The Future of Digital Hearing Aids

Brent Edwards, Ph.D.

Submitted to:
Trends in Amplification’s special issue on digital hearing aids

Address correspondence to:

Brent Edwards, Ph.D.
Executive Director, Starkey Hearing Research Center
2150 Shattuck Ave., Suite 408
Berkeley, CA 94704
(510)-845-4876 x11
brent_edwards@starkey.com

ABSTRACT

Hearing aids have advanced significantly over the past decade, primarily due to the maturing of digital technology. The next decade should see an even greater number of innovations to hearing aid technology, and this paper attempts to predict in which areas the new developments will occur. Both incremental and radical innovations in digital hearing aids will be driven by advances in the following areas: (i) wireless technology, (ii) digital chip technology, (iii) hearing science, and (iv) cognition. The opportunities and limitations for each of these areas will be discussed. Additionally, emerging trends such as connectivity and individualization will also drive new technology and these are discussed within the context on the areas given above.

Keywords: hearing aid, digital, wireless, cognition

INTRODUCTION

Hearing aid technology has progressed dramatically over the past ten years. The introduction of digital signal processing (DSP) into hearing aids in 1996 allowed advanced signal processing algorithms to be implemented. In 2005, 93% of the hearing aids sold in the US had DSP in them[1]. Over half of the prescribed hearing aids include directional microphones, providing verifiable improvements to speech understanding in noise. Open-canal products have increased in popularity because of improved comfort and the elimination of occlusion problems, even though the amount of gain provided by these devices is limited by the design.

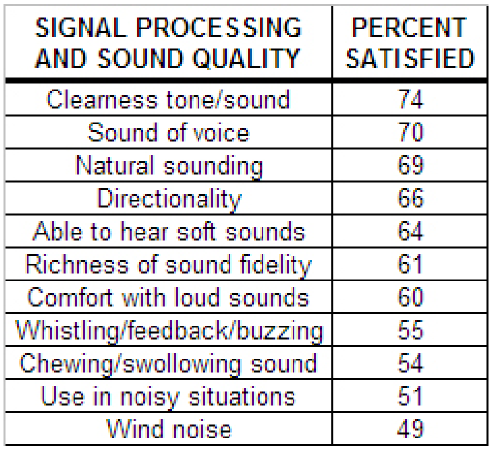
Few people would have predicted such advances in the hearing aid industry at the beginning of the 1990s. Few would have even thought at that time that multiband compression would become the *de facto* standard processing for hearing impairment—a significant body of research had been published prior to 1990 that indicated compression was unnecessary and perhaps detrimental. Directional microphones had been tried in hearing aids, as had noise reduction and even open-canal fittings by 1990, none with much success.

So, what changed to make them successful today? Technology advanced enough to enable their application in a usable fashion: multiband compression could be implemented in a small form factor and with low noise; the directivity of directional microphones improved and they were designed to allow switching to omnidirectionality to avoid noise issues; feedback cancellation allowed greater gain in open-canal devices and the acoustics were improved to increase the usable bandwidth.

New technologies are developed and are successful in the marketplace when they address the unmet needs of the consumers. Recent market data indicates that 71% of hearing aid users express overall satisfaction with their hearing aids, but there remain several well defined areas that need improving [2]. Table 1 shows customer satisfaction data from MarkeTrak VII that identify current unmet needs that digital processing can address. As can be seen, there are many areas of opportunity for digital technology to provide improvement, such as improvements to the perception of wind noise and better loudness placement, which will drive new digital technology development.

Industry innovations occur in either incremental steps or in radical changes. The incremental innovations are easier to predict because they involve natural progressions of existing technology. Radical innovations are difficult to predict because they involve new concepts with no current examples. They also often lead to disruptive technologies that completely change the marketplace of an industry [3].

These types of innovation often involve bringing technology from one field into another, and the impact of these newly introduced technologies may be predicted by those knowledgeable in both fields. The introduction of DSPs and the application of feedback cancellation were radical innovations but could have been predicted by those who were aware of DSP use in non-hearing aid fields and who were able to see their potential benefit to hearing aid users.



SIGNAL PROCESSING AND SOUND QUALITY	PERCENT SATISFIED
Clearness tone/sound	74
Sound of voice	70
Natural sounding	69
Directionality	66
Able to hear soft sounds	64
Richness of sound fidelity	61
Comfort with loud sounds	60
Whistling/feedback/buzzing	55
Chewing/swollowing sound	54
Use in noisy situations	51
Wind noise	49

TABLE 1

Thus, while predictions about the future are often tenuous, estimates of where future potential benefits lie from new technology are not entirely ungrounded. This paper will attempt to outline where the hearing aid industry is heading and what new digital technologies and applications will be developed.

DIGITAL WIRELESS TECHNOLOGY

Digital signal processing revolutionized the hearing aid industry ten years ago and resulted in new applications that provided new benefit to the hearing impaired. Prior to its introduction, the possible benefit of digital technology to hearing aids was not well understood and many studies were conducted comparing digital hearing aids with analog hearing aids to determine if digital technology was providing benefit. Today, the benefit is clear, and what is also clear is that the use of DSP in a hearing aid was a revolutionary breakthrough that changed the hearing aid industry in unexpected ways. People have now started to wonder what the next revolutionary innovation will be. The most likely candidate—the one most likely to produce new applications and new patient benefits—is digital wireless technology.

Analog Wireless

Wireless technology has existed in the hearing aid industry for many years in the form of analog systems. These systems typically consist of a transmitter that is attached to a sound source, such as a lecturer's microphone or a movie theater's audio system, and a receiver that is connected to the hearing aid to receive the wirelessly transmitted signal. Examples of these systems are a microphone on a teacher that transmits an FM signal to an attachment on a BTE's direct audio input, or a loop system plugged into a lecturer's microphone in an auditorium whose electromagnetic signal is received by a telecoil inside of a hearing aid.

In the US, neither FM systems nor loop systems have achieved significant success outside of specialized uses such as in a classroom. Their success has been limited by: (i) cost (a typical FM system costs thousands of dollars) (ii) the requirement that other people use an accessory or that an establishment install a wireless system, (iii) the requirement that accessories be carried around by the hearing aid wearer for use when they are needed, (iv) the general incompatibility across systems [4], (v) difficulties with electromagnetic interference and creating a homogeneous field strength with loop systems [5].

New digital wireless technology will improve upon all of these limitations and add more functionality.

Technical Benefits

Digital wireless technology transmits a higher fidelity signal than do analog systems. With a typical wireless analog system, the signal quality decreases the further the receiver is from the transmitter. Digital signals preserve their fidelity with greater consistency. The quality remains good up to some limiting distance, beyond which the quality drops dramatically. This becomes the usability distance, within which the user can be sure that the sound they hear will be uncorrupted by distortion and noise. This ability of digital wireless is in part due to error correction coding, a technique that detects when errors occur in the wireless data and corrects them. Digital coding schemes are also more resistant to interference from electromagnetic signals and to interference from other devices wirelessly transmitting in the area.

The large number of companies developing digital wireless technology—over 5000 companies have registered to create Bluetooth products [6]— helps to advance the technology as well as drives down its cost and size. Digital wireless technology is lower in power and size than its analog counterparts, which improves its application to hearing aids.

Connectivity

In the future, hearing aids will be wirelessly connected to a wide array of audio products. This will be possible because digital wireless technology is becoming ubiquitous in consumer electronics.

An increasing number of products are being produced with wireless capabilities. More importantly, audio products that hearing aid wearers want to listen to are being made with digital wireless technology embedded in the product, making them easier to connect to hearing aids wirelessly. If a television, for example, is transmitting its audio wirelessly, then a wireless receiver can be added to the hearing aid so that the hearing aid wearer can listen to TV audio that is not subject to room reverberation and not worry about bothering others in the room with a loud TV.

All of this wireless development would still not make connectivity easier for hearing aid wearers if every device transmitted their sound with different technology. Bluetooth, however, has become a standard that manufacturers have agreed to use when they digitally transmit their audio. This allows other products with a Bluetooth receiver to pick up the transmitted audio and play it without any specialized design requirements. A single Bluetooth receiver in or attached to a hearing aid can receive sound from all sorts of sound sources: televisions, radios, cellphones, mp3 players. The use of Bluetooth for public broadcast systems as an alternative to loop systems has also been suggested [7].

Hearing aid companies are now creating Bluetooth accessories that plug into a BTE’s direct audio input. They allow cellphone audio to be transmitted directly to the hearing aid and that pick up the wearer’s voice and transmit it back to the cellphone. These accessories essentially convert the hearing aid into a hands-free cellphone earpiece. Microphones are also being manufactured that can be worn by the hearing aid wearer’s companion so that their voice is wirelessly transmitted directly into the hearing aid. With this technology, the ratio of the speaker’s voice to the background noise is improved well beyond the ratio improvement provided by a directional microphone on a hearing aid. As hearing aids become wirelessly connected to an increasing number of devices over the next several years, control of connectivity will become an important issue. User interface development and usability designs will become an increasingly important aspect of hearing aids.

This connectivity to audio products will be only the beginning of new benefits that digital wireless technology will provide.

The Bluetooth protocol provides connectivity not only for audio but also for non-audio data such as control signals. When using Bluetooth to listen to a cell phone, for example, the wireless digital signal passes the sound back and forth between the phone to the earpiece and also transmits commands such as volume control, answer, mute, and hang up. This capability will allow hearing aids to control other products with user controls on the hearing aid.

In the consumer electronics field, wires that are currently used to transmit data and control signals between products will eventually be replaced by wireless technology: transmitting pictures from a digital camera to the PC, transmitting audio from a DVD player to speakers. Bluetooth is already being used to replace programming cables used to program hearing aids, and new applications will be developed that provide new benefits to hearing aid wearers and audiologists.

Yanz [8] described a future where all audio sources communicate with a hearing aid wirelessly, and suggested that text-to-speech could be used in computers to relay e-mail wirelessly to hearing aids. Clearly, connectivity between the hearing aid and many devices will be the norm. Many more possibilities for interaction between hearing aids and audio products—or even non-audio products—are possible because of use of the Bluetooth standard for wireless connectivity.

Ear-to-ear

Wireless ear-to-ear communication describes the situation where the left and right hearing aids of a bilaterally-fit wearer communicate wirelessly with each other. This functionality has been recently introduced into the industry, albeit at the low data rate of 315 bits per second. Current applications for this communication are synchronization of left and right volume controls and a few other basic functions.

As the wireless data rate increases, more functionality will become possible. Eventually, a pair of hearing aids will be considered as a single system rather than as two separate hearing aids. With ear-to-ear connectivity, every function within the hearing aids can become synchronized. Processing could also be shared between the aids to overcome DSP chip limitations, where algorithms are computed in only one hearing aid and the results shared with the other rather than calculating the algorithm in both hearing aids independently. With this approach, computations are shared between the aids, overcoming computational limitations on any one hearing aid chip. The disadvantage of this, of course, would be that the two hearing aids are dependent on each other and do not function as well when the other is absent.

Once data rates for ear-to-ear communication increase enough to pass audio between them (requiring a rate of tens of thousands of bits per second rather than the current hundreds of bits per second), speech understanding in noise can be improved using beamforming techniques [9]. At its most basic level, the signal from both hearing aids can be added together to increase the signal-to-noise ratio for a target signal in front of the wearer. Figure 1 shows a directional pattern that can be achieved with this approach. Also shown with a dashed line is a directional pattern achieved by current directional microphones for comparison.

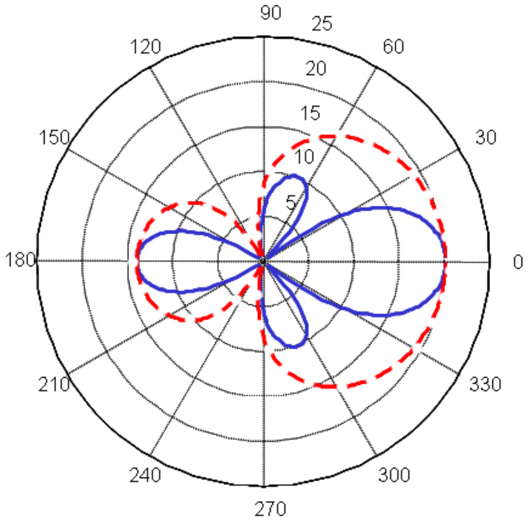


Figure 1. Free-field polar patterns for beamforming (solid line) and a first-order directional (dashed line).

More complex algorithms such as adaptive beamforming and blind source separation will likely be applied when high data rate ear-to-ear audio transmission occurs, and the challenge in the application of these algorithms will be to ensure that speech understanding is improved without sacrificing sound quality.

Binaural perception will become an industry focus once ear-to-ear communication becomes mature. With multiband compression, noise reduction, and other adaptive algorithms operating independently at the two ears, there is the possibility that binaural cues are being distorted by hearing aids[10-12]. Wireless communication between hearing aids allows the possibility for algorithms that attempt to restore binaural perception to normal [13]. To date, little is known about the effect of independent hearing aids on such binaural phenomenon as localization and spatial release from masking. These effects will be discussed later in this paper, but ear-to-ear wireless communication could provide a mechanism for addressing any interactions between hearing aids and binaural perception by attempting to preserve binaural cues with processing synchronized between the ears.

Limitations

The reason that digital wireless technology isn’t in every hearing aid today is because of power consumption. Currently, a Bluetooth chip requires over 30 mW to transmit and receive audio. Most hearing aids require less than 1 mw of power in total, so adding a Bluetooth chip would increase the power consumption dramatically and reduce the battery life of the hearing aid. Until this power problem is solved, Bluetooth chips will not likely be added as a component within a hearing aid. Yanz [8] suggested an interim solution of a general-purpose relay device with a large battery that sits near the hearing aid, receives Bluetooth signals, and then relays them to the hearing aid using a wireless technology that requires less power than Bluetooth. This solution would trade lower hearing aid power consumption for the need of an accessory, but would provide the widespread connectivity described earlier if the usability were designed to be simple.

As digital wireless chips continue to be designed smaller and lower in power, these limitations will disappear and it is likely that the majority of hearing aids will have wireless receivers embedded in them in the same way that the majority of hearing aids today have DSPs. When this happens, hearing aids will contain new ear-to-ear algorithms and will be connected to at most any audio source that the wearer wants to hear. The engineering challenge will be to make connecting to these sources as easy as possible for the hearing aid wearer.

DSP ALGORITHMS

Digital signal processing has reached a state of maturity in the hearing aid industry. Most hearing aids have a similar set of DSP algorithms that includes multiband compression, noise reduction, feedback cancellation, directional processing, and environment classification. Many thought-leaders in the industry have suggested that DSP chip development has outpaced the industry’s ideas for its application—i.e., that DSP chips in hearing aids now have more capabilities than companies know what to do with—and that we should not expect much future development in DSP functionality. In fact, the opposite is true.

Every major hearing aid company spends a considerable effort squeezing the signal processing that they want to provide into the restricted capabilities of hearing aid DSPs. In doing so, they often simplify the algorithms—making them less complex than what the engineer originally planned—in order for the algorithm code to fit within the restricted clock cycles and memory of the DSP chip. This is somewhat akin to scaling back the graphics on a computer game because the video card or CPU isn’t powerful enough to handle all of the 3-D features that the software could provide—the basic functionality is there, but the experience is not nearly as good as it could be if the hardware were more powerful.

In order to keep their current drain well below 1 mA, DSP chips in hearing aids run their clock speeds at just a few MHz, as opposed to general-purpose DSPs used in consumer electronics that can run at hundreds and thousands of MHz. The programming and data memory in hearing aid DSPs are also restricted to a few tens of thousands of words of RAM, rather than the hundreds of thousands or even millions of words of RAM in general-purpose DSPs. Because of these hardware restrictions, algorithms currently found in hearing aids have been simplified so that they all can run on a single DSP chip and fit in its memory.

Current hearing aid DSP chip limitations also restrict the introduction of new types of algorithms that can run on more powerful commercial DSPs but not on hearing aid DSPs.

These facts mean two things for the future: (i) current hearing aid algorithms will improve over time as hearing aid DSP chips become more powerful, and (ii) algorithms not yet seen in the hearing aid industry will be introduced when hearing aid DSP chips become capable of running them.

The limitation with what hearing aids can do resides in the chip technology, not in the knowledge of what can be done with them.

That being the case, what DSP algorithm innovations can we expect in the future?

Improved Algorithms

Algorithms that currently exist in hearing aids will be improved and refined as DSP capabilities increase and as we learn more about the benefit that current algorithms provide.

As a simple example, consider noise reduction. The telecommunication industry provides an example of how noise reduction and speech enhancements in hearing aids can be improved; cellphones have considerably more sophisticated noise reduction algorithms because of their more powerful DSP chips. Whereas current hearing aid noise reduction algorithms rely on envelope statistics and simple environment classifiers to function, similar algorithms in telecommunication use speech production models that attempt to simulate the acoustics of the vocal tract and resonances in the mouth and nasal cavity as a part of their speech detection and noise reduction systems.

As the speed and memory of hearing aid chips increase, the more sophisticated versions of current hearing aid algorithms will be developed by hearing aid companies, either through internal development or translation from universities and other industries, providing additional benefit to the hearing aid wearer.

New Algorithms

New computationally intensive algorithms will also be introduced as DSP chips increase in capability. Many of these new algorithms will also be borrowed from other industries that process audio, because they have had many years with more powerful chips to develop and optimize their processing schemes. For example, the music recording industry has sophisticated audio processing algorithms for compression, pitch shifting, and other effects that have been optimized by highly critical listeners. Most of these algorithms from other industries, however, will require considerable work to modify them for use in hearing aids. There are several reasons for this.

First, as already stated, hearing aids always have less powerful DSP capabilities than other products that do not have the same size and power constraints. This means that significant work will still exist to simplify algorithms and to integrate them with existing hearing aid algorithms. Many algorithms from other industries will have to be translated from 32-bit floating point implementations into more difficult 16-bit fixed point implementations.

Second, most audio industries have very specific types of sound that they process. The telecommunication industry usually processes speech at high signal-to-noise ratios; the music industry only processes voice and musical instruments, often separated into individual tracks; the teleconference industry only processes sounds that exist in conference rooms such as speech and HVAC noise.

Hearing aids, however, have to be able to process all possible sounds with imperceptible distortion and good perceived quality for someone listening all day long. In other words, they have to be able to handle every sound and any sound in all possible combinations. Algorithms that are designed to only work with headsets in an office cannot simply be ported to a hearing aid without serious alteration to ensure that they work in all of the conditions that a hearing aid wearer might experience. Customers do not return their cellphones because the sound of a fork on a plate wasn’t processed properly.

Third, algorithms in other industries were designed for normally-hearing listeners. If and how they would have to be modified for listening by those with hearing impairment is unknown. Wider auditory filters, loudness recruitment, and changes to forward masking functions may cause hearing impaired listeners to prefer different processing designs than those optimized for normally-hearing listeners. The interaction of new algorithms with other hearing aid algorithms such as multiband compression will also have to be carefully investigated to ensure that algorithms work together gracefully.

Intelligent Systems

Hearing aids today have many automatic features: turning directionality and noise reduction on and off, classifying the environment that the user is in (e.g., car, noisy restaurant, quiet office) and making adjustments to the hearing aid settings. This automation will continue to evolve, but learning will also be added to hearing aids, making them “intelligent”.

Current adaptive algorithms in hearing aids should not be classified as intelligent because they lack learning, which is the ability to improve behavior over time in response to sensor information. Techniques such as neural networks, fuzzy logic and genetic algorithms have been researched extensively in academia for use in systems that learn behavior and alter how they work in an optimal way, and we should expect their emergence into the hearing aid industry.

One application for intelligent systems is to assist with individualized fittings. The proper fitting of the parameters of a hearing aid by the audiologist or hearing instrument specialist to the needs of the hearing aid wearer is critical to the success of the hearing aid. Unfortunately, not all dispensers are skilled at providing the best hearing aid setting for their patient needs, and often getting the proper fit requires several office visits. A hearing aid that can automatically alter how it works over time to better fit the needs of the hearing aid wearer would benefit those patients who were not fit by an expert fitter. The dispenser would also benefit by not having to spend as much office time fine-tuning the hearing aid parameters. The challenge with implementing intelligent systems in hearing aids is to ensure that the system is able to adapt over time such that the sound processing is improved for the hearing aid wearer.

Durant *et al.* [14] implemented a genetic algorithm that adjusted the parameters of a feedback canceller in a hearing aid such that the feedback canceller improved its performance over time. The genetic algorithm required the wearer to assess the sound quality of the hearing aid with different parameter settings, and the algorithm used the listener’s responses to continually adjust and improve the feedback canceller and the resulting sound quality. One can imagine that this approach could be applied to many aspects of hearing aid use. Such a system would have to be to designed to be easy to use and to ensure that the hearing aid continues to improve as it adapts rather than mistakenly get worse.

HEARING SCIENCE

The science of auditory perception is a mature field, as is our understanding of the psychoacoustics of hearing impairment. Surprisingly little of the research in these areas have contributed to hearing aid design and hearing aid fitting. The articulation index has been used to optimize the audibility of speech, and loudness recruitment data has led to the design and fitting of multiband compression. Attempts to design other hearing aid algorithms based on the psychoacoustics of hearing impairment, such as the application of spectral contrast enhancement to compensate for the broader auditory filters of the hearing impaired [15], have not been successful.

The future will see the successful application of hearing science to DSP technology innovations, but most of the advances will require an integrated development of new diagnostics, signal processing, and validation measures as discussed later on. The most direct application of hearing science to new digital technology in the future will be the application of auditory models to hearing aid signal processing.

Auditory Models

Auditory models have been used successfully in a variety of audio processing applications, e.g., in perceptual vocoders such as mp3 and as front-ends to automatic speech recognition systems. Multiband compression might even be considered a simplistic model of cochlear function. The application of auditory models to hearing aid processing seems logical given that hearing aids attempt to compensate for changes to auditory function. Auditory models are one way to understand normal and impaired auditory function, and certainly illuminate how processing might compensate for the difference.

Auditory models may also help with non-hearing loss related algorithms such as environment classification. Humans can recognize sound sources and environments with much greater accuracy than computer-based systems; modeling the way that the human auditory system processes sound may provide insight into the best approach for designing DSP-based sound-source identification and environment classification.

The application of sophisticated auditory models to hearing aids has been prevented thus far by the computational limitations of hearing aid DSPs. As these DSPs become more powerful, however, the possibility of applying auditory models becomes more realistic.

Models that could prove to be beneficial when implemented in hearing aids include cochlear models that simulate level-dependent filter bandwidths and suppression with resolution equivalent to cochlear filters[16], modulation filterbank models that represent the perception of envelopes in different frequency regions[17; 18], and temporal-spectral models that represent how we perceive complex features[19]. Such auditory models have been derived from perceptual and physiological data on how sound is perceived. To the extent that these models can be modified to reflect auditory perception by the hearing impaired, they could improve hearing aid design by modeling the changes to perception from an individual's specific loss.

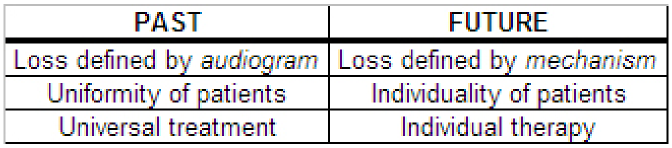
Bondy *et al.* [20] applied this approach to derive the optimal linear gain prescription for a given audiogram. A model of the cochlea and auditory nerve was used to determine the auditory nerve's response to speech for a normal auditory system and for impaired auditory systems with varying amounts of hearing loss. Bondy *et al.* calculated linear gain fitting algorithm parameters that brought the model of the impaired systems' auditory nerve response as close to normal as possible. The fitting prescription that resulted from this model-based approach was similar to the NAL-R fitting prescription [21] that was derived using a combination of theory and empirical data. Bondy *et al.*'s results demonstrate that auditory models can be used to optimize hearing aid function that had previously required empirical data to derive. The use of an auditory model also provides an explanation for why the NAL-R fitting algorithm has been successful: the optimal gain was that which brought the auditory nerve response of the damaged auditory system closest to the response of an undamaged auditory system. While this application did not require the model to function on the hearing aid DSP chip because the application was a fitting algorithm, one can imagine using the same model to determine proper hearing aid processing instantaneously within the hearing aid itself.

As another example, Shi *et al.* [22] designed a signal processing strategy that compensated for the change to cochlear phase response caused by hearing impairment. The instantaneous phase responses of both a healthy cochlea and a damaged cochlea were modeled, and then the difference in phase was applied to the signal in order to restore the normal phase response to the hearing impaired listener. Limited results indicated an improvement to speech understanding and sound quality in some subjects.

Both of these approaches are similar to the general strategy described by Edwards [23], who proposed that hearing aid processing should restore the psychoacoustic and physiological measures of a damaged auditory system to normal. Accurate models of normal and impaired auditory function can be used to facilitate this approach.

Individualization

Hearing aid technology will change as the industry alters how it approaches the pathologies and needs of individual hearing impaired patients. The biotech industry is in a similar transition in its approach to disease, diagnoses, and treatment, and Table 2 has been adapted from a table created by a biotech industry analyst [24]. The left column in Table 2 identifies how hearing aid patients have been addressed up until now, and the right column identifies how this will change in the future.



PAST	FUTURE
Loss defined by *audiogram*	Loss defined by *mechanism*
Uniformity of patients	Individuality of patients
Universal treatment	Individual therapy

TABLE 2

As the first entry in Table 2 indicates, hearing loss will become less defined by diagnostic measures, such as the audiogram, and more defined by the mechanism of the loss. Today, hearing aids are primarily fit to the audiogram of the hearing aid wearer, yet the nature of an individual’s hearing loss is more complex than that simple description.

Pure-tone thresholds do not identify whether a sensorineural hearing loss is caused by damage to the outer hair cells, the inner hair cells or a mixture of both. A rule of thumb has typically been that hearing loss up to approximately 60 dB HL is from outer hair cell loss and greater levels of loss are a result of additional damage to inner hair cells. In all likelihood, even losses below 60 dB HL contain a mixture of inner and outer hair cell damage.

Additional mechanisms of hearing loss include changes to the endocochlear potential. Schmiedt *et al.* [25] has suggested that presbycusis may result from damage to the cochlear lateral wall, reducing the voltage within the cochlea and altering the function of the hair cells. In this case, the hair cells are not damaged, just altered in function, and amplification will not cause auditory nerves to respond at the same level as they would with a healthy cochlea.

Clearly, in order to best treat the hearing loss of a patient, the physiology of their hearing loss must be understood. To do so, additional diagnostic procedures are needed from which the mechanism of hearing loss can be estimated. For example, the amount of compression at a specific frequency region can be estimated using a masked-threshold technique [26], which may provide information on the health of outer hair cells in that frequency region. Otoacoustic emissions have been demonstrated to be correlated with compression as well [27], where the growth of OAEs with increasing stimulus level matched the growth of loudness with stimulus level. Since the slope of the loudness growth function has been assumed to be related to the state of outer hair cell health, this measure of OAE response may also be useful in estimating the residual compression. Such information could be used to alter hearing aid signal processing or to design new algorithms based on a better understanding of the mechanism of someone's hearing loss.

The second entry in Table 2 indicates that patients with the same diagnostic characteristics of hearing loss, and maybe even the same mechanism of loss, will no longer be treated as having the same needs. While the general approach of the industry is to treat hearing aid wearers as the same if they have identical loss, the reality is that they respond differently to the same treatment. This may in part be because they have different mechanisms of hearing loss, but may also be because they have other differences as well.

These other differences between patients include dexterity, lifestyle, speech understanding ability, and cognitive ability. Each of these differences may result in one patient requiring different technology than another patient who has similar levels of hearing loss.

These individual differences will require different treatments to hearing impairment, as indicated by the third entry in Table 2. Different hearing aid technologies and feature settings will be applied as we understand the individual differences of the patients better and what their corresponding needs are. For example, the finding that IQ test scores have been positively correlated with speech understanding benefit from fast-acting compression[28] suggests that different compressor time constants might be prescribed for patients with different cognitive ability.

The increased commonplace of mobile and home computing will allow those individual needs to be met with innovative therapies integrated with hearing aid solutions. Some patients will require more assistance in adapting to their hearing aids than others, and home administered therapies such as LACE [29] could become a common method to assist patients in optimizing their use of their hearing aid technology. LACE trains users to improve their hearing with their hearing aids and adapts itself to the performance of the user. If the patient improves quickly, then LACE adjusts its difficulty quickly; if the patient has more difficulty adapting to their hearing aid and has difficulty with the tasks in LACE, then the program adjusts its difficulty slowly. One can imagine that hearing aids will adapt over time as patients adapt to their new technology in the same way that LACE training adapts the difficulty of its tests to the subject's performance. Combined with the intelligent algorithms in hearing aids discussed earlier, hearing aids become systems that are designed to refine their treatment to the individual needs of the user.

Assessment Procedures

Standard assessment procedures for measuring hearing aid benefit have focused on audibility-related performance with speech understanding measured in the presence of speech-shaped noise. Audibility is one aspect of auditory perception that is now well understood and is essentially a solved problem for hearing aids for mild and moderate levels of impairment.

Auditory perception is defined by much more than audibility, however. Supra-threshold processing can affect not only speech intelligibility, but also sound quality and factors that affect our ability to extract information about the world through what we hear. To determine how digital signal processing is affecting these effects, we need assessment procedures that are sensitive to more than audibility effects.

How does the perception of noise reduction artifacts vary with hearing loss configuration? What is the impact of multiband compression on the perception of echoes? These more complex aspects of auditory perception must now be addressed. Additional areas of investigation include the perception of amplitude and frequency modulation, cross-frequency coherence, binaural perception, and timbre. A more sophisticated understanding of how hearing impairment and hearing aid processing affects complex auditory processing such as source segregation, auditory streaming, feature extraction and auditory-visual integration also need to be better understood in order to better design the signal processing within hearing aids. Some of these issues will be addressed in the next section.

COGNITION

The hearing aid research community and the hearing aid industry in general take a bottom-up approach to hearing impairment research and hearing aid design. They are concerned with how the impairment in the auditory periphery alters the auditory signal, and how hearing aids change this peripheral representation. Diagnostics assess the function of the auditory periphery, hearing aids are designed to account for changes to auditory processing in the cochlea, and validation procedures assess speech understanding ability that is primarily affected by audibility.

A significant amount of auditory perception, however, is top-down, involving the cognitive system. Hearing impairment and hearing aids likely have an impact on this higher-level function. Cognitive function and its interaction with both hearing impairment and hearing aids have not receiving much clinical or research effort. The interaction between hearing aids and cognitive function are also not considered in the design of hearing aids.

In the future, hearing aids will be designed to not only take into account the effect of processing on signal representation in the auditory periphery, but also to take into account the impact of processing on cognitive function.

Attention and Effort

A common complaint of the hearing impaired is that listening in noisy situations is an exhausting experience, and a hearing impaired person is far more tired after an hour of conversing in a noisy situation than someone with normal hearing. This is likely due to the increased listening effort necessary to understand speech through the distorted auditory system.

Communication is a complex process that embodies far more than audibility-related auditory function. When listening to speech in a noisy situation, linguistics and context information are used to assist in the speech understanding process. Sentences with inaudible words, such as in the sentence "The hungry cat chased a small grey ________," can still be accurately understood with above chance probability because of context and linguistics. The missing word in the example can be anticipated to be "mouse" because of the topic, because of the modifiers "small" and "grey", because it must be a noun, and perhaps because the person listening was able to determine that the word was a single syllable even though the phonemes were unidentifiable. If the missing word occurs earlier in the sentence, such as "a ________, small and grey, was being chased by a hungry cat," the listener can hold the sentence in memory, then go back and fill in the missing word after hearing the whole sentence.

These are cognitive aspects of speech understanding that affect the amount of attention and effort that the cognitive system expends during communication. In actual conversation (as opposed to standard speech-in-noise tests), the listener is also generating thoughts that are produced by what they are hearing, creating relationships between different sentences while drawing higher-level contexts, storing information in memory, and thinking about what they are going to say during the conversation in response to what they are hearing. In other words, far more cognitive activity is involved in conversation than is tested with phoneme recognition tests or simple speech in noise tests. Figure 2, adapted from Sweetow and Henderson-Sabes [29], graphically illustrates this complex situation. Of course, listeners may be taxing their attentional system even more by performing secondary tasks during conversation, such as reading a menu or driving.

If speech information is being missed due to poorer audibility from hearing loss in the auditory periphery, the cognitive system will have to work harder to maintain an acceptable level of understanding. Situations may exist where a hearing impaired person understands speech as well as a normal hearing person but is relying more on processing of context and linguistic information to help interpret parts of speech that are inaudible. Pichora-Fuller *et al.* [30] have demonstrated that older hearing impaired listeners benefit more from context in speech than normally-hearing older listeners, possibly due to the hearing impaired listeners' more frequent use of their cognitive system to assist in speech understanding. In the same study, they also demonstrated that background noise babble affects word memory in the same way that hearing impairment does, suggesting that distortion to the speech signal either by hearing impairment or by additive noise causes the cognitive system to function more poorly. The possibility also exists that the combination of hearing impairment and background noise may cause an even greater impairment to the cognitive system.

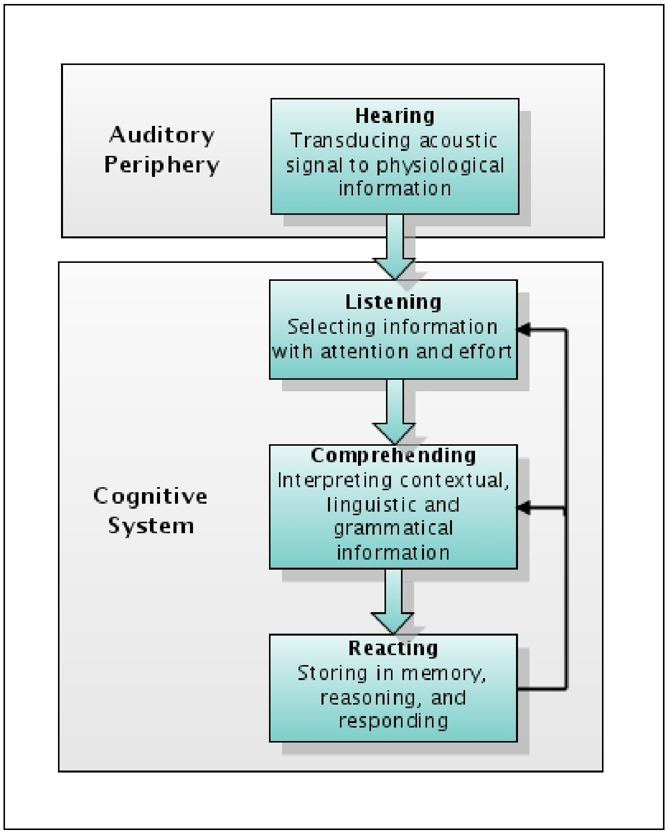


Figure 2. Components of communication. Adapted from Sweetow and Henderson-Sabes[29].

A fundamental concept in attention and effort is that the cognitive system has limited resources available at any given time, and as one system is tasked more, other systems have their capabilities negatively impacted[31]. Several researchers have demonstrated that poorer speech understanding and memory function in the aging population that is normally attributed to a decline in brain function are in part caused by a deterioration of the auditory periphery [32-34]. Deterioration to the perceptual system (bottom-up) can impair the cognitive system (top-down) by increasing the cognitive load necessary for auditory processing and limiting the cognitive ability left for other functions.

When more cognitive resources are needed to process speech in noise, fewer resources are available for other cognitive tasks. McCoy *et al.* [35] found that older subjects with hearing impairment performed worse in a word recall task than a similar age group with normal hearing. Their conclusion was that the additional cognitive resources required by the hearing impaired group to understand words in sentences impaired their ability to remember the words because fewer cognitive resources were available. Schneider *et al.* [32] found a similar interaction between hearing ability and speech comprehension.

These results and others indicate that hearing impaired listeners expend greater effort than normally-hearing listeners even when the two groups are understanding speech at the same level of performance. This greater effort not only denies cognitive resources for other activities, but could account for their self-reported increased level of stress and exhaustion when having a conversation in a noisy environment.

Whether or not current hearing aid processing reduces or increases listening effort is unknown. Preliminary evidence [36] using a dual-attention task suggests that signal-to-noise ratio improvement resulting from directionality can reduce listening effort. Additional research needs to be conducted into which hearing aid algorithms improve listening effort and attentional demands, and for what levels of hearing impairment and under what conditions these improvements occur.

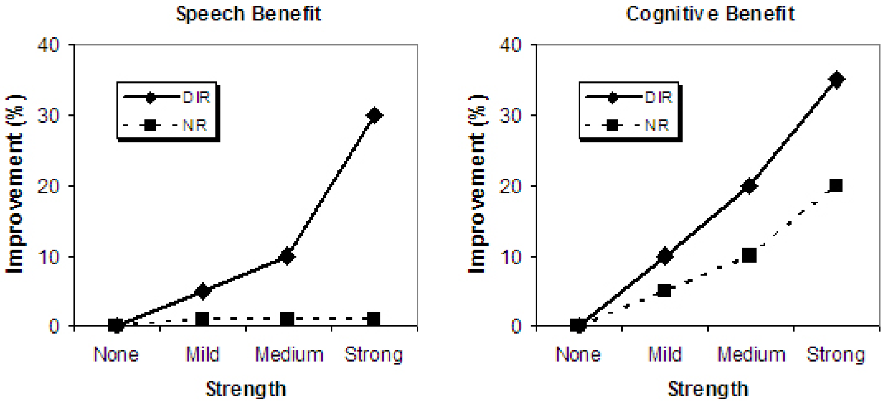


Figure 3. Future measures of hearing aid benefit. The left panel shows theoretical improvements to speech understanding from noise reduction and directionality. The right panel shows theoretical improvements to listening effort from noise reduction and directionality.

If this line of research proves successful, a new dimension of hearing aid benefit will be associated with hearing aid technology. Figure 3 shows possible future specifications for noise reduction and directional microphone benefit. The left figure represents the current state of characterizing hearing aid benefit, in which an increase in directional strength increases speech understanding while an increase in noise reduction strength has no impact on speech understanding. The figure on the right hypothesizes one possible future outcome, in which both algorithms are shown to provide cognitive benefit by reducing the listening effort required for speech understanding. If such interactions between hearing aid processing and cognitive function are discovered, cognitive function metrics such as listening effort could be used by hearing aid companies to select between different signal processing designs and to improve current ones. Both patients and dispensers will also appreciate the greater extent to which signal processing provides benefit to the hearing aid wearer, and increased user satisfaction is possible.

Auditory Scene Analysis

Auditory scene analysis is ”the organization of sound scenes according to their inferred sources” [37]. It is the ability to make sense of the world around us from what we hear, to take a complex auditory signal that consists of sound from multiple sources and be able to separate the individual auditory components and “hear” the individual sound sources. The ability to pay attention to one person speaking while several other speakers are also heard, or to perceive music from a band as consisting of individual instruments playing rather than one jumbled cacophony, is a result of our cognitive ability performing auditory scene analysis.

Research in this field has determined that listeners are able to easily combine acoustic components across frequency and time into individual sources by identifying certain features that bind acoustic components together. These features include:

- common harmonicity
- common onsets and offsets
- common amplitude and frequency modulation
- common spatial location
- common timbre.

Listeners pre-attentively group together sound using these auditory features into auditory objects which then allows them to focus their attention on a specific sound source, e.g. a conversation to their left or a trumpet in a jazz ensemble. An example of this ability was demonstrated by Summerfield and Assman [38], where subjects’ ability to identify two simultaneously spoken vowels was improved when the fundamental frequency of the two vowels differed. Harmonicity was used as a cue to separate temporally and spectrally overlapping speech components into two separate auditory objects, i.e., two vowels.

The difficulty that hearing impaired listeners have understanding speech in noisy environments such as a loud restaurant, even when all sounds are audible, may be related to a dysfunction in their auditory scene analysis process. A room full of people speaking is often described by people with significant hearing impairment as sounding like a jumble akin to a bee hive, where they can hear but they can’t understand speech. This deficit could result from an inability to separate sound components into auditory objects, preventing the listener from focusing attention on and listening to a single talker.

The effect of hearing impairment and hearing aid processing on auditory scene analysis will become a significant research effort in the near future. The possibility exists that current hearing aids may interfere with auditory scene analysis ability [39]. If interactions are found, hearing aids could be developed with the specific goal of improving a listener’s auditory scene analysis ability.

Algorithms such as multiband compression and noise reduction can alter the amplitude modulations, onsets, offsets and perceived locations of sounds—cures necessary for the creation of auditory objects—and therefore could impact auditory scene analysis ability. If this occurred, listeners would have difficulty focusing their attention on specific sound sources, and their ability to understand speech in the presence of other talkers would be affected along with other auditory activities such as listening to music. Freyman *et al.* [40] have demonstrated that informational masking, a phenomenon associated with auditory scene analysis, affects a listener's ability to understand speech in the presence of other talkers, and that perceived spatial separation between the talkers improves a person's ability to understand the target speaker. Any interference on sound source localization by hearing aids may affect improvements to speech understanding caused by spatial separation[41].

Other high level functions that occur in the mid-brain could also be affected by hearing impairment and hearing aids. Hearing impaired listeners have a more difficult time understanding speech in reverberation than normally-hearing listeners. The binaural auditory system is designed to suppress echoes, a phenomenon known as the Precedence Effect or the Law of the First Wavefront whereby the auditory system attends to the first instance of a sound and suppresses the perception of subsequent echoes. The impact of hearing impairment and hearing aid processing is not well understood, but research in this area could suggest hearing aid designs that help hearing impaired listeners understand speech in noise by allowing normal auditory function such as the Precedence Effect to operate effectively.

Finally, auditory scene analysis may have other applications to hearing aids. Edwards [39] noted that models of auditory scene analysis have been applied to computer speech recognition systems, and he suggested that similar models could be implemented in hearing aids as a way of pre-processing speech to improve speech understanding by the hearing impaired. Clearly, significant work in the combined fields of auditory scene analysis and perception with hearing aids needs to be conducted to better understand how these two fields can be combined to produce better hearing aids.

In general, the assessment of hearing aid benefit needs to be applied to auditory function that is mitigated by more than audibility. The functioning of the complete auditory and cognitive systems need to be assessed when determining the benefit from hearing aids. This will lead to a better understanding of the needs of the hearing impaired, and will provide additional metrics from which to compare different hearing aid technologies. Basing hearing aid designs on simple measures of speech understanding ability in speech-shaped noise do not capture the complexities of auditory perception and cannot determine whether hearing aid technology is improving or making worse complex auditory and cognitive function. With the introduction of new performance measurement procedures, hearing aid technology will be improved in ways that cannot be assessed today, and hearing aid wearers will better appreciate the benefit provided to them by hearing aids, which will possibly produce more satisfied hearing aid users.

SUMMARY

As digital hearing aid technology matures, new innovations become more difficulty to develop. Straightforward engineering approaches have driven applications up until now, but future advances will require collaboration across many fields including psychoacoustics, signal processing, and clinical audiology.

The methods by which new digital hearing aid technology is developed are about to change. Concepts of connectivity and individuality will drive much of the new applications. As the interaction between hearing aid processing and complex auditory and cognitive function becomes better understood, new concepts in digital hearing aid technology will be developed to account for these interactions. As DSP chips become more advanced in capability, improvements to current algorithms will be made and new algorithms will be created with inspiration from such sources as auditory models and other audio industries.

Patient benefit should drive all of this development, and producing evidence of this benefit when new technology is introduced will become more commonplace as evidence-based practice becomes more popular. This alone will cause engineering development to work closely with audiology and auditory science to so that new diagnostic measures and validation procedures are developed in conjunction with new digital technology[42; 43].

REFERENCES

1. Strom KE. The HR 2006 Dispenser Survey. *Hear Rev.* 2006;13(6):16-39.

2. Kochkin S. MarkeTrak VII: Customer satisfaction with hearing instruments in the digital age. *Hear J.* 2005;58(9):30-42.

3. Christensen CM. *The Innovator's Dilemma*. Cambridge, MA: Harvard Business School Press; 1997.

4. Beecher F. A vision of the future: A 'concept hearing aid' with Bluetooth wireless technology. *Hear J.* 2000;53(10):40-44.

5. Ross M. Telecoils are about more than telephones. *Hear J.* 2006;59(5):24-28.

6. Yanz JL, Roberts R, Colburn T. The ongoing evolution of Bluetooth in hearing care. *Hear Rev.* 2006;*in press*.

7. Myers DG. In a looped America, hearing aids would be twice as valuable. *Hear J.* 2006;59(5):17-23.

8. Yanz JL. The future of wireless devices in hearing care: a technology that promises to transform the hearing industry. *Hear Rev.* 2006;13(1):18-20.

9. van Veen BD, Buckley KM. Beamforming: a versatile approach to spatial filtering. *IEEE ASSP Magazine.* 1988;5:4-24.

10. Van den Bogaert T, Klasen TJ, Moonen M, Van Deun L, Wouters J. Horizontal localization with bilateral hearing aids: without is better than with. *J Acoust Soc Am.* Jan 2006;119(1):515-526.

11. Besing J, Koehnke J, Zurek P, Kawakyu K, Lister J. Aided and unaided performance on a clinical test of sound localization. *J Acoust Soc Am.* 1999;105:1025.

12. Desloge J, Rabinowitz W, Zurek P. Microphone-array hearing aids with binaural output Part I: Fixed-processing systems. *IEEE Trans Speech Audio Proc.* 1997;5:529-542.

13. Klasen TJ, Moonen M, Van den Bogaert T, Wouters J. Preservation of interaural time delay for binaural heraing aids through multi-channel wiener filtering based noise reduction. Paper presented at: Proc. IEEE-ICASSP, 2005.

14. Durant EA, Wakefield GH, Van Tasell DJ, Rickert ME. Efficient perceptual tuning of hearing aids with genetic algorithms. *IEEE Trans Speech Audio Proc.* 2004;12(2):144-155.

15. Baer T, Moore BC, Gatehouse S. Spectral contrast enhancement of speech in noise for listeners with sensorineural hearing impairment: effects on intelligibility, quality, and response times. *J Rehabil Res Dev.* 1993;30(1):49-72.

16. Zhang X, Heinz MG, Bruce IC, Carney LH. A phenomenological model for the responses of auditory-nerve fibers: I. Nonlinear tuning with compression and suppression. *J Acoust Soc Am.* Feb 2001;109(2):648-670.

17. Dau T, Kollmeier B, Kohlrausch A. Modeling auditory processing of amplitude modulation. II. Spectral and temporal integration. *J Acoust Soc Am.* Nov 1997;102(5 Pt 1):2906-2919.

18. Dau T, Kollmeier B, Kohlrausch A. Modeling auditory processing of amplitude modulation. I. Detection and masking with narrow-band carriers. *J Acoust Soc Am.* Nov 1997;102(5 Pt 1):2892-2905.

19. Chi T, Ru P, Shamma SA. Multiresolution spectrotemporal analysis of complex sounds. *J Acoust Soc Am.* Aug 2005;118(2):887-906.

20. Bondy J, Becker S, Bruce I, Trainer L, Haykin S. A novel signal processing strategy for hearing aid design: neurocomputation. *Sig Proc.* 2004;84(7):1239-1253.

21. Byrne D, Dillon H. The National Acoustic Laboratories' (NAL) new procedure for selecting the gain and frequency response of a hearing aid. *Ear Hear.* Aug 1986;7(4):257-265.

22. Shi L, Carney LH, Doherty KA. Correction of the peripheral spatiotemporal response pattern: a potential new signal-processing strategy. *J Speech Lang Hear Res.* 2006:, in press.

23. Edwards B. Signal processing, hearing aid design, and the psychoacoustic Turing test. Paper presented at: IEEE ICASSP, 2002; Orlando, FL.

24. Burrill S. Biotech state of the industry. Paper presented at: BayBio2005: Returns on Innovation; April, 2005; San Mateo, CA.

25. Schmiedt RA, Lang H, Okamura HO, Schulte BA. Effects of furosemide applied chronically to the round window: a model of metabolic presbyacusis. *J Neurosci.* Nov 1 2002;22(21):9643-9650.

26. Oxenham AJ, Plack CJ. Suppression and the upward spread of masking. *J Acoust Soc Am.* Dec 1998;104(6):3500-3510.

27. Epstein M, Florentine M. Inferring basilar-membrane motion from tone-burst otoacoustic emissions and psychoacoustic measurements. *J Acoust Soc Am.* Jan 2005;117(1):263-274.

28. Gatehouse S, Naylor G, Elberling C. Benefits from hearing aids in relation to the interaction between the user and the environment. *Int J Audiol.* Jul 2003;42 Suppl 1:S77-85.

29. Sweetow R, Henderson-Sabes J. The case for LACE (Listening and Communication Enhancement). *Hear J.* 2004;57(3):32-38.

30. Pichora-Fuller MK, Schneider BA, Daneman M. How young and old adults listen to and remember speech in noise. *J Acoust Soc Am.* Jan 1995;97(1):593-608.

31. Kahneman D. *Attention and Effort*. Englewood Cliffs, NJ: Prentice-Hall; 1973.

32. Schneider BA, Daneman M, Murphy DR, See SK. Listening to discourse in distracting settings: the effects of aging. *Psychol Aging.* Mar 2000;15(1):110-125.

33. Lindenberger U, Baltes PB. Sensory functioning and intelligence in old age: a strong connection. *Psychol Aging.* Sep 1994;9(3):339-355.

34. Schneider BA, Daneman M, Murphy DR. Speech comprehension difficulties in older adults: cognitive slowing or age-related changes in hearing? *Psychol Aging.* Jun 2005;20(2):261-271.

35. McCoy SL, Tun PA, Cox LC, Colangelo M, Stewart RA, Wingfield A. Hearing loss and perceptual effort: downstream effects on older adults' memory for speech. *Q J Exp Psychol A.* Jan 2005;58(1):22-33.

36. Edwards B, Hafter E, Sarampalis A. Cognitive issues with hearing aids. Paper presented at: Amer Acad Audiol; April 6-8, 2006; Minneapolis, MN.

37. Bregman A. *Auditory Scene Analysis*. Cambridge, MA: MIT Press; 1990.

38. Summerfield Q, Assmann PF. Perception of concurrent vowels: effects of harmonic misalignment and pitch-period asynchrony. *J Acoust Soc Am.* Mar 1991;89(3):1364-1377.

39. Edwards B. Hearing Aids and Hearing Impairment. In: Greenberg A, Popper and Fay, ed. *Speech Processing in the Auditory System*. New York, NY: Springer; 2003.

40. Freyman RL, Balakrishnan U, Helfer KS. Spatial release from informational masking in speech recognition. *J Acoust Soc Am.* May 2001;109(5 Pt 1):2112-2122.

41. Kalluri S, Shinn-Cunningham B, Edwards B. Effect of hearing-aid compression on spatial unmasking. Paper presented at: Amer Acad Audiol; April 6-8, 2006; Minneapolis, MN.

42. Cox RM. Evidence-based practice in provision of amplification. *J Am Acad Audiol.* 2005;16:419-438.

43. Edwards B. What outsiders tell us about the hearing industry. *Hear Rev.* 2006;13(3):88-92.