Hearing and Aging Effects on Speech Understanding: Challenges and Solutions

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Development of effective, evidence-based solutions to overcoming communication barriers imposed by hearing loss is critical in our rapidly aging population.

Why Does Grandma Seem So Withdrawn Lately?

The scene is your annual Thanksgiving dinner. Your grandmother has been smiling throughout the dinner, but you can tell that she is not following the conversation. She often interjects the conversation with an off-topic comment, and when asked a question, she may respond with an answer that does not relate to the conversation. When someone asks, "Have you heard from Faith recently?" she might respond irritably, "Yes, I washed my face this morning." She is 85 years old, and you are concerned she may be losing cognitive function.

But is it her cognitive status, her hearing ability, or a combination of the two that prevents her from fully engaging in the conversation? The answers to these questions can be difficult to sort out. A hearing loss of just a mild-to-moderate degree can have a significant impact on one's ability to understand speech in background noise, even if communication in quiet, one-to-one settings remains unimpaired (Dubno et al., 1984).

However, cognitive processes such as working memory or speed of processing may also interfere with communication in background noise (Pichora-Fuller, 2003). Previous studies have shown that hearing loss is associated with cognitive decline (Lin et al., 2013). Clearly, this link between cognitive decline and hearing loss supports the importance of older adults, such as your grandmother, receiving a comprehensive audiological evaluation and suggestions for managing a hearing loss, if identified. Yet, older adults are often reluctant to pursue help for their hearing difficulties because of assumptions regarding the high cost of hearing aids or how the use of hearing aids may appear to others. Their friends may have shared negative experiences regarding hearing aid discomfort or inadequate performance in background noise. And, when an individual finally makes a decision to seek help, he or she may find that the communication barriers resulting from hearing loss can be difficult to overcome, even with appropriate diagnosis and management, for the reasons described in this article.

The Audiological Evaluation

What can the audiological evaluation reveal about your grandmother's ability to participate in a conversation at a crowded dinner table? The typical evaluation assesses peripheral hearing function in each ear by measuring detection of pure tones at a wide range of frequencies (0.25-8 kHz) and plotting these thresholds as an "audiogram" and by measuring the ability to understand one-syllable words presented in quiet at conversational levels ("speech recognition"). **Figure 1** displays pure-tone thresholds at a range of frequencies for a typical younger adult with normal hearing and a typical older adult with hearing loss. The *y*-axis plots the levels (in dB hearing level [HL]) at which the listener can just barely hear the sound. In this case, the reference for decibels is the average thresholds for a large group of normal-hearing individuals who have no ear diseases, so smaller values (near 0 dB HL) indicate normal hearing and larger values indicate hearing loss. Note that the *y*-axis is reversed from the typical plotting convention so that the audiogram plots better thresholds nearer the top and poorer thresholds nearer the bottom.

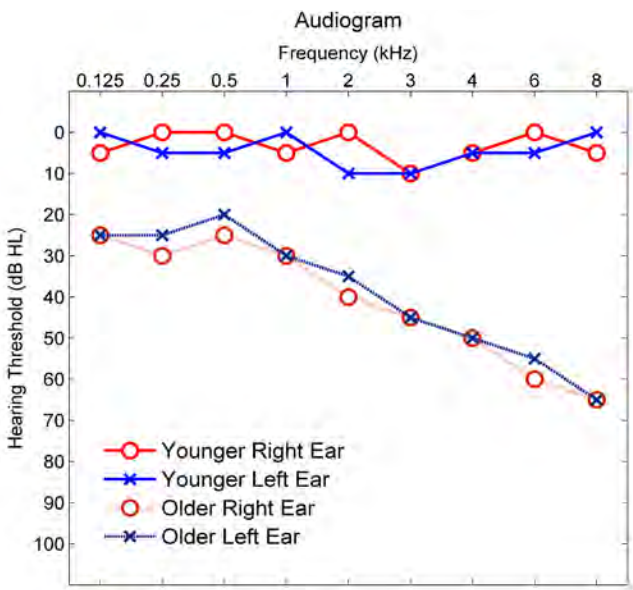

Figure 1. *Pure-tone thresholds as a function of frequency ("audiogram") for a typical younger adult with normal hearing (**solid lines**) and typical older adult with hearing loss (**dotted lines**). When thresholds are plotted on an audiogram, lower thresholds (near 0 dB hearing level [HL]) are near the top, indicating better hearing, and higher thresholds are near the bottom, indicating hearing loss (see text). According to the audiogram, the older adult has a mild hearing loss in the low frequencies, sloping to a moderately severe hearing loss in the high frequencies, which represents a typical pattern of age-related hearing loss.*

From the audiogram and one or more measures of speech recognition, the audiologist interprets the results to assess the type of hearing loss and the integrity of each part of the peripheral auditory system. The ear is composed of three main parts that contribute to audition: the outer ear (pinna and ear canal), the middle ear (eardrum, air-filled middle ear cavity, and middle ear bones), and the inner ear (cochlea and auditory nerve).

One issue might be a conductive hearing loss that usually indicates a pathology in the outer or middle ear, such as middle ear fluid or fusing of the middle ear bones, which prevents their movement in response to sound. These are examples of pathologies that prevent the conduction of sound through the middle ear. In contrast, a sensorineural hearing loss suggests a pathological condition in either the cochlea or the auditory nerve. The "sensory" component refers to the cochlea, and the "neural" component refers to problems primarily in the auditory nerve.

The sensory part of the inner ear is the cochlea that contains the organ of Corti. Lying on the organ of Corti are two types of sensory hair cells, the outer and inner hair cells. The inner hair cells transduce the sound and convert the sound vibrations into electrical energy. The outer hair cells serve as cochlear amplifiers to control the function of the inner hair cells. The gain of this amplifier can be increased or decreased by efferent neural connections that bring control of signals from the brain via olivocochlear reflexes that project from

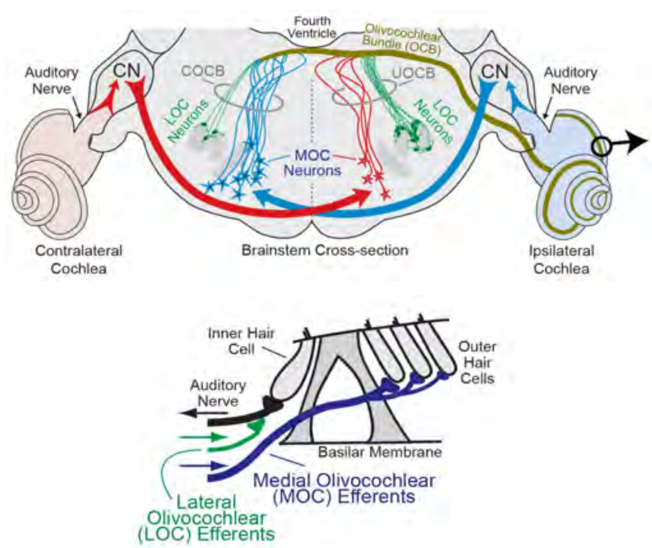

Figure 2. *A schematized anatomic view of the olivocochlear reflexes to the right cochlea. **Top:** outline of a transverse section of a cat brainstem showing the locations of lateral olivocochlear (LOC; **green**) and medial olivocochlear (MOC; **blue and red**) neurons. The pathways for the ipsilateral (stimulated cochlea; **blue**) and contralateral (unstimulated cochlea; **red**) MOC reflexes to the right ear join the olivocochlear bundle (OCB; **gold**). The axons from LOC and MOC neurons form the OCB, which is composed of crossed (COCB) and uncrossed (UOCB) components. The COCB is accessible near the fourth ventricle. CN, cochlear nucleus. The S-shaped gray structure is the lateral superior olivary nucleus, and the gray structure medial to it is the medial superior olivary nucleus. **Bottom:** schematic of the organ of Corti showing the main terminations of MOC neurons (**blue**) on outer hair cells and of LOC neurons (**green**) on the dendrites of auditory nerve fibers. From Guinan (2006), with permission.*

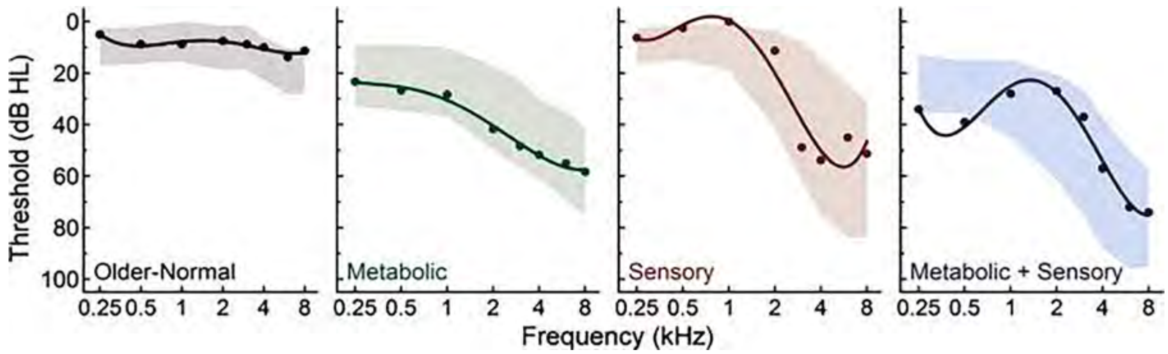

Figure 3. *Example audiograms are provided for the four major audiometric categories (phenotypes).* ***Shaded areas*** *correspond to the distribution of data labeled in these categories by experts. The "Older-Normal" and "Metabolic" phenotypes are similar to the audiograms for younger and older adults in* ***Figure 1****, respectively. The "Sensory" phenotype shows normal hearing in the low frequencies, dropping to a moderately severe hearing loss in the high frequencies, and the "Metabolic + Sensory" audiogram shows a moderate hearing loss in the low frequencies, dropping to a severe hearing loss in the high frequencies. Modified from Vaden et al. (2017), with permission.*

the superior olivary complex in the brainstem to the outer hair cells (depicted in **Figure 2**). Refer to Lonsbury-Martin et al. (2017) and Brownell (2017) for more detailed descriptions of cochlear mechanics.

The most common type of hearing loss in older adults is sensorineural hearing loss or presbyacusis. The audiograms of individuals with presbyacusis can be classified into four main categories or phenotypes (displayed in **Figure 3**): older normal, metabolic, sensory, and metabolic + sensory (Dubno et al., 2013). The metabolic category results from a loss of the endocochlear potential (positive voltage found in cochlear fluid). Because the endocochlear potential supplies power to the outer hair cells (see **Figure 2**), a decrease in the voltage can reduce the hair cells' ability to amplify incoming sounds. The metabolic category is typified by a flat mild hearing loss in the low frequencies gradually sloping to greater hearing loss in the high frequencies. The sensory phenotype is typified by a moderate-to-severe hearing loss in the high frequencies that may result from exposure to noise or drugs that are known to damage hearing. The metabolic + sensory phenotype is characterized by a low-frequency hearing loss similar to the metabolic phenotype and a moderate-to-severe high-frequency loss similar to the sensory phenotype. At present, the relationship between these hearing loss patterns and real-world hearing difficulty remains unknown, but in the future, the identification of a specific audiometric category may assist with determining possible hearing loss etiologies and with management planning.

The Audiogram Does Not Predict Speech Understanding in Noise

Patients with more severe hearing loss can expect greater speech understanding difficulties. A severe hearing loss would correspond to thresholds in the range of 60-90 dB HL. Nevertheless, the audiogram is not a good predictor of speech recognition in realistic conditions, such as in a noisy environment (Souza et al., 2007). Clinical measures of speech recognition in noise using words (Words-in-Noise [WIN] test; Wilson et al., 2007) or sentences (Quick Speech in Noise [QuickSIN] test; Killion et al., 2004) are becoming more common in audiological evaluations. But even these tests may not account for all of the difficulties experienced by older adults. Anderson et al. (2013a) investigated factors contributing to the variance in self-assessment of hearing ability in older adults using the Speech, Spatial, and Qualities of Hearing Questionnaire (SSQ; Gatehouse and Noble, 2004). In addition to the SSQ, the test measures included pure-tone thresholds, QuickSIN scores, and the frequency following response (FFR), a scalp-recorded measure of electrical activity that mirrors the timing and frequency aspects of the auditory stimulus. They found that the pure-tone thresholds and QuickSIN scores contributed to 15% of the variance in the SSQ score, and the FFR to a speech syllable accounted for an additional 15% of variance in the SSQ score. Therefore, factors in addition to peripheral hearing sensitivity, as indicated on the routine audiogram, may contribute to speech understanding difficulties.

Hidden Hearing Loss

Studies performed in the last decade have provided increasing evidence of peripheral hearing deficits that are not revealed in the audiogram or through otoacoustic emissions testing (a measurement of the sounds generated by the hair cells in the inner ear; Dubno et al., 2013). This type of deficit is now referred to as "hidden hearing loss" (Schaette and McAlpine, 2011). Aging may lead to one type of hidden hearing loss, a disruption of synapses (connections) between inner hair cells and auditory neurons that carry signals to the brain. This form of hidden hearing loss has been termed cochlear synaptopathy. Evidence of age-related cochlear synaptopathy was found in a mouse model (Sergeyenko et al., 2013). These older mice had normal-hearing thresholds, but neural firing to sounds above the threshold was reduced.

Varying degrees of cochlear synaptopathy may accompany sensorineural hearing loss, which may lead to frustrations experienced by patients and/or audiologists if audiometric thresholds do not predict success with management through hearing aids or cochlear implants. It is hoped that future research will be successful in developing proxy measures of synaptopathy that can be reliably obtained in a clinical setting.

"Don't Talk So Fast!"

The term "hidden hearing loss" may also be applied to processing deficits that affect the individual's ability to process the temporal or frequency properties of speech stimuli. For example, aging appears to have pronounced effects on the ability of the auditory system to preserve the precise timing characteristics of speech. We use timing cues, such as vowel duration, to distinguish words that differ in voicing, which occurs when the vocal folds of the larynx or voice box vibrate as air passes from the lungs to the oral cavity. For example, the vowel in "wheat" preceding the final voiceless consonant /t/ is shorter than the vowel in "weed" preceding the final voiced consonant /d/. In everyday conversational speech, the final consonant is not sufficiently audible for listeners to make that perceptual judgment without the vowel duration cue. Older adults have reduced ability to identify words on the basis of these and other temporal cues compared with younger adults (Gordon-Salant et al., 2008). In other words, an older adult would require a longer vowel duration to perceive "weed" versus "wheat." So, the next time you are speaking to your grandmother, try to slow down your rate of speech a bit to increase her ability to use these cues.

The perceptual consequences of disrupted temporal processing include a reduced ability to understand speech that is spoken rapidly or with an accent. As we age, we may find ourselves relying on open captions when watching many television shows or we may have difficulty understanding the younger relative who speaks rapidly. Decreased temporal processing may also affect the ability to understand speech in challenging listening environments, such as in background noise or in reverberant environments. These are the environments in which hearing aids are the least effective but where older adults report their greatest communication problems. As a result, older adults begin to avoid these troublesome listening situations and may avoid using their hearing aids.

"Why Are You Shouting?"

When the listener does not understand what was said, the natural tendency is for the speaker to repeat him/herself at a higher level. But the listener may then complain that the speaker is shouting. Individuals with hearing loss may need speech to be spoken at 70 dB sound pressure level (SPL; higher than average conversational speech) to understand the same message that might be understood at 30-40 dB SPL by someone with normal hearing; yet, at 100 dB SPL, speech becomes equally loud for individuals with either hearing loss or normal hearing. Thus, a person with normal hearing will have a dynamic range (difference between threshold and maximum tolerable loudness levels) of approximately 100 dB, but the individual with sensorineural hearing loss may have a dynamic range of 50 dB or less. This reduced dynamic range may lead to problems when trying to provide enough amplification to make soft sounds audible while limiting amplification for loud sounds so that they are not uncomfortably loud.

The loss of outer hair cells is one mechanism that may explain the reduced dynamic range observed in people with hearing loss. In the normal-hearing ear, the outer hair cells have abundant efferent connections that regulate the amount of amplification applied to sounds (see **Figure 2**). When outer hair cells are lost, low-level signals are not detected and there is no amplification provided to the signal by the outer hair cells. As the signal level is increased, there is a spread of excitation to neighboring hair cells, which then triggers cochlear amplification of the signal, resulting in an abrupt perceived increase in loudness. This rapid growth in loudness can occur when the sound level is increased by only 10 or 20 dB.

Another mechanism that may explain the reduced dynamic range is a disruption in the auditory system's maintenance of a stable firing rate over a period of time. The maintenance of a steady internal environment is known as homeostasis. A change in the balance of excitatory and inhibitory neurotransmission is one homeostatic mechanism that is associated with aging and hearing loss (Caspary et al., 2013). Communication between two neurons occurs through neurotransmission; neurons are more likely to fire when they receive excitatory input and less likely to fire when they receive inhibitory input. One possible result of the loss of inhibitory input with aging or hearing loss is an increase in spontaneous neural firing and exaggerated responses to auditory stimuli.

Electrophysiological (electroencephalographic [EEG]) studies have documented exaggerated responses to sounds presented at conversational listening levels of about 65-70 dB SPL. The FFR shows exaggerated subcortical responses to the speech envelope (slowly varying amplitude variations in speech) in older adults with sensorineural hearing loss (Anderson et al., 2013b). This exaggeration of responses to auditory stimuli may be especially pronounced in the cortex. Magnetoencephalographic (MEG) responses (observed on recordings of magnetic fields produced by electric currents in the brain) show overrepresentation of the speech envelope in older adults compared with younger adults (Presacco et al., 2016). Exaggerated responses to the speech envelope may help to explain why older adults find hearing aid-amplified sound so overwhelming when they first start wearing hearing aids.

"Why Is Speech So Unclear?"

Older adults often report they can hear the talker, but they cannot understand what is being said. Speech understanding may be reduced by deficits in the auditory system's ability to represent the timing and frequency cues of speech. The typical presbyacusic hearing loss compromises audibility in the high frequencies to a greater extent than in the low frequencies (see **Figure 1**). Therefore, merely amplifying the overall level of sound results in excessive amplification in the low frequencies where hearing is relatively normal and in perception of lower frequency background noise. Modern hearing aids are able to selectively amplify specific frequencies, within the limitations of the hearing aid microphone and circuitry. However, frequency selectivity (ability to detect differences in frequency) is often decreased in individuals with sensorineural hearing loss compared with individuals with normal hearing regardless of stimulus presentation level (Florentine et al., 1980). Therefore, the hearing aid user may not achieve maximum benefit from selective amplification of specific frequency channels.

The auditory system is organized tonotopically from the cochlea to the cortex; that is, low-to-high frequencies are represented in spatial order. For example, the cochlea is maximally responsive to high frequencies at the basal end (near the middle ear) and maximally responsive to low frequencies at the apical end (top of the cochlear spiral). This spatial organization is preserved throughout the auditory system. Hearing loss, however, may alter the tonotopic organization of central auditory structures.

For example, the C57 mouse model is used to study hearing loss effects because these mice commonly experience sensorineural hearing loss relatively early in the adult life span. C57 mice show disrupted tonotopic organization in the inferior colliculus, the auditory region of the midbrain, such that neurons that normally fire best to high-frequency sounds begin to respond more to low frequencies (Willott, 1991). Tonotopic changes may also occur in the auditory cortex of the brain. For example, when excessive noise damages hair cells in specific frequency regions in the cochlea (e.g., 3-6 kHz), stimulation with signals at these frequencies does not produce a response in cortical neurons in corresponding frequency regions but instead produces a response in neurons from adjacent cortical regions (Engineer et al., 2011).

Because of changes in frequency selectivity and tonotopicity, selective amplification of specific frequencies will not completely compensate for a decreased ability to discriminate between speech sounds based on subtle frequency differences. For example, the consonant /g/ has higher frequency energy than the consonant /d/. Although the two consonants differ in their place of articulation in the vocal tract, the place differences are not visible to the listener from viewing the talker's lips, and, therefore, the listener with hearing loss may have difficulty discriminating between words like "gust" and "dust" on the basis of frequency differences alone.

"Why Do I Still Have Trouble Understanding Speech with My Hearing Aids?"

Let us assume that your grandmother has been fit with hearing aids after being diagnosed with a mild-to-moderate hearing loss. You have been looking forward to the next family gathering, and you are hoping she participates more in the conversation. Your grandmother certainly seems more engaged, and yet she is still asking others to repeat what was said, especially when the background noise levels are high, such as in a restaurant. It is important to remember that although hearing aid digital technology has improved dramatically in the last few decades, amplification cannot fully compensate for neural-processing deficits.

Hearing aid algorithms attempt to provide appropriate amplification to compensate for hearing loss at each frequency and to maintain sound levels within the dynamic range of the listener, based solely on the audiogram and measures of loudness discomfort. These algorithms also attempt to improve ease of listening in noise using directional microphone and noise reduction strategies so that the listener does not exert as much effort to understand what is being said. However, it can be difficult to evaluate the real-world effectiveness of amplification, particularly in a clinical setting. Audiologists use probe-microphone measurements to verify the appropriateness of the hearing aid fitting. During probe-microphone measurement, the audiologist places a thin tube in the ear canal a few centimeters from the ear drum. This tube is attached to a microphone, and the hearing aid is then placed alongside the tubing in the ear canal. Speech and other stimuli are presented at varying levels, and the audiologist determines if the amplified sound levels reaching the eardrum adequately compensate for hearing loss based on the pure-tone thresholds. Although verifying hearing aid fitting in this way is important, this measurement does not provide information about how speech is being processed by the inner ear, the central auditory system, and the brain.

Because of the limitations of probe-microphone measurements, interest in the use of EEG measures to assess the benefit of hearing aids is increasing. Several studies have focused on verifying detection of speech signals using EEG recordings in infants or other individuals who may not be able to provide feedback (e.g., Easwar et al., 2015). These measures may be useful in determining if amplification is providing sufficient audibility to detect speech consonants across a range of frequencies, but the effectiveness of EEG measures for providing information about the ability of the brain to discriminate between consonants has not yet been demonstrated (Billings et al., 2012). Furthermore, a detection measure may not be as relevant for an individual who can provide feedback about the audibility of different speech sounds.

What may be more useful is a measure that can provide information about the processing of conversational level speech rather than soft, threshold-level sounds. Age- and hearing (loss)-related deficits in temporal and frequency processing are observed at listening levels well above the speech threshold. A few studies have assessed the effects of amplification on the neural processing of conversational level speech stimuli (e.g., Jenkins et al., 2017), but more research is needed to determine if EEG measures can be used to assess improvements in neural processing in a clinical setting, with the goal of improved performance.

Figure 4. *Example of an in-ear electrocencephalographic (EEG) mount shown as a single earplug (**left**) and in the ear (**right**). Own work by Mikkelsen.kaare, Creative Commons Attribution-ShareAlike 4.0 International Public License (CC BY-SA 4.0). commons.wikimedia.org/w/index.php?curid=51268329.*

Despite advancements in digital noise reduction and directional microphone technologies, understanding speech in noise continues to be the greatest challenge experienced by individuals who use hearing aids. The main limitation is that current technology is unable to distinguish between a target talker, who should be amplified, and a background of multiple talkers, who should be attenuated. Generally, hearing aid algorithms use multiple microphones to focus amplification in the direction of whomever the listener is facing. It is reasonable to assume that the listener is usually facing the speaker. However, there may be times when the listener hears an interesting fragment from another speaker in the group and would prefer to listen in on that conversation without turning his/her head. Hearing aids generally will not be able to quickly and easily adjust to this scenario.

Future Directions

These limitations in current digital noise reduction technology have led to an interest in the development of cognitively driven or attention-driven hearing aids (Das et al., 2016). This research is based on evidence of the ability of EEG or MEG measurements to reveal the listener's object of attention (Ding and Simon, 2012; O'Sullivan et al., 2015). The idea behind the research is that discreet in-the-ear electrodes might be used to convey information to the hearing aid regarding the listener's focus of attention. The hearing aid processing algorithm would then selectively amplify the desired speech stream of interest to the listener. **Figure 4** shows an in-ear EEG mount. Another recent innovation is the "visually guided hearing aid prototype" that uses an eye tracker mounted on a pair of eyeglasses to track the direction of the listener's gaze (Kidd et al., 2013), which may indicate the listener's focus of attention. The information regarding the direction of gaze is then used to maximize the directionality of a multimicrophone array.

The idea of "brain-controlled" hearing aids is certainly appealing. Nevertheless, the ability to benefit from this strategy is still limited by the ability of the auditory system to accurately process the amplified signal. As mentioned in **The Audiological Evaluation**, aging and hearing loss can disrupt the processing of the timing and frequency aspects of speech. The potential for neuroplastic changes in the aging auditory system has not yet been fully explored. There is some evidence that the use of hearing aids over time may improve the neural processing of speech signals, and that changes in cortical processing relate to improvements in cognitive function (Karawani et al., 2018), but more research is needed to explore the limits of neuroplasticity.

Outcomes may be improved if hearing aid use is supplemented with auditory training. But evidence for the potential benefits of auditory training to provide long-term improvement of perception and neural function has been mixed. A large-scale randomized control trial was conducted to evaluate the effects of supplementing hearing aid use with 10 hours of auditory training with Listening and Communication Enhancement Training (LACE) in 279 veterans and found that LACE training did not result in better outcomes than those obtained with standard-of-care hearing aid intervention alone (Saunders et al., 2016). Another study assessed the effects of 40 hours of auditory-based cognitive training in 29 older adults with and without hearing loss and found that the training improved performance on the QuickSIN and also reduced exaggeration of the speech envelope in older adults with hearing loss (Anderson et al., 2013b). Although the Anderson et al. study suggests that a sufficient number of hours of training may engender neuroplastic changes, the improvement in perception was relatively small and would not be considered clinically significant. It is possible that a behavioral measure of perception obtained in a laboratory setting does not capture training-related improvements that are experienced in real-life settings. Older adults with hearing loss expend more effort to understand speech, especially in noisy settings. An individual who expends considerable effort to understand what is said will not be able to maintain that level of effort over the long term. When effort cannot be sustained, speech perception may decrease and the individual begins to withdraw from the conversation. An objective measure of cognitive effort, such as pupillometry (a measure of pupil size and reactivity), may be a more sensitive assessment of training benefits than measures of speech recognition alone. Kuchinsky et al. (2016) found that twenty 90-minute sessions that trained word recognition in noise resulted in pupillometry changes that reflected a decrease in cognitive effort and improved word recognition in 29 older adults with hearing loss. Many questions remain unanswered regarding the potential for training to improve speech understanding in older adults. Studies are underway to assess the benefits of training that target age-related temporal processing deficits and auditory-cognitive interactions in older adults. A better understanding of training strategies that engender neuroplastic changes in older adults should lead to better outcomes and improved communication and social function in older adults.

Summary

Age-related hearing loss has many potential consequences for the quality of life, including social withdrawal and possible loss of cognitive function. It is therefore important to provide timely audiological assessment and management to individuals who appear to be having difficulty hearing and understanding speech. Nevertheless, aging brings additional challenges to identifying the source of speech-understanding problems, including disruptions in the transmission or processing of speech stimuli that can occur at all levels of the auditory system and the brain. Age-related cognitive decline may also contribute to speech-understanding problems. Therefore, it is imperative to identify and manage hearing loss to minimize the impact of cognitive decline. These disruptions may limit the benefit that can be obtained from hearing aid amplification and auditory training. Research is ongoing to optimize hearing aid technology using neural feedback regarding the listener's focus of attention. The development of effective auditory training programs may also improve hearing aid outcomes. Improved assessment and management protocols should improve the ability of older adults (including your grandmother) to maintain a healthy, active social life despite hearing loss.

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BioSketches

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Statement of Ownership, Management, and Circulation

Publication title:	*Acoustics Today*
Publication number:	1557-0215
Filing Date:	9/18/18
Issue frequency:	Quarterly
No. of issues published annually:	4
Annual Subscription price:	$5
Complete mailing address of known office of publication:	AIP Publishing LLC, 1305 Walt Whitman Road, Suite 300, Melville, NY 11747-4300
Contact person	Waylon Butler 516-576-2278

Full names and complete mailing addresses of publisher, editor, and managing editor:
Publisher: AIP Publishing LLC, 1305 Walt Whitman Road, Suite 300, Melville, NY 11747-4300
Editor: Dr. Arthur N. Popper, Acoustical Society of America, 1305 Walt Whitman Road, Suite 300, Melville, NY 11747-4300
Owner: Acoustical Society of America, 1305 Walt Whitman Road, Suite 300, Melville, NY 11747-4300
Known bondholders, mortgages, and other security holders owning or holding 1 percent or more of total amount of bonds, mortgages, or other securities: None

Tax Status	Purpose, function and nonprofit status of this organization and the exempt status for Federal income tax purposes: Has Not Changed During Preceding 12 Months
Publication title:	*Acoustics Today*

Issue date for circulation data below: July 2018

Extent and nature of circulation:	Average No. of Copies Each Issue During Preceding 12 Months	No. of Copies of Single Issue Published Nearest to Filing Date
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■ If the publication is a general publication, publication of this statement is required. Will be printed in the **Winter** issue of this magazine. ☐ Publication not required.

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Roy Levenson
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Date 9/24/18

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