transducers used in hearing aids: these are the microphones that are used to pick up sounds and the receivers that are used to generate the sound after processing by the hearing aid circuitry. Both microphones and receivers have changed remarkably since the 1950s, becoming smaller and more efficient. The microphones must respond over a wide frequency range and have low internal noise despite their small size. This is challenging, but, in principle, the problem has been solved. As stated by Killion, Van Halteren, Stenfelt, and Warren (Chap. 3), "Modern hearing aid transducers have virtually eliminated the bandwidth and response limitations of the past: microphones and receivers with 16-kHz bandwidth and high-fidelity response are now available." Despite this, most hearing aids currently on the market do not provide useful amplification for frequencies above about 5 kHz (Moore et al. 2001; Aazh et al. 2012). Furthermore, most manufacturers of hearing aids incorporate low-level expansion (gain reduction when the signal level decreases below a certain value) to prevent microphone noise and circuit noise from being audible. This can lead to reduced intelligibility for weak speech sounds (Moore et al. 2004; Plyler et al. 2007).

An important issue in hearing aid design is the dynamic range of the input. This refers to the very large range of sound levels that can be encountered in everyday life. To restore hearing to "normal" for a person with a hearing loss would require that sounds with levels close to 0 dB sound pressure level (SPL) were above the low-level noise inherent in the microphone and analog-to-digital converter. At the other extreme, peak levels of 116 dB SPL or more can occur from a variety of sources, such as at live concerts. Although in principle hearing aid microphones can handle this wide dynamic range of 116 dB, in practice the microphone preamplifier will often clip or saturate for input sound levels above about 110 dB SPL because of limitations in the voltage supplied by the hearing aid battery. In addition, as mentioned earlier, the analog-to-digital converters used in hearing aids typically have 16-bit resolution, which gives a maximum dynamic range of only approximately 96 dB. As a result, some hearing aids produce annoying distortion when listening to higher level sounds such as live music (Madsen and Moore 2014). Some methods for extending the input dynamic range of hearing aids are described in Chap. 8.

Many hearing aids incorporate two or more microphones and can use these to create directional characteristics. This can be useful when listening in noisy situations provided that the directional characteristic can be "pointed" toward the desired sound source and away from the undesired signal. Chapter 3 describes the directional characteristics of such systems, including the effects of microphone position and mismatched microphones. Chapter 4 describes how more precisely focused directional characteristics can be achieved via signal processing and the transfer of signals between bilaterally fitted hearing aids. Chapters 6 by Souza, 7 by Akeroyd and Whitmer, and 8 consider the effects of directional characteristics on speech perception, spatial hearing, and music perception, respectively.

Chapter 3 also describes transducers that transmit sound by bone conduction; the transducer vibrates the bones of the skull and the vibrations are transmitted through the skull to the cochlea. Such transducers are useful for two types of hearing loss:

1. Permanent conductive (or mixed conductive and sensorineural) hearing loss that is not responsive to surgical or pharmaceutical intervention, where sound is not transmitted effectively to the cochlea by the usual air conduction pathway; the special transducers bypass the conductive mechanism and effectively eliminate the conductive component of the hearing loss.
2. Unilateral hearing loss. For people with unilateral hearing loss, a major problem is a reduced ability to hear sounds coming from the side with hearing loss (Moore and Popelka 2013). To alleviate this problem, sound can be picked up by a microphone on the side with hearing loss and transmitted to the opposite functioning cochlea via bone conduction.

In either case, the sound may be delivered via a vibratory transducer mounted on a pedestal that penetrates the skin and is implanted in the skull, via an active or passive device fixed to the skull underneath the intact skin, or via a dental device held against the teeth.

1.3.6 Signal Processing in Hearing Aids

Chapter 4 describes the signal processing that is used in digital hearing aids. Such processing has become much more elaborate and more complex over successive generations of digital hearing aids. The signal-processing algorithms can be broadly divided into three categories: (1) processing to restore audibility, including multichannel amplitude compression and frequency lowering; (2) "sound cleaning," via partial removal of background noise, reduction of acoustic feedback (whistling), reduction of wind noise, and selective attenuation of intense transient sounds; and (3) automatic environment classification to allow the hearing aid to change its settings automatically and appropriately in different listening situations.

Most of the signal processing in hearing aids operates in a frequency-dependent manner. To achieve this, a running spectral analysis (a time-frequency analysis) of the input signal is required. Chapter 4 gives an overview of the different types of time-frequency analysis that are used in hearing aids and discusses the advantages and disadvantages of each approach. The chapter then describes the multichannel amplitude compression that is used almost universally in hearing aids to compensate for the reduced dynamic range of hearing-impaired people (as described in Chap. 6). The main aim of multichannel compression is to restore the audibility of weak sounds while preventing intense sounds from becoming uncomfortably loud. Compression systems vary in how rapidly they react to changes in the input sound level, and they can be broadly classified as fast acting or slow acting. The compression speed varies markedly across different brands of hearing aid. The advantages and disadvantages of fast-acting and slow-acting amplitude compression are discussed.

When a person has a severe high-frequency loss, it may be difficult to apply sufficient gain (amplification) to restore audibility. A potential solution to this problem is to apply frequency lowering. With this, high frequencies are moved downward to a frequency range where the hearing loss is less severe. Chapter 4 describes the various methods that are used in hearing aids to implement frequency lowering. The chapter also describes the outcomes of studies evaluating the benefits of frequency lowering. Although the benefits of frequency lowering for speech intelligibility in everyday life are still uncertain, frequency lowering usually does not lead to poorer intelligibility, and it has some beneficial side effects. Specifically, frequency lowering reduces the likelihood of acoustic feedback and, because lower gains are required to restore audibility, it also reduces the possibility of damage to residual hearing.

Chapter 4 next considers various ways of "cleaning" sounds with the goals of improving the intelligibility of speech in noisy situations and improving sound quality and listening comfort. Although most hearing aids incorporate some form of noise reduction, this mainly improves listening comfort rather than intelligibility. Substantial gains in intelligibility can be achieved by the use of directional microphones (see also Chaps. 6 and 7) but there are still limitations. Other forms of processing include simulation of the effects of the pinna (for BTE aids), partial compensation for reverberation, wind noise reduction, and suppression or cancellation of acoustic feedback. Although hearing aids can improve the ability to understand speech in noise, the performance of hearing-impaired people wearing hearing aids rarely approaches that of normal-hearing people. It is clear that much work remains to be done in this area.

The last part of Chap. 4 deals with the automatic classification of environments. Many hearing aids incorporate methods for classifying acoustic environments, for example, speech in quiet, speech in noise, or music. Once an environment has been identified, the settings of a hearing aid may be adjusted automatically. For example, if speech in noise is detected, a highly directional microphone characteristic might be selected, whereas if music is detected, an omnidirectional microphone might be selected.

1.3.7 Wireless Connectivity and Power Requirements

Chapter 5 describes ways in which signals can be transmitted wirelessly from various external devices (remote microphones, conventional and mobile telephones, televisions, stereos, computers, tablets) to hearing aids and between bilaterally fitted hearing aids. Transmission from remote devices can provide an improvement in signal-to-noise ratio and can largely eliminate adverse effects of room echoes and reverberation. This in turn leads to improved sound quality and a better ability to understand speech, especially in adverse listening conditions. Improvements in signal-to-noise ratio and sound quality can also be achieved with wireless transmission directly to hearing aids from a variety of public address systems such as in theaters, lecture halls, places of worship, airports, train stations, and bus stations. The variety of methods used for wireless transmission to hearing aids and the benefits and limitations of each method are described. Factors affecting usability are discussed, including battery consumption. The problem of a lack of international standardization is also discussed.

1.4 Perception of Sound via Hearing Aids

1.4.1 Speech Perception

Chapter 6 describes the effects of hearing loss and of hearing aids on the perception of speech. Sensorineural hearing loss nearly always leads to problems in understanding speech, especially in noisy or reverberant situations. Generally, the greater the hearing loss, as measured using the audiogram, the greater the difficulty in understanding speech. However, there is often considerable variability in speech perception ability across people with similar audiograms, and the factors underlying this variability are poorly understood.

In cases of mild to moderate hearing loss, hearing aids can provide substantial benefit. For severe sensorineural hearing loss, the ability to analyze and discriminate sounds that are well above the detection threshold is reduced and this limits the benefit provided by hearing aids. In cases of profound or total loss of hearing, so little auditory function remains that a conventional hearing aid is ineffective and a cochlear implant may be a better alternative. Cochlear implants, which are widely used to treat severe and profound hearing loss in both children and adults, bypass the missing or remaining dysfunctional sensory structures altogether and activate the remaining VIIIth cranial nerve fibers directly; see Clark et al. (1987) and Zeng et al. (2003). For people with residual low-frequency hearing but severe or profound hearing loss at medium and high frequencies, the combination of a hearing aid and a cochlear implant may be more effective than either alone (Dorman and Gifford 2010; Zhang et al. 2014).

Chapter 6 considers the influence of several factors that may contribute to individual differences in auditory performance and benefit from hearing aids, including individual differences in the underlying patterns of cochlear and neural damage and individual differences in cognitive ability. The chapter describes how sensorineural hearing loss can arise from many causes, including damage to (1) the outer hair cells, affecting the operation of the active mechanism in the cochlea and leading to loss of sensitivity to weak sounds and reduced frequency selectivity and loudness recruitment (Robles and Ruggero 2001); (2) the inner hair cells, leading to more "noisy" transmission of information and, in extreme cases, dead regions in the cochlea (Moore 2001); (3) the stria vascularis, disturbing the metabolism of the cochlea and affecting the operation of both inner and outer hair cells and neural processes (Schmiedt 1996); (4) the synapses between inner hair cells and neurons, with effects similar to those of inner hair cell damage (Kujawa and Liberman 2009); and (5) neurons in the auditory nerve and higher up in the auditory pathway, causing a general reduction in the ability to discriminate sounds (Schuknecht 1993) and in the ability to combine input from the two ears (Durlach et al. 1981; Moore et al. 2012a).

Some speech perception problems of the hearing impaired, such as a poor ability to understand soft speech, arise primarily from reduced audibility; part of the speech spectrum falls below the elevated absolute thresholds (Humes and Roberts 1990). These problems can, in principle, be alleviated via the amplification provided by hearing aids. However, hearing aids have proved to be much less effective in improving the ability to understand speech in noisy or reverberant conditions (Plomp 1978). Chapter 6 reviews the effects of hearing loss on speech perception and discusses the extent to which hearing aids can compensate for those effects. The chapter describes the acoustic cues that are present in the speech signal and how those cues are affected by the signal processing that is used in hearing aids, especially multichannel amplitude compression. The chapter also describes several different types of masking that can affect speech perception and describes how hearing aids affect these different types of masking. The types include (1) "energetic masking," which occurs when the pattern of responses in the auditory nerve is similar for the masker alone and the masker plus the target speech (Brungart et al. 2006); (2) "modulation masking," which occurs when the patterns of amplitude modulation in the masker make it more difficult to detect and discriminate patterns of amplitude modulation in the target speech (Stone et al. 2011; Jørgensen et al. 2013); and (3) "informational masking," which occurs when the target speech and masker are confusable and/or similar, for example, when two people with similar voices speak at the same time (Brungart et al. 2001; Lunner et al. 2012).

The majority of hearing aid users are older than 60 years of age (see Chap. 2), and some auditory abilities, such as sensitivity to temporal fine structure, decline with increasing age even for people whose audiograms remain within the normal range (Moore et al. 2012a, b; Füllgrabe et al. 2015). Reduced sensitivity to temporal fine structure seems to be associated with difficulty in understanding speech in background sounds (Füllgrabe et al. 2015). It may also be associated with a reduced ability to judge harmony in music (Bones and Plack 2015). In addition, cognitive abilities tend to decline with increasing age, and this probably also contributes to difficulty in understanding speech in background sounds (Akeroyd 2008; Füllgrabe et al. 2015). At present, hearing aids do little to alleviate the effects of suprathreshold deficits in auditory or cognitive processing, except indirectly, for example, by the use of directional microphones to improve the signal-to-background ratio.

Chapter 6 includes a review of the effectiveness for speech perception of the major types of signal processing that are used in hearing aids. An important take-home message is that the effectiveness of different types of processing varies across acoustical situations and across individuals. Hence, when programming a hearing aid and selecting the types of signal processing that should be activated for optimal speech understanding, every individual's hearing ability should be treated as unique. Much remains to be learned as to how to set up a hearing aid optimally for the individual listener.

1.4.2 Spatial Perception

Chapter 7 describes the influence of hearing loss and hearing aids on spatial perception. Spatial perception refers to the ability to use spatial cues to better understand speech in the presence of background noise or to judge the location of sounds in space. Generally, the accuracy of sound localization is greatest for judgments of azimuth (along the left–right dimension in the horizontal plane). Accuracy is somewhat poorer for front–back and up–down sound localization. The chapter considers each of these separately.

Chapter 7 describes the two main methods by which the accuracy of sound localization has been measured. In one method, called "source discrimination," two sounds are presented from different directions, ϕ_1 and ϕ_2, and the listener has to decide if the order of presentation was ϕ_1 then ϕ_2 or ϕ_2 then ϕ_1. Usually, a threshold corresponding to the smallest difference between ϕ_1 and ϕ_2 that can be reliably detected is determined. This is usually called the minimum audible angle (MAA) (Mills 1958), although in Chap. 7 it is called the $\mathrm{JND_{MAA}}$ to emphasize that it is a just-noticeable difference. In the second method, called "source identification," a sound is presented from any one of an array of loudspeakers (or from one of an array of "virtual" sources using sounds presented via headphones). The task is to report the direction of the sound, for example, by identifying the loudspeaker that it emanated from or by pointing toward the perceived source. Several different measures have been used to quantify localization accuracy using the source identification method, and these measures and their interrelations are described in Chap. 7; the recommended measure is the root-mean-square error in degrees, *D*. To allow comparison of results across studies using different measures, in Chap. 7 all measures are converted to *D* where possible.

Chapter 7 presents evidence showing that for left–right sound localization, hearing-impaired people tend to be less accurate than normal-hearing people. However, some of the effects that have been attributed to hearing loss may be a consequence of age because the experiments have often compared results for young normal-hearing and older hearing-impaired subjects; see Moore et al. (2012b) and Füllgrabe et al. (2015) for discussion of this point. Bilaterally fitted hearing aids on average lead to a slight worsening in left–right discrimination relative to unaided listening, although Akeroyd and Whitmer argue that this effect is too small to have a noticeable effect in everyday life. However, unilateral aiding can lead to a distinct worsening in left–right localization. Hence, aided performance is almost always better with bilateral than with unilateral hearing aids.

Hearing impairment tends to have a greater deleterious effect on sound localization in the front–back and up–down dimensions than on sound localization in the left–right dimension. Hearing aids do not generally improve front–back or up–down discrimination, but they also usually do not make it markedly worse.

1.4.3 Music Perception

Chapter 8 describes the effect of hearing aids on the perception of music. Most hearing aids are designed primarily with the goal of improving the ability to understand speech, but many users of hearing aids also want to listen to music via their aids. Music is a more difficult signal to handle than speech because its spectrum varies widely across different types of music and different listening venues, it can cover a very wide range of sound levels, it can have a high crest factor (ratio of peak-to-root-mean-square value), and there can be significant energy in music over a very wide range of frequencies (Chasin and Hockley 2014). Unlike speech, there is no such thing as a “typical” music spectrum.

Chapter 8 considers the characteristics required of microphones, amplifiers, signal processors, and receivers to provide a relatively undistorted, high-fidelity, noise-free representation of musical signals. In many current hearing aids, the requirements are not met, so distortion can occur with high-level inputs and sound quality can sometimes be low (Madsen and Moore 2014). Chapter 8 describes ways in which these problems can be alleviated. The chapter also describes the effects on music perception of some of the signal-processing algorithms that are used in hearing aids, including wide dynamic range compression (WDRC), active sound feedback cancellation, frequency lowering, wind noise reduction, other types of noise reduction, and acoustic transient reduction. WDRC can help to make soft passages in music audible while preventing loudness discomfort for high-level sounds, but there are side effects of WDRC processing that can degrade sound quality and make it harder to hear out individual instruments or voices in a mixture (Madsen et al. 2015). An alternative approach called adaptive dynamic range optimization (ADRO) is described in Chap. 8. This is basically a slow-acting form of multichannel amplitude compression that may be preferable to fast-acting compression for listening to music.

Chapter 8 also considers possible deleterious effects of the time delays produced by the signal processing in hearing aids (including frequency-dependent delays), of the limited bandwidth of hearing aids, and of ripples in the frequency response of hearing aids. A general take-home message in relation to the use of hearing aids for music listening is “do no harm.” In other words, perform the minimum signal processing necessary to make the music audible and comfortably loud.

1.5 Clinical Verification of Hearing Aid Performance

Chapter 9, by Munro and Mueller, is concerned mainly with methods for fitting hearing aids and methods for verifying that the fitting is correct in terms of the sound delivered to the tympanic membrane. It is widely accepted that hearing aids should be fitted according a method that has been validated in clinical studies. Such methods include Desired Sensation Level (DSL) v5 (Scollie et al. 2005), National Acoustics Laboratories, Non-Linear, version 1 (NAL-NL1; Byrne et al. 2001) and version 2 (NAL-NL2, Keidser et al. 2011), and CAM2 (previously called CAMEQ2-HF; Moore et al. 2010). As stated by Munro and Mueller, “no validated prescription method has been clearly shown to be superior to any of the other methods in terms of patient benefit (e.g., greater satisfaction, less residual disability). However, clinical studies have clearly shown that when a well-researched prescriptive approach is used and appropriate gain is delivered to the tympanic membrane across frequencies, speech intelligibility is enhanced, and there is improved patient benefit and satisfaction.” Despite this, many manufacturers of hearing aids use their own proprietary fitting methods that have not been subjected to independent peer-reviewed evaluation. Even when the manufacturer’s fitting software allows a “standard” prescriptive method to be selected, the real-ear output of the hearing aid often differs from that prescribed by the selected method (Aazh et al. 2012). Hence, it is important that the output of the hearing aid is checked and adjusted where necessary using measurements with a probe microphone placed in the ear canal close to the tympanic membrane.

There are many types of test signals that can be used for verification of hearing aids, including pure tones, swept tones, narrow bands of noise, speech, and artificial speech like signals (Dreschler et al. 2001; Holube et al. 2010). Generally, speech or speech like signals are preferred, because other signals may activate signal-processing algorithms such as acoustic feedback cancellation or noise reduction, giving misleading results. There are also many ways of expressing the output of the hearing aid in the ear canal, including insertion gain, real-ear aided gain, and output level in decibels SPL. Chapter 9 considers these various measures in detail. Munro and Mueller advocate the use of output level in decibels SPL because "it enables easy visualization of the interrelationship between assessment data, the level of unamplified speech, and the amplification characteristics, which are typically measured in different units and at different reference points." The authors also advocate use of the speech intelligibility index (ANSI 1997) as a standard way of assessing the extent to which the audibility of speech has been restored, although they point out some limitations of this approach.

Chapter 9 describes many of the technical and practical problems encountered when making real-ear measurements of the output of hearing aids. Methods of solving or alleviating those problems are described. The chapter also describes methods for verifying the correct operation of features of the hearing aid such as frequency lowering, directional microphones, noise reduction, and acoustic feedback reduction.

1.6 Validation of Hearing Aid Performance

Chapter 10, by Whitmer, Wright-Whyte, Holman, and Akeroyd, focuses on validation of the performance of hearing aids, especially via the use of questionnaires. The main goal is to assess whether the hearing aids meet the needs of the individual user, in other words to assess "if they alleviate disability and handicap, or if they relieve restrictions or limitations due to hearing loss." As well as being used for assessing the benefit of hearing aids relative to listening unaided for a specific individual, questionnaires may be used to evaluate the effectiveness of different types of signal processing (e.g., linear amplification vs. WDRC; Moore et al. 1992) or different types of hearing aids (e.g., bone-anchored vs. tooth-mounted aids for unilateral hearing loss; Moore and Popelka 2013).

Chapter 10 reviews the very large number of questionnaires that have been developed for the purpose of validation of hearing aid performance and describes the great variety of domains that have been addressed. The domains include frequency of use, effectiveness for speech in quiet, effectiveness for speech in noise and/or reverberation, ability to use the telephone, sound quality, extent of auditory fatigue, ease of listening, changes in self-esteem, ease of operation, aversiveness of sounds, loudness of sounds, binaural and spatial hearing, effects on social life, quality of life, residual activity limitation, and willingness to purchase. Some questionnaires focus on specific populations, such as users of bone-anchored hearing aids (see Chap. 3), or on specific problems, such as the quality of the aid user's own voice.

Chapter 10 discusses a problem in the use of questionnaires to evaluate the benefit provided by hearing aids. A respondent may be unable to judge the benefit in a specific situation and may give a response reflecting the difficulty experienced in that situation rather than reflecting the benefit. This problem can be reduced by asking respondents to describe situations that they have experienced and can comprehend and then asking them to rate difficulty without and with hearing aids only in the experienced situations. Even then, the task may be difficult because the respondents usually have not directly compared experiences without and with hearing aids. Assuming that they are currently using hearing aids, they have to imagine and remember their listening experience before they were fitted with hearing aids, and this process of recall may be influenced by many biases.

Another issue addressed in Chap. 10 is "rational noncompliance." This occurs when a client rejects an option, such as having two aids as opposed to one, where there would be objective benefit from having two aids, at least in terms of speech intelligibility and sound localization. The key idea here is that of "burdens." For example, an extra hearing aid requires more batteries and more maintenance and may involve greater perceived stigma. The net benefit of an extra hearing aid reflects a balance between performance improvements and burdens. Put simply, an extra hearing aid may not be worth the bother.

Chapter 10 also discusses the distinction between benefit and satisfaction. If a person has unrealistically high expectations of hearing aids, then even if the hearing aids lead to measurable improvements in speech perception, satisfaction will be low. In contrast, if expectations are low, even small objective benefits may be associated with high satisfaction.

Finally, Chap. 10 discusses the use of tests of speech perception for validation of hearing aids. Although many speech tests have been developed and used in clinical evaluations of different types of hearing aids or different types of signal processing within hearing aids, speech tests are rarely used to evaluate the effectiveness of hearing aids for individual clients in the clinic. A basic problem is that the majority of speech tests are artificial, involving listening without visual information to isolated words or sentences without context and in the absence of reverberation. The results of such tests may give little insight into the effectiveness of hearing aids in everyday life. Although some speech tests with greater realism have been developed, these mostly focus on one aspect of realism, for example, providing context, simulating the effects of reverberation, or providing visual information. A speech test that simulates realistic listening conditions and that could be used for validation in the clinic has yet to be developed.

1.7 Concluding Remarks

This chapter has given an overview of the many factors that are relevant to the design, fitting, and usefulness of hearing aids. It has also indicated areas of uncertainty, where further research is needed. Chapter 11, by Gerald Popelka and Brian Moore, describes possible future directions for hearing aids and hearing aid research.

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References

Aazh, H., Moore, B. C. J., & Prasher, D. (2012). The accuracy of matching target insertion gains with open-fit hearing aids. *American Journal of Audiology*, 21, 175–180.

Akeroyd, M. A. (2008). Are individual differences in speech reception related to individual differences in cognitive ability? A survey of twenty experimental studies with normal and hearing-impaired adults. *International Journal of Audiology*, 47 (Suppl 2), S53–S71.

ANSI (1997). *ANSI S3.5–1997. Methods for the calculation of the speech intelligibility index*. New York: American National Standards Institute.

Bentler, R., & Mueller, H. G. (2013). *Modern hearing aids: Verification, outcome measures, and follow-up*. San Diego: Plural.

Bones, O., & Plack, C. J. (2015). Losing the music: Aging affects the perception and subcortical neural representation of musical harmony. *Journal of Neuroscience*, 35, 4071–4080.

Brungart, D. S., Simpson, B. D., Ericson, M. A., & Scott, K. R. (2001). Informational and energetic masking effects in the perception of multiple simultaneous talkers. *The Journal of the Acoustical Society of America*, 110, 2527–2538.

Brungart, D. S., Chang, P. S., Simpson, B. D., & Wang, D. (2006). Isolating the energetic component of speech-on-speech masking with ideal time-frequency segregation. *The Journal of the Acoustical Society of America*, 120, 4007–4018.

Byrne, D., Dillon, H., Ching, T., Katsch, R., & Keidser, G. (2001). NAL-NL1 procedure for fitting nonlinear hearing aids: Characteristics and comparisons with other procedures. *Journal of the American Academy of Audiology*, 12, 37–51.

Chasin, M., & Hockley, N. S. (2014). Some characteristics of amplified music through hearing aids. *Hearing Research*, 308, 2–12.

Clark, G. M., Blamey, P. J., Brown, A. M., Gusby, P. A., Dowell, R. C., Franz, B. K.-H., & Pyman, B. C. (1987). *The University of Melbourne-Nucleus multi-electrode cochlear implant*. Basel: Karger.

Dillon, H. (2012). *Hearing aids*, 2nd ed. Turramurra, Australia: Boomerang Press.

Dorman, M. F., & Gifford, R. H. (2010). Combining acoustic and electric stimulation in the service of speech recognition. *International Journal of Audiology*, 49, 912–919.

Dreschler, W. A., Verschuure, H., Ludvigsen, C., & Westermann, S. (2001). ICRA noises: Artificial noise signals with speech-like spectral and temporal properties for hearing instrument assessment. *Audiology*, 40, 148–157.

Durlach, N. I., Thompson, C. L., & Colburn, H. S. (1981). Binaural interaction in impaired listeners. *Audiology*, 20, 181–211.

Füllgrabe, C., Moore, B. C. J., & Stone, M. A. (2015). Age-group differences in speech identification despite matched audiometrically normal hearing: Contributions from auditory temporal processing and cognition. *Frontiers in Aging Neuroscience*, 6, Article 347, 1–25.

Holube, I., Fredelake, S., Vlaming, M., & Kollmeier, B. (2010). Development and analysis of an International Speech Test Signal (ISTS). *International Journal of Audiology*, 49, 891–903.

Humes, L. E., & Roberts, L. (1990). Speech-recognition difficulties of the hearing-impaired elderly: The contributions of audibility. *The Journal of Speech and Hearing Research*, 33, 726–735.

Jørgensen, S., Ewert, S. D., & Dau, T. (2013). A multi-resolution envelope-power based model for speech intelligibility. *The Journal of the Acoustical Society of America*, 134, 436–446.