Hear, Now, and in the Future: Transforming Hearing Aids Into Multipurpose Devices

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New technologies are helping modern hearing aids to better assist those in need and evolve from devices some people need to wear into personal assistants that anyone will want to wear.

The human sensory perception system is remarkable, enabling us to sense and understand the world around us almost effortlessly. Our sensors perform transductions of natural stimuli into electrical signals of neural impulses. A sophisticated computational system in the cerebral cortex of the brain efficiently processes and interprets these sensory inputs. Our perception and cognition systems enable us to build, understand, and track a model of our surroundings.[1] We take actions based on the processing of all this information and continually learn from our experiences (see Figure 1). This process appears so effortless that we tend to take our perceptual capabilities for granted. This is especially true for our sense of hearing. This auditory system enables us to decipher a cacophony of sound waves from multiple sources, decoding a complex mix of signals with information embedded in a wide range of frequencies and intensities.

The human ear is an amazing instrument with incredible capabilities that should awe any engineer. A healthy human ear and the auditory processing system work together to enable us to hear a sound pressure level that is smaller than one-billionth of a variation in the atmospheric pressure. This astounding hearing threshold corresponds to air vibrations on the order of an atomic diameter. On the upper side of the scale, the energy level of the loudest sound we can tolerate is 1 trillion times that of the softest sound we can hear. This incredible dynamic range is enabled by various stages of amplifications as sound waves travel though the ear canal, vibrate the eardrum, and set in motion the three tiny ossicular bones inside the middle ear. This results in a traveling wave

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within the fluid-filled cochlea that gets further amplified by the outer hair cells and ultimately converted into neural pulses by the inner hair cells in the cochlea that are carried toward the auditory cortex by the nerve fibers (Figure 2).

In addition to sound intensity, the frequency range of a healthy human hearing system spans three orders of magnitude, from 20 Hz to 20 kHz, with the highest sensitivities in a range of about 500 Hz to 6 kHz—the typical frequency range of human speech. The cochlea acts as a frequency analyzer, decomposing acoustic waves into narrow frequency bands along its length. This tonotopic arrangement of signal processing is preserved all the way into the auditory cortex, enabling sophisticated sound perception capabilities.

As amazing as our sense of hearing is, its capabilities generally degrade as we age or subject it to unhealthy levels of noise. In fact, hearing loss is the third most common chronic physical condition in the United States and more prevalent than diabetes and cancer.[2]

HEARING LOSS: HEALTH IMPACT AND COMORBIDITIES

Helen Keller, an American author, disability rights advocate, and activist, who was both deaf and blind, noted: "Blindness cuts us off from things, but deafness cuts us off from people." Beyond the loss of communication, untreated hearing impairment adversely impacts people's quality of life, increasing the risk of falls, social isolation, depression, and cognitive decline.[3] In fact, hearing loss was identified as the largest single modifiable risk factor for cognitive decline, which ideally should be addressed midlife for optimal benefit.[3] Furthermore, epidemiologic studies have shown that untreated hearing loss is associated with higher impairment for activities of daily living, including driving, managing medications, ambulation, and bathing.[4]

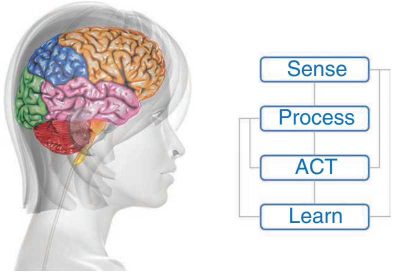


FIGURE 1. The human perception and cognition system, which processes and understands multisensory inputs from our surroundings, guiding our actions and helping us to continually learn from our experiences. (©Shutterstock.com/SciePro.)

Hearing loss is also correlated with many chronic health conditions, including cardiovascular disease (CVD),[5] falls,[6] diabetes,[7] and cognitive decline.[8] Compared to individuals with normal hearing, people with mild, moderate, and severe hearing impairment, respectively, had a two-, three-, and five-fold increased risk of incident all-cause dementia over more than a decade of follow-up.[9] Another study indicated significant memory deficits in people with age-related hearing loss who did not use hearing aids compared to those without hearing loss.[10] However, memory function was significantly better and much closer to the performance of those with normal hearing in a similar group of individuals matched for hearing loss who did use hearing aids.

Empirical evidence increasingly supports the benefits of sound amplification for those with hearing loss, but a number of factors have kept adoption rates low for the past several decades; currently, only one-third of those with hearing loss in the United States wear hearing aids.[11] Why is the adoption rate for hearing aids so low?

HEARING AIDS: A BRIEF LOOK BACK

Early hearing aids, called *ear trumpets*, were created in the 17th century. They amplified sound energy by propagating it through a tubular, funnel-shaped conduit. The German composer Ludwig van Beethoven famously used an ear trumpet [Figure 3(a)]. More recently, hearing aid development paralleled that of the telephone, transistors, and integrated circuits, making devices smaller and more reliable. The creation of the carbon microphone and small, low-power-output transducers transformed hearing aids from large, body-worn instruments to devices that fit entirely on or in the user's ears (Figure 3). By the late 20th century, digitally programmable analog and fully digital hearing aids provided more sophisticated signal processing and greater flexibility to compensate for a wide variety of hearing losses. Wireless connectivity between hearing aids and accessory devices was introduced, and the first commercial devices capable of connecting directly to smartphones were launched in 2014.

Despite these advances in digital technology and wireless connectivity, the stigma associated with hearing loss and the use of hearing aids has remained, in part, because society sees hearing loss (and deafness) as a "disability" rather than a treatable medical condition. In addition, the single-purpose functionality and bulky designs of traditional hearing aids have not helped increase their use. A 2009 BBC article, "Ouch! It's a Disability Thing. The Shame of Wearing Hearing Aids," was accompanied by an image of a typical and clearly visible device of the day (Figure 3). Modern designs integrating new technologies are helping to reduce the stigma of hearing aids as well as endowing them with additional functionalities.

REDEFINING HEARING AIDS: TOWARD MULTIFUNCTIONAL DEVICES

In recent years, there have been significant strides in the design and capabilities of many electronic devices that we use in our daily lives. Enhancements in form factors have facilitated the better integration of technologies in our day-to-day interactions, and innovations in functionalities have significantly expanded their benefits. The introduction of the iPhone in 2007 was followed by relentless functionality upgrades and competitive devices integrating new technologies. This has transformed what was a single-function device, used only for making phone calls, to a multipurpose computer that is a camera, GPS navigator, calendar, web browser, music library and player, and provider of many other applications.

The primary function of the hearing aid is, and will continue to be, to enable users to hear better and understand conversations in a wide variety of situations, thereby supporting more effective participation in social interactions. However, as these tiny devices can now fit comfortably in and around our ears and are always worn, hearing aids can and will provide additional functions and benefits. Built-in Bluetooth radio has become a standard feature for modern hearing aids. Incorporating connectivity enables pairing with smartphones, enabling direct streaming of phone calls, music, audiobooks, podcasts, and other content directly into the ear. In essence, hearing aids can now serve an additional purpose of in-ear sound monitors much like consumer electronic earbuds but with the advantages of being tuned to the user's hearing, having comfortable ergonomics and all-day battery life.

In 2018, we introduced artificial intelligence (AI)-enabled devices, transforming what were more traditional hearing aids into multifunctional health and communication devices with integrated sensors.[23] These devices continuously classify sound and enhance speech intelligibility, stream audio from companion devices and accessories, monitor physical and

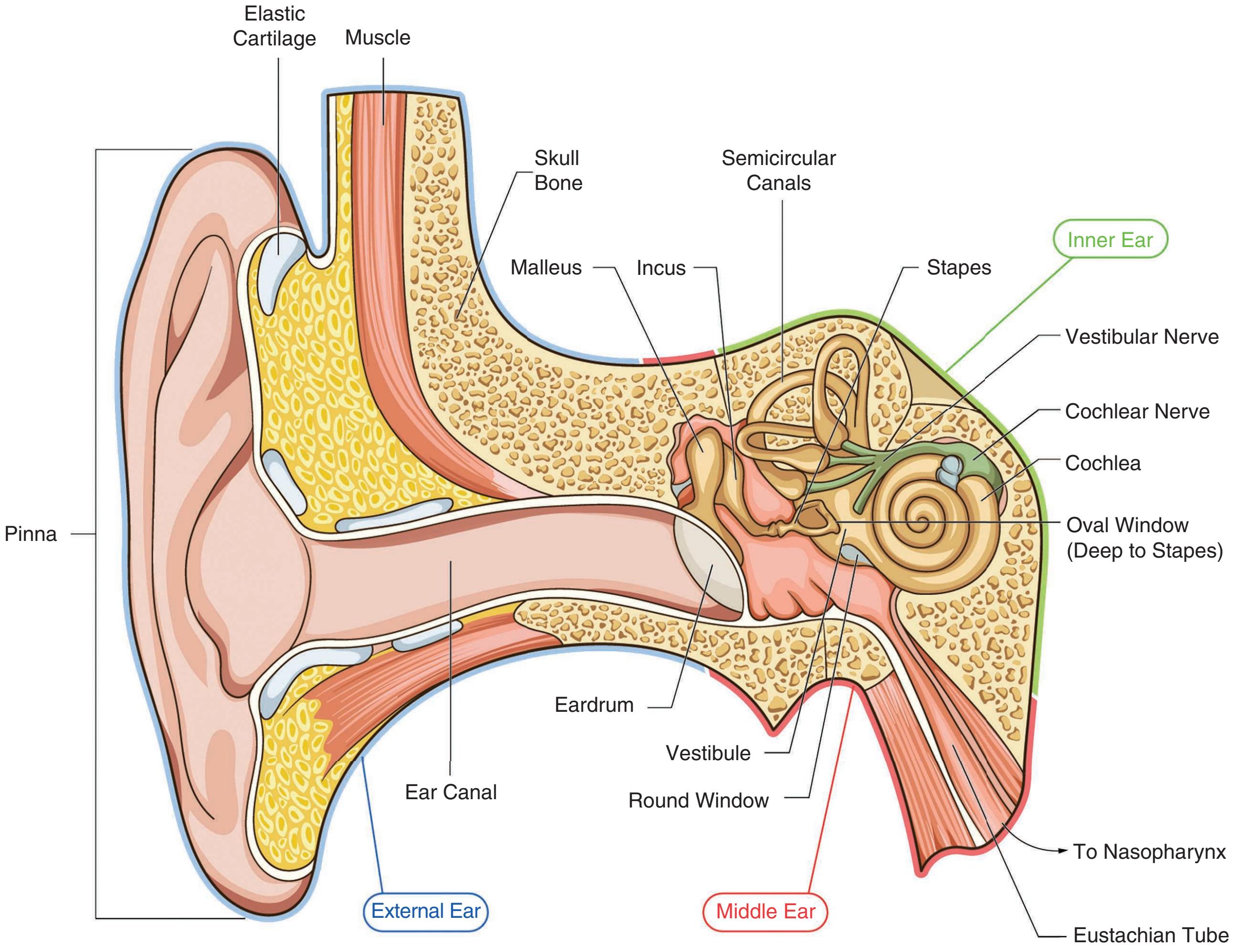


FIGURE 2. The human ear is a marvel of biological evolution that provides an astounding dynamic range of hearing in both the frequencies and intensity levels of sound energies. (©Shutterstock.com/MedusArt.)

cognitive health, automatically detect falls and send alerts, translate languages, and serve as personal assistants with connectivity to the cloud. New technologies and features promise to alleviate the stigma surrounding hearing aids and transform them from devices that one "has to wear" into devices that one "wants to wear."

MODERN DESIGNS AND ACOUSTIC SIGNAL PROCESSING

> *The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it.*[15]

Modern hearing aid designs have taken a significant step in this direction. Benefitting from the miniaturization of key components—microphones, speakers, digital signal processing chips, wireless radios, electronic circuit boards, batteries, and so on—hearing aids have evolved into attractive form factors that can be conveniently, and often discreetly, worn in and around the ears. With years of optimizations, the modern devices are ergonomic and comfortable, enabling wearers to use them all day; indeed, people may forget they have them on. Figure 4 shows state-of-the-art hearing aids representing three design styles: 1) standard postauricular form factors, called *receiver-in-canal devices*; 2) in-the-canal custom devices that are designed to fit the unique ear geometry of the individual wearer; and 3) invisible-in-the-canal devices that are small enough to be placed deep inside the ear canal.

In addition to the advances in mechanical and electrical designs that have led to the modern device form factors, innovations in acoustic system designs and signal processing have been crucial in achieving seamless user experiences. These include smart algorithms based on AI and machine learning that automatically recognize various sound signals from the surrounding environment and can amplify those that enhance understanding and communications while suppressing those that constitute background noise. Directional beamforming can enhance the signal-to-noise ratio (SNR), and binaural audio signal processing can reduce noise and preserve important spatial cues for sound localization. The elimination or significant reduction of audio feedback that can result from the proximity of the microphones and speakers that are embedded in the devices further enhances the audial experience.

Modern hearing aids also incorporate a nonlinear sound amplification algorithm, replicating the auditory processing scheme in a healthy human cochlea. This is implemented via a sound-intensity-dependent expansion–compression algorithm that expands low-level soft sounds by applying higher amplification factors while compressing high-intensity loud sounds by limiting their amplification. The audibility threshold for hearing-impaired patients, which represents the lowest sound levels they can hear, is often much higher than that for people with normal hearing, while the threshold of tolerance for loud sounds stays at similar levels. This causes the dynamic range of hearing for people with hearing loss to reduce substantially. Thus, hearing aids are required to map a wider range of natural sound levels from the environment to a narrower window of sensitivity to tolerance levels for an auditory system with hearing loss. Overall, the goal for hearing aid designs and signal processing algorithms is to ensure an ergonomic and comfortable fit, both mechanically and acoustically, as well as the reduction of listening effort and the associated cognitive load required to understand conversations and other sounds in day-to-day interactions.

AI AND MACHINE LEARNING

In recent years, a new paradigm of computing has gained rapid adoption, one that is based on training systems with data rather than programming them up front with a set of predefined rules. Inspired by the study of human

FIGURE 3. (a) Ludwig van Beethoven's ear trumpet.[12] (b) A Zenith A3A vacuum tube hearing aid (1944).[13] (c) The Sonotone 1010 hearing aid (1952), one of the first devices to use transistors.[14] (d) A typical hearing aid in 2009, referenced by the BBC in an article. (©Shutterstock.com/Andras_csontos.)

perception, cognition, and intelligence, these systems and applications are designed to learn from data, very much like we humans learn from our experiences and the information we glean from our surroundings (Figure 1). This emerging era of intelligent systems based on machine learning was envisioned long ago. A Dartmouth Workshop in 1955 proposed the term *AI*[16] and asserted "Every aspect of learning or any other feature of intelligence can be so precisely described that a machine can be made to simulate it." This vision is now becoming real with the astonishing pace of development in machine learning algorithms, massively parallel computing architectures, and the large-scale digitization of data, enabling numerous autonomous and interactive technologies.[17]

Now, AI is propelling hearing aids into the future, not only by enhancing hearing and intelligibility functions but by adding new capabilities. Based on machine learning technology, hearing aids can decipher which sounds are important and automatically adjust to amplify just those sounds while suppressing background noise. Imagine you are sitting with a friend outdoors at a coffee shop on a busy street. In this environment, there are noises all around you: the conversation you're having, background chatter from other people, traffic noises, and aircraft overhead. Today's hearing aids can make sense of this cacophony by using onboard AI technology. They can separate and identify various sounds, amplify the conversation, enhance speech clarity, and reduce background noise. They give you a superhuman hearing capability.

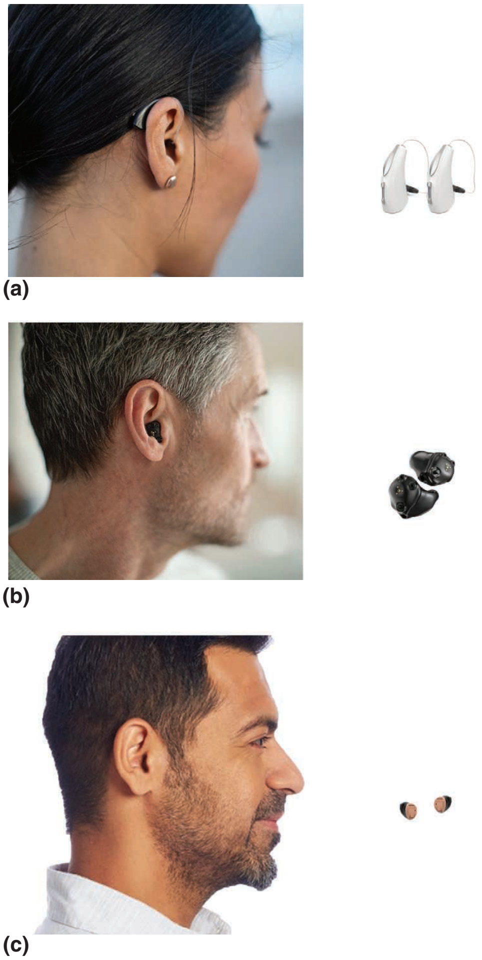


FIGURE 4. With the miniaturization of components and a focus on ergonomic designs, hearing aids have transformed into modern devices, as exemplified by state-of-the-art devices with distinct form factors. (a) Standard postauricular designs, called *receiver-in-canal devices*. (b) In-the-canal custom devices designed to fit the unique ear geometry of the wearer. (c) The smallest hearing aids—invisible devices placed deep inside the ear canal.

ACOUSTIC ENVIRONMENTAL CLASSIFICATION: RECOGNIZING SOUNDS

Derived from auditory scene analysis,[18] acoustic environmental classification (AEC) is a computational process by which signal processing is used to mimic the auditory system's ability to separate individual sounds in real-world listening environments. AEC classifies sounds into discrete "scenes," or environments, that are primarily based on temporal and spectral features.[19] Modern hearing aids use AEC to classify listening environments (for example, quiet places, living rooms, restaurants, auditoriums, and so on) and automatically enable sound management features (for instance, directional microphones, noise reduction, feedback control, and so on) that are the most appropriate.[20] Most AEC systems combine two processing stages: feature extraction and feature/pattern classification followed by postprocessing and environmental sound classification (Figure 5). The accuracy of an AEC system depends on the number of feature parameters, sound classes, and the statistical model that is used.

Supervised machine learning models that have been trained on large, known data sets have been employed to improve classification accuracies. For example, an AEC system we developed features eight automated sound classes: music, speech in quiet areas, speech in loud noise, speech in noise, machines, wind, noise, and quiet. It prioritizes speech intelligibility in noise by making adjustments in the gain, compression, directionality, noise management, and other parameters appropriate for each specific class. The classification accuracy of many hearing aid systems peaks at 80–90%; problems are most likely to arise in the categorization of compressed pop music, strongly reverberated speech, and tonal and fluctuating noises.[21] For this reason, automatic adjustment—even driven by machine learning with large amounts of data—is not always sufficient, especially in challenging listening environments.[22] These situations may be better served by user-prompted, on-demand analysis and automatic adjustments for enhanced speech clarity.

EDGE AI: ENHANCING SPEECH INTELLIGIBILITY

Understanding conversations in noisy environments is difficult for most of us, but it is particularly challenging for hearing-impaired individuals.[33] Beyond automatic acoustic classification and adjustments, aggressive speech enhancement algorithms that are selected and initiated by users can be very helpful when people are confronted with challenging listening situations. Ideally, such a feature should have a simple interface, where the user initiates assistance through a control, such as a double-tap or push button. When so prompted, a hearing aid can capture an "acoustic snapshot" of the listening environment and optimize speech intelligibility by accordingly adjusting parameters.

We developed an on-demand edge AI computing solution to enhance speech clarity. A double-tap gesture on a device is picked up by microelectromechanical system (MEMS)-based motion sensors.[23] The on-demand and adaptive parameter adjustments include gain offsets, noise management settings, directional microphone settings, and wind noise management, to name a few. No smartphone or cloud connectivity is needed; all computational power is achieved through "on-the-ear" processing. Studies have shown[24] that most users found this mode easy to operate and preferred it over audiogram-based prescribed hearing aid settings when communicating in restaurant noise, automobiles, and reverberant environments (Figure 6).

During the COVID-19 pandemic, health and government officials encouraged or mandated community-wide face mask wearing to reduce airborne transmission. This practice, in combination with social distancing, helped slow the spread of the virus, but it also posed a barrier to clear, empathetic communication, particularly for those with hearing loss.[25] We assessed the differences in sound attenuation through face masks via acoustic measurements on many commercially available styles.[26] Figure 7 illustrates the differences for a range of mask types. The data were normalized to a condition where no mask was worn. The results suggested that, while all face masks reduced important high-frequency information, there was significant variation across fabric, medical, and paper masks, especially those equipped with a plastic window. One unexpected finding was that face masks and shields equipped with transparent plastic panels had an enhancement of several decibels in low/mid frequencies, with a reduction in high frequencies. These data illustrate the challenge of using a predetermined compensation scheme with fixed high-frequency gain adjustment to account for the impact of face mask use.

These findings kindled the development of user-activated automatic

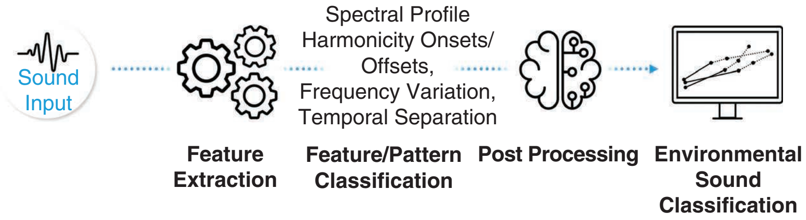


FIGURE 5. An AEC system incorporated in hearing aids for the automatic recognition of sound environments. The architecture includes feature extraction from sound signals captured by embedded microphones, pattern classification with machine learning algorithms, postprocessing, and environmental sound classification.

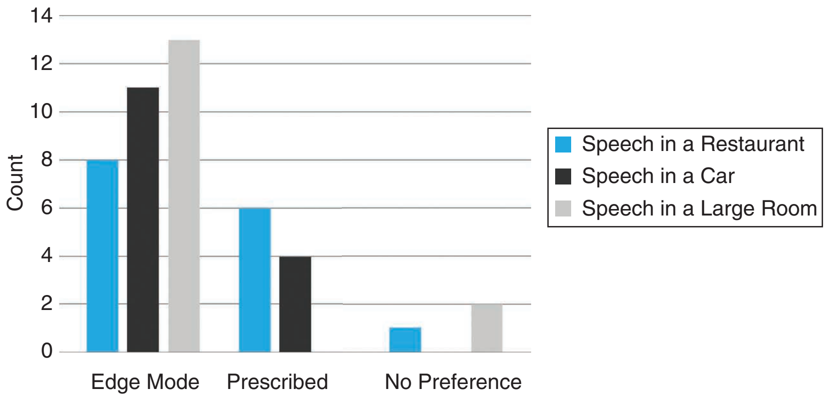


FIGURE 6. The user preferences of 15 hearing-impaired patients for on-demand edge AI technology versus prescribed settings. The legend shows the acoustic scene.

assessment and adjustment for masks in our hearing aids. The original mode uses an onboard AI model trained with machine learning to optimize speech intelligibility and sound quality by assessing levels of speech and noise. The edge mode for masks dynamically adjusts multiple feature parameters, including gain, output, noise management, and directional microphones. Therefore, unlike simple gain offsets used in other "mask mode" programs, this one is "agnostic" to which mask is worn, the distance between communication partners, and the presence of background noise. All required signal processing is performed using ear-level hearing aid computations, with no connection to a smartphone or the cloud. In laboratory testing of hearing aid users, both the AI-actioned adjustment and a "manual" mask mode offset program were significantly preferred by hearing aid users over the "normal" prescription targets when the talker was using a medical-grade N95 face mask. Ongoing research is evaluating whether edge mode for masks will be preferred versus the mask mode offset program when a broader array of face masks is used, similar to those depicted in Figure 7.

In addition to algorithms executed on processors in hearing aids, another emerging speech enhancement strategy is based on deep neural network (DNN) architectures that combine the increased computational processing power available on companion wearable and mobile devices, such as smartphones, with the benefits of using the additional device microphones as input sources when they are closer to the target sound. As a special subcategory within the field of machine learning, DNN architectures use multiple layers of interconnected computational nodes, referred to as *neurons*. Each layer is composed of a large number of neurons representing the "width" of the network. The number of layers defines the "depth." The human cerebral cortex consists of an enormous number of interconnected biological neurons, which enables it to process a multitude of sensory information in a hierarchy of increasing sophistication. In so doing, it teases out complex patterns and correlations and helps people understand and navigate the world. Inspired by the structure and function of the cerebral cortex, DNN-based AI systems are increasingly solving problems that were previously considered tractable only through human intelligence.[17]

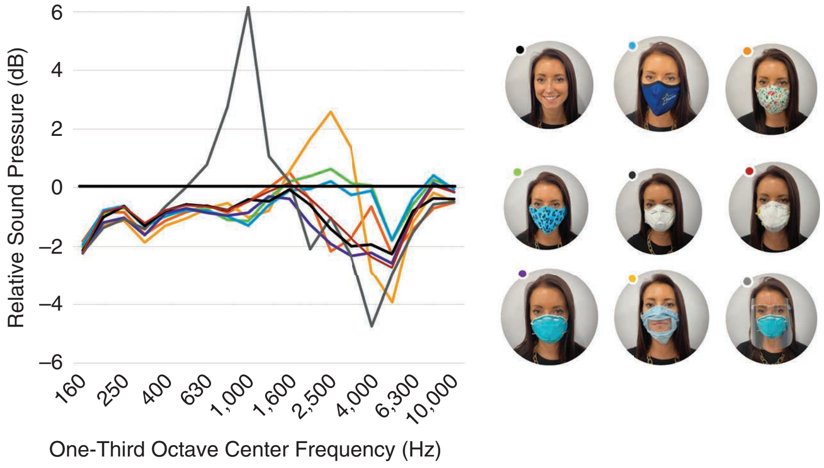


FIGURE 7. The acoustic impacts that different face masks have on attenuating speech signals (colored lines) compared to when no face mask is worn (the reference zero line, in black). The measurements were made using a head and torso simulator manikin.

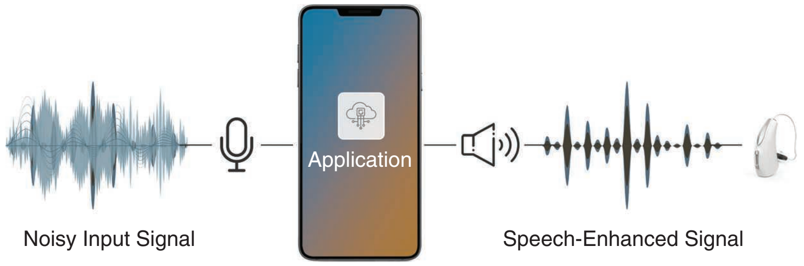


FIGURE 8. Smartphone-based DNN speech enhancement.

Research has demonstrated the value of DNNs for improving speech intelligibility in a wide range of SNRs and noise types while maintaining speech quality.[42, 43] Figure 8 is a high-level schematic of a DNN-based speech enhancement feature introduced in 2020.[44] Field test results demonstrated the overall preference versus hearing aid-only processing for understanding speech in noisy environments for users with hearing losses ranging from mild to profound. Additional analysis revealed a positive correlation between the degree of hearing loss and this algorithm preference. This was most likely due to system delays introduced by "off-boarding" algorithm processing to a smartphone, and it suggests that hearing aid users with greater degrees of hearing loss tolerate increases in signal processing complexity that contribute to system delays if they improve SNRs, while those with better hearing are less likely to tolerate additional lags. As such, this feature is recommended only for users with severe-to-profound hearing loss.

MONITORING HEALTH AND WELLNESS: TRACKING ACTIVITY AND ENGAGEMENT

In addition to improvements in speech intelligibility, embedded sensors and AI are transforming hearing aids into multifunctional health devices. These can detect if the user experiences a fall and automatically send alerts to designated contacts, continuously collect physical metrics, monitor physical activities, and measure social engagement. For several years, inertial measurement unit (IMU) sensors have been built into hearing aids to measure a user's movement, which, in combination with the classification of the listening environment via an AEC system, can be harnessed to monitor physical activity and social engagement. The results can then be displayed on a mobile application (Figure 9).

Why should tracking physical activity be important to hearing? Research suggests that modifiable risk factors for CVD may play a role in developing age-related hearing loss.[5] Daily physical activity tracking has been promoted as a means to reduce cardiovascular risk, and studies have shown that achieving 10,000 steps per day reduces aging individuals' body mass index.[27] A recent study evaluated the efficacy and effectiveness of advanced AI-enabled hearing aids in tracking step counts in real-world conditions. The authors reported that the hearing aids were more accurate than wrist-worn activity tracking devices.[28] Since these devices are more likely to be worn more continuously, their data capture should also show a more complete picture of users' activity levels.

In addition to physical steps, the American Heart Association, the American College of Cardiology, and the American College of Sports Medicine have identified sedentary behavior and physical inactivity as major modifiable CVD risk factors, especially in an aging population. They have advocated reducing CVD risk by promoting 30 min of daily exercise and reducing sedentary behavior.[29] Additionally, the American College of Sports Medicine has recommended that daily flexibility exercises be completed to maintain joint ranges of movement and musculoskeletal strength.[30] To that end, hearing aids can automatically track daily steps, other exercise, and standing (for at least 1 min in a 1-h period) to encourage users to be more physically active.[31]

It has been well established that people who receive benefit from hearing aids will use them on a daily basis. At issue, however, is how much hearing aid use is necessary to achieve potential cognitive and socialization benefits. While research has demonstrated that people who use their hearing aids more than 8 h/day are more satisfied than those who use their hearing aids less,[32] there is little evidence about whether the type of listening environment is important (and predictive) to success. Many people with hearing loss report difficulty understanding speech in the presence of background noise.[33] While communication in noisy environments is a top driver of success with hearing aids,[34] the majority of new hearing aid users wear the devices in generally favorable listening environments.[35] Hearing aid "datalogging" has been recommended to identify those who are not using, or only minimally using, their aids so that clinicians can provide appropriate rehabilitation and support, particularly for new users.[36] Although datalogging provides an objective measure that is a more accurate representation of hearing aid use than "self-report" measures, which are often overreported,[37] it also requires clinical intervention via face-to-face and telehealth appointments.

Accordingly, we incorporated measures of "social engagement" that automatically monitor and report 1) hours of daily hearing aid use; 2) time spent in listening environments where speech is present, either in quiet or noisy backgrounds; and 3) the diversity of listening environments encountered during each 24-h period, classified by machine learning algorithms.[31] By displaying a daily social engagement score directly in an app, this simple tool empowers hearing aid users to challenge themselves to use their devices and communicate with others in a wide variety of quiet and noisy environments. Users can even designate family members and professional caregivers to monitor daily progress in real time via a companion application.[38] The systems and methods for collecting and presenting user data are architected with strict

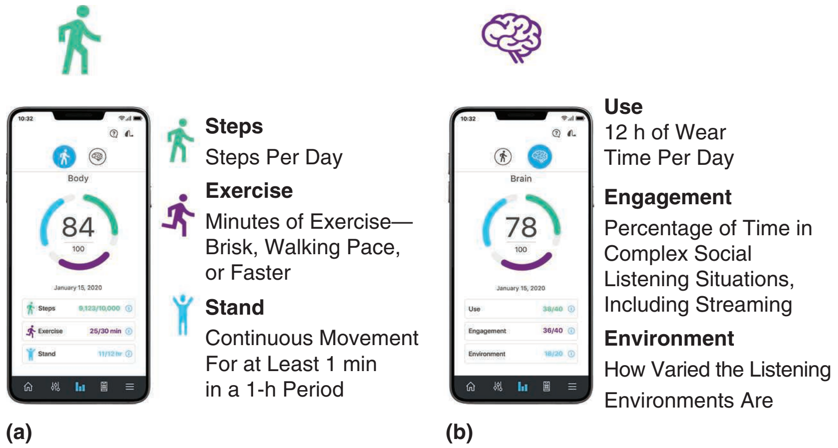


FIGURE 9. Advanced hearing aids with embedded MEMS accelerometers quantify and track physical activities and social engagements. (a) A "body score" is based on steps, exercise, and standing, and (b) a "brain score" is calculated from hearing aid use, engagement, and environments.

security and privacy protocols and in compliance with legal and ethical requirements. These patient-centered tools may encourage people to use their hearing aids in difficult listening environments more often. They also can provide clinicians with the information they need to better optimize hearing aids for a wider range of situations.

AUTOMATIC FALL DETECTION AND ALERTS

Approximately 40% of adults 65 and older fall once or more per year, resulting in serious morbidities, mortality, and health-care costs.[39] In addition, studies have reported a significant positive association between the severity of hearing loss and reports of falls, even when adjusting for demographic, cardiovascular, and vestibular balance function.[6] Forward and backward falls, trips, slips, and falls to the side have all been frequently observed in aging adults.[40] We have developed an ear-level fall detection algorithm using IMU sensors embedded in custom and standard hearing aids that are designed to be highly sensitive to these events (Figure 10). Once a hearing aid detects a fall, an alert is automatically sent to previously designated contacts. If the wearer has recovered and does not need help, the alert can be promptly canceled. A recent study evaluated the sensitivity and specificity of the fall detection algorithm based on the acceleration rate, estimated falling distance, and impact magnitude for bilateral hearing aids compared to a commercially available, neck-worn personal emergency response system.[41] On average, the ear-worn fall detection system had comparable or higher sensitivity and specificity rates than the pendant in laboratory conditions simulating forward and backward falls and near falls (Figure 11).

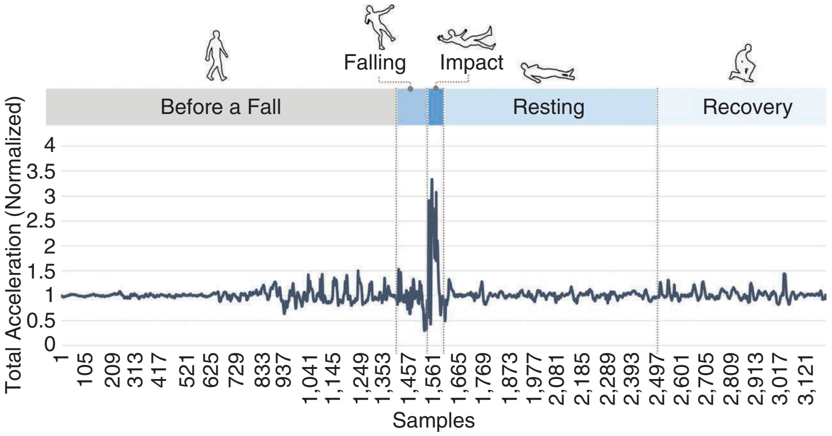
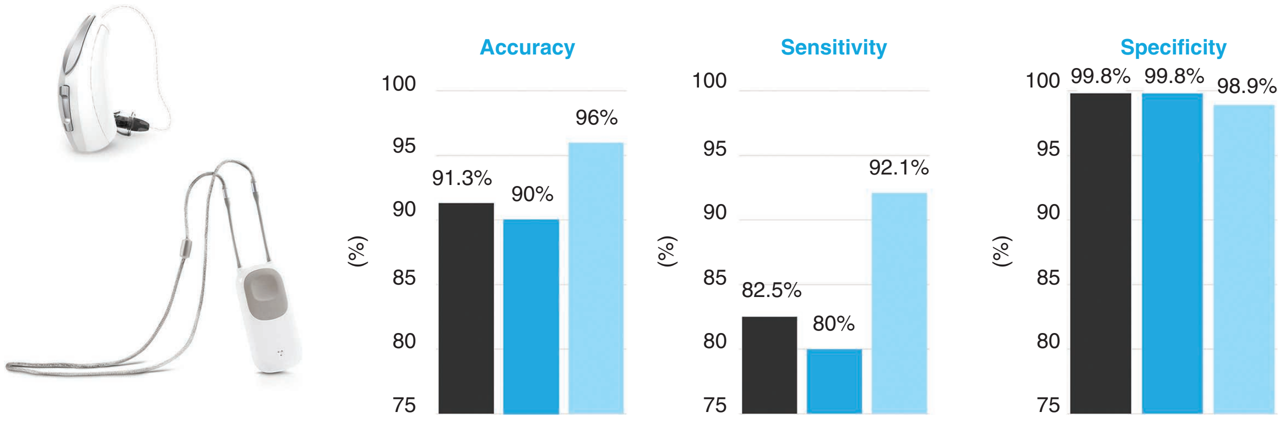


FIGURE 10. The automatic detection of a fall based on real-time analysis of MEMS accelerometers embedded within advanced hearing aids. After a fall is detected, an alert message is sent to designated contacts via a smartphone.



Device	Accuracy (%)	Sensitivity (%)	Specificity (%)
⬛ AutoAlert Pendant	91.3	82.5	99.8
🟦 Livio Edge AI (Normal Sensitivity)	90	80	99.8
🟦 Livio Edge AI (High Sensitivity)	96	92.1	98.9

FIGURE 11. The measured fall detection accuracy, sensitivity, and specificity for a neck-worn pendant (AutoAlert) versus Livio Edge AI hearing aids with normal and high-sensitivity settings.

These data suggest that hearing aids with fall detection technology may provide a suitable alternative to more traditional devices, affording hearing-impaired patients a potentially lifesaving feature without requiring additional equipment to be worn and maintained.

PERSONAL VIRTUAL ASSISTANT: TOWARD OMNISCIENCE IN THE EAR

A high-tech in-ear communication device that gives the wearer access to a private, all-knowing virtual assistant that immediately answers questions and can translate languages has long been a dream of sci-fi fans and techies. Now, it is becoming a reality. Advanced hearing aids incorporate personal assistant technology that can be activated by a simple double-tap on the ear. Users can ask general questions, troubleshoot hearing aid issues, speak commands to change the hearing aid volume, mute hearing aids, change memories, and set reminders for medications and other tasks. Hearing aids incorporating personal assistants utilize natural language processing technology with powerful machine learning algorithms running on servers in the cloud. This enables wearers to use conversational language, such as, "What's the weather today?" and, "Who won the Super Bowl in 1982?" Settings can be controlled by simply saying, "Turn up my hearing aids" or, "Increase the volume of my hearing aids." Users can even say things like, "Find my phone" or, "I lost my phone," and the virtual assistant will help locate a misplaced smartphone by ringing the device, even if it is locked or in silent mode.

While it is convenient to have an in-ear personal assistant that discreetly answers questions, presents information, and facilitates controlling devices with natural voice commands, automatic medication reminders could save lives. According to the World Health Organization, adherence to chronic medication is only about 50%, resulting in ~125,000 deaths and up to 25% of hospitalizations, costing the U.S. health-care system ~US$300 billion annually. Connectivity to cloud computing resources via smartphones also enables hearing aids to present an ear-worn language translator. Current devices support 27 languages, with the target one spoken discretely into the ear after near-real-time translation. Wearers can also choose to have a spoken language transcribed onto a smartphone screen, which can help them understand conversations in challenging environments. While we are still some way from achieving the versatile capabilities of an omniscient assistant, such as JARVIS ("Just A Rather Very Intelligent System") of the Marvel *Iron Man* movies, the personal assistant available with current-generation hearing aids provides a glimpse of the future to come.

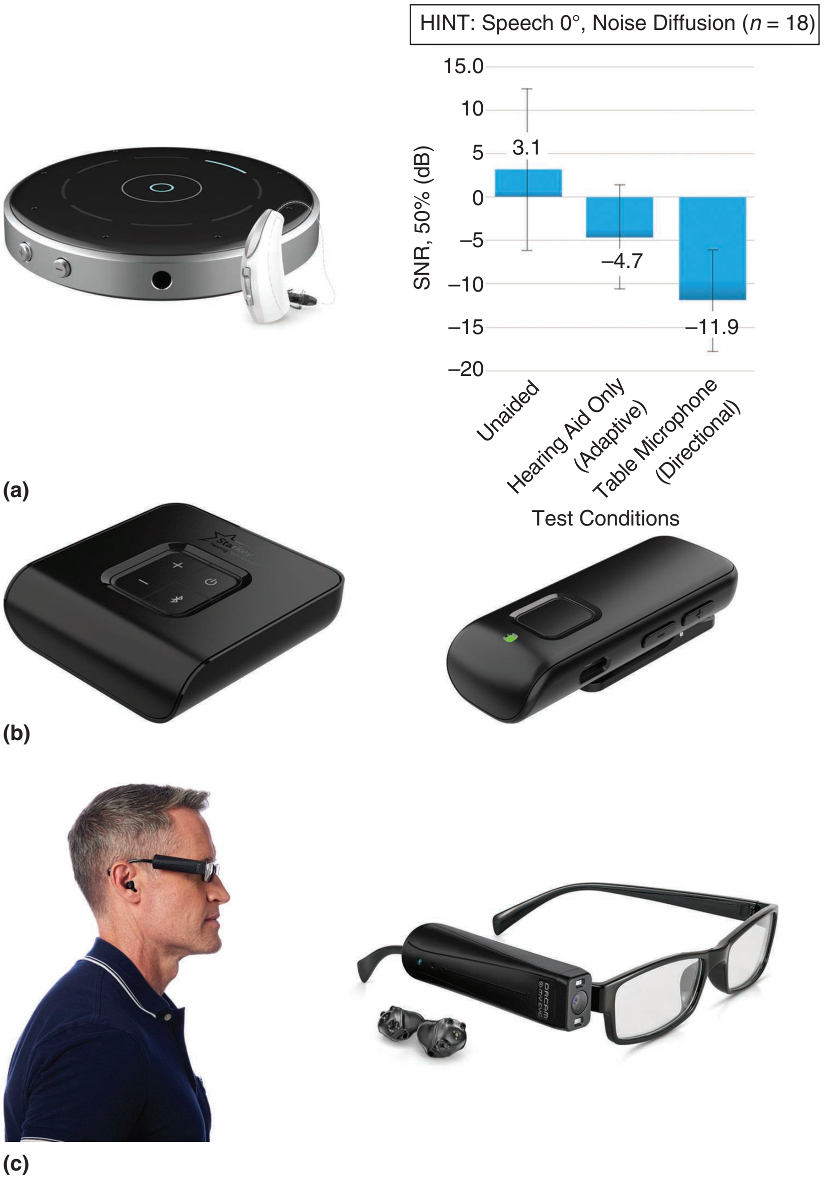


FIGURE 12. Modern hearing aids with embedded connectivity technologies have become part of an ecosystem of connected devices. Examples include (a) directional and remote microphones, (b) television streamers, and (c) vision aids.

ECOSYSTEM OF CONNECTED DEVICES

In addition to the smartphones that serve as gateways to the cloud, the integration of connectivity technologies has enabled modern hearing aids to become part of an ecosystem of connected devices. Examples of accessory devices include remote microphones, television streamers, and vision aids (Figure 12). Speech understanding in noisy environments is a major challenge for many individuals with sensorineural hearing loss, and sometimes hearing aids alone are not enough, even with directional microphones, AEC, and AI. To address this, manufacturers have started incorporating machine learning and edge computing in hearing aids to improve speech intelligibility in noise by using new multipurpose wireless accessories[45] employing as many as eight spatially separated microphones and sophisticated directional beamforming technology to divide listening environments into segments. In "automatic" mode, a table microphone can dynamically switch the direction of its beam to focus on the active speaker in a group while simultaneously reducing competing background speech and noise from other directions. In "manual" mode, the user can opt to focus on one or two speakers in a group and change the direction of the beam or beams by simply touching the top of the device. In "surround" mode, all microphones are active, and sound is amplified from every direction. Automatic and manual modes are optimized for listening to speech in noise, and surround mode is primed for listening to speech in quiet conditions.

> The integration of connectivity technologies has enabled modern hearing aids to become part of an ecosystem of connected devices.

A table microphone provides the best listening benefit when placed at the center of a group or close to a single conversational partner. In one laboratory study, 18 participants with hearing loss completed a speech intelligibility test while unaided, helped by AI custom rechargeable hearing aids alone, and assisted by a table microphone. As shown in Figure 12, the table microphone had a median SNR improvement for the Hearing in Noise Test of 7.2 dB compared to hearing aids alone and a 15-dB SNR improvement compared to the unaided condition. Depending on the speech stimulus, this may translate into 50% or more improvement in speech understanding in challenging environments. Where table microphones can be directly paired with hearing aids, there is no need for smartphones and cloud-based computing.

Earlier, we discussed the comorbidity between hearing loss and other important health conditions. Recent work[46] has assessed the relationship of common, frequently coexisting, sensory and cognitive impairments with various health states and found that particular combinations of visual, auditory, and cognitive declines relate in distinct ways to different types of disabilities, self-rated overall health, and mortality. Because hearing loss and vision often provide complementary inputs necessary for speech understanding (using acoustic information and lipreading cues), research has also focused on systems that can integrate auditory and visual information, pairing AI hearing aids with wearable cameras via wireless connections to provide hearing enhancement and audio descriptions of the visual world at the same time.[47]

By helping to alleviate the third most prevalent chronic physical health condition and enabling people to hear better and communicate more effectively, hearing aids are crucially important medical wearable devices. However, their adoption has historically been low, in part due to stigma associated with assistive technologies and the single-purpose nature of traditional devices. In this article, we reviewed the recent developments that are transforming hearing aids into multifunctional connected health and communication devices with embedded sensors and AI technologies. With modern ergonomic designs, improved sound quality and enhanced speech intelligibility, passive and continuous health monitoring, and personal assistants as gateways to the vast world of information in the cloud, modern hearing aids are morphing from devices one needs to wear into devices one wants to wear.

So, what is next? Further advances in AI technology will bring unprecedented levels of speech intelligibility in challenging listening environments. Modern hearing aids can already track your health, but in the future, they will be able to alert you to health issues before they happen. Imagine a hearing aid that can track your heart rate and core body temperature, sense when your blood oxygen levels are low, and send you a message before the issue becomes a serious health emergency. Hearing aids of the future could also sense your moods, detect the onset of anxiety and depression, and alert caregivers and loved ones for early intervention and help.

Tomorrow's hearing aids will know what you need before you do. Seamlessly integrated within an ecosystem of technologies that sense, compute, and connect, what we now know as hearing aids will become increasingly more sophisticated and versatile conduits to information, serving as our ubiquitous personal assistants. As our understanding of the human sensory perception system continues to deepen and sensory augmentation technologies continue to advance at a rapid pace, we may be on the verge of attaining superhuman sensory, perceptual, and cognitive abilities beyond the natural limits of our biological systems. No matter how these technologies and their uses evolve, it is clear that devices worn in and around our ears will play a crucial role in enhancing our lives and experiences.

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