Hearing Aids Can't Solve the Cocktail Party Problem—Yet

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The Cocktail Party Problem

It is Saturday and you look forward to dinner at your favorite restaurant. The evening is perfect, and you walk through the candlelit garden to join your friends inside. The menu looks exciting and the wine choices are exquisite. What could go wrong? You find out as soon as the restaurant starts filling up. The hubbub around you becomes overwhelming and stops you from conversing with your companions. This failure to solve the "cocktail party problem" (Cherry, 1953) is a common consequence of hearing loss.

What Hearing Loss Is Like

Most young people with normal hearing cope remarkably well in a noisy restaurant or at a cocktail party. They can selectively listen to the person they want to hear (the "target") and ignore the background sounds, and, in essence, solve the cocktail party problem. However, the functioning of the auditory system tends to worsen with increasing age (Anderson et al., 2018) and with exposure to noise and certain chemicals, and this is associated with greater difficulty at the cocktail party.

The most common measure of hearing function is the audiogram, which is the minimum sound level required to detect sinusoids with different frequencies, usually ranging from 0.125 to 8 kHz. The thresholds are specified relative to the average threshold at each frequency for young people with no known hearing problems and have units of decibels hearing level (HL) (Le Prell, 2018). Thus, a person with normal hearing would have thresholds close to 0 dB HL at all frequencies. The most commonly used overall measure of hearing is the pure-tone average (PTA) threshold across 0.5, 1, 2, and 4 kHz, which are the frequencies that are most important for speech perception. The boundary between normal and impaired hearing is usually taken as a PTA of 15 or 20 dB HL, although hearing losses of less than 15 dB are associated with deficits in the ability to understand speech in noise (Smoorenburg, 1992).

There are several methods of classifying the severity of hearing loss. A common one in the United States, based on the PTA, is slight (16-25 dB HL), mild (26-40 dB HL), moderate (41-55 dB HL), moderately severe (56-70 dB HL), severe (71-90 dB HL), and profound (>91 dB HL) (Clark, 1981). However, the descriptors do not accurately reflect the degree of difficulty experienced in everyday life (Clark, 1981). Because of this, self-reported listening difficulty is also important. About 10% of people who go to a clinic complaining of hearing problems turn out to have "normal" audiograms (Parthasarathy et al., 2020).

In 2019, about 20% of the world's population had a PTA >20 dB HL (Haile et al., 2021). This percentage is increasing as a result of longer life spans and greater exposure to recreational noise (Olusanya et al., 2019).

Hearing and Types of Hearing Loss

Hearing loss can result from dysfunction of several parts of the auditory system. **Figure 1** shows the structure of the peripheral part of the human auditory system.

Transmission of Sound to the Cochlea and Conductive Hearing Loss

Sound travels down the auditory canal and causes the eardrum to vibrate. These vibrations are transmitted through the middle ear by three bones, the malleus, incus, and stapes, to the oval window, a membrane-covered opening in the bony wall of the inner ear. The part of the inner ear concerned with hearing is the spiral-shaped cochlea. The stapes lies on top of the oval window. When the oval window moves inward, a second

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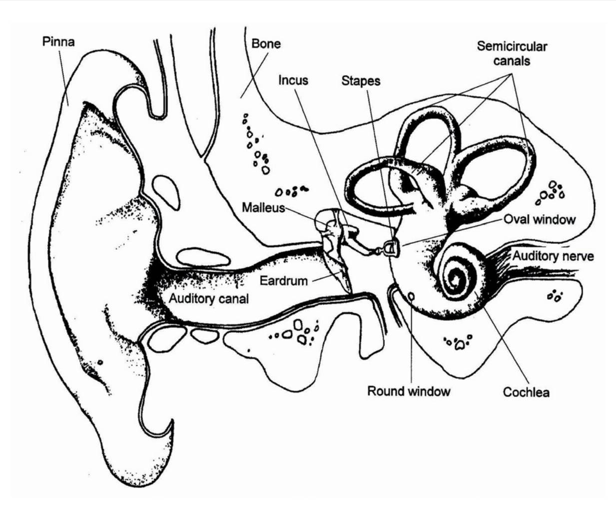


Figure 1. *Schematic illustration of the outer, middle and inner ears. Reproduced from Moore (2012), with permission.*

membrane-covered opening, the round window, moves outward, and vice versa. The middle ear ensures the efficient transfer of sound from the air to the fluids in the cochlea by acting as an impedance-matching device.

"Conductive" hearing loss occurs when sound is not conducted effectively to the cochlea because of wax in the ear canal, infections of the outer or middle ear, or the growth of bone in the middle ear. Conductive hearing loss is similar to an attenuation of the sound. It is often treated with medicines or surgery, usually with good hearing outcomes.

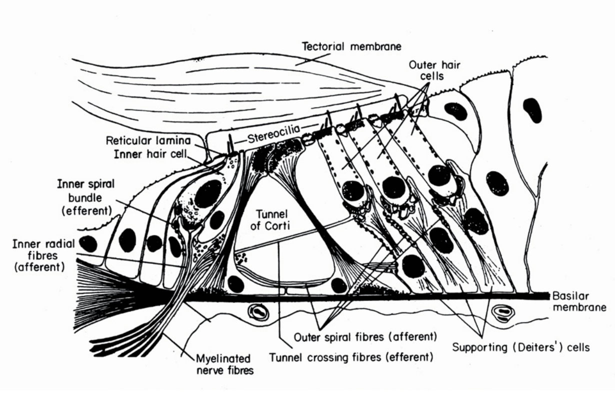
Analysis of Sound in the Cochlea and Sensorineural Hearing Loss

The most common type of hearing loss, sensorineural hearing loss, is caused by dysfunction of the cochlea or the auditory nerve. This can lead to several types of perceptual deficits, only some of which are compensated by hearing aids. **Figure 2** shows a schematic cross section of the cochlea. The cochlea is filled with almost incompressible fluids and has bony rigid walls. It is divided along its length by the basilar membrane (BM). Two types of sensory hair cells run along the BM, the outer hair cells (OHCs) and inner hair cells (IHCs), both of which have tiny hairlike tufts at their tops called stereocilia. The tectorial membrane runs along the tops of the OHCs and IHCs. The region bounded by the BM, OHCs, IHCs, and tectorial membrane is called the organ of Corti. The end of the cochlea near the oval window is called the base and the other end is called the apex. When the oval window moves, a pressure difference is applied across the BM, causing it to move. The response to sinusoidal stimulation is a wave that moves along the BM from the base toward the apex. The amplitude of the wave increases at first and then decreases. At the base, the BM is narrow and stiff, whereas at the apex, it is wider and much less stiff. Consequently, high-frequency sounds produce maximum displacement of the BM near the base, whereas low-frequency sounds produce maximum displacement toward the apex. The frequency that evokes the maximum response at a given point on the BM is called the "characteristic frequency" (CF).

Each neuron of the auditory nerve is connected via a synapse to a specific IHC. When the BM vibrates, there is a sideways movement of the stereocilia of the IHC that depends partly on vibrations on the top side of the organ of Corti (Altoè et al., 2022). As a result, an electric current flows through the IHC, leading to release of a neurotransmitter at the synapse and the initiation of "spikes" in the auditory nerve. Each neuron also shows tuning and has a CF. In a normal healthy ear, each point on the BM and each neuron are sharply tuned, responding with high sensitivity to a limited range of frequencies. The sharp tuning and high sensitivity depend on an active mechanism involving movements of the OHCs (Robles and Ruggero, 2001).

Dysfunction of the OHCs is common following noise exposure or with increasing age (Wu et al., 2021; Wu

Figure 2. *Cross section of the cochlea, showing the basilar membrane, the tectorial membrane, and the organ of Corti. Reproduced from Moore (2012), with permission.*



and Liberman, 2022). This impairs the operation of the active mechanism, with three main consequences. First, it reduces the amount of BM vibration around the peak of the vibration pattern, especially for low-level sounds, resulting in an elevation in the pure-tone threshold as measured by the audiogram.

A second consequence of OHC dysfunction is reduced frequency selectivity. This is the ability to "hear out" or resolve the sinusoidal components of complex sounds. For example, if you simultaneously strike two tuning forks tuned to different frequencies, such as 256 and 440 Hz, you hear two separate tones, each with a distinct pitch. This ability depends on the tuning that occurs on the BM; each point can be regarded as a band-pass filter. In a normal ear, these filters, often called the auditory filters, have bandwidths at medium and high CFs that are 12-13% of the CF (Glasberg and Moore, 1990). Dysfunction of the OHCs causes the filters to broaden by a factor up to four (Moore, 2007), thereby reducing the ability to determine the spectral shape of sounds, which is important for distinguishing speech sounds and for understanding speech in background sounds (Baer and Moore, 1994). It also reduces the ability to hear out individual musical instruments or groups of instruments in a mixture (Madsen et al., 2015).

A third consequence of OHC dysfunction is related to the fact that, in a normal ear, the response on the BM is a compressive function of the input level for frequencies close to the CF. For example, a 10 dB increase in input level may produce only a 2.5 dB increase in response on the BM (Robles and Ruggero, 2001). This compresses the large range of sound levels encountered in everyday life (about 120 dB) into a much smaller range of responses on the BM, reducing "saturation" of the responses of the neurons in the auditory nerve. This allows us to hear over a wide range of levels, from the rustling of dry leaves to a loud rock band. OHC dysfunction reduces or abolishes the compression on the BM, and this reduced compression is thought to contribute to an effect called loudness recruitment (Moore, 2004). Once the sound level exceeds the detection threshold, the loudness grows more rapidly than normal with increasing sound level. At high-sound levels, the loudness for an ear with OHC dysfunction "catches up" with the loudness for a normal ear. Consequently, a person with OHC dysfunction can only hear comfortably over a small range of sound levels; this is described as having a reduced dynamic range.

There may also be dysfunction of the IHCs, the synapses that connect the IHCs to the neurons of the auditory nerve, and of the neurons themselves. Synaptic dysfunction, called synaptopathy, is associated with noise exposure (Kujawa and Liberman, 2009; Wu et al., 2021) and increasing age (Wu et al., 2021). Following synaptopathy, the auditory nerve may degenerate, although in humans, this can take many years. Unless the dysfunction is extreme, it has little effect on the audiogram because only a few nerve spikes are sufficient for a sound to be detected (Lobarinas et al., 2013). This type of dysfunction has been called "hidden hearing loss" (Schaette and McAlpine, 2011) or "hidden hearing disorder" (Moore et al., 2019) because its effects are not apparent in the audiogram. Synaptopathy reduces the number of neurons conveying information from the ear to the brain, leading to a more "noisy" representation of sounds, and this may result in a lack of clarity of speech, especially in noisy places.

One aspect of perception that may be especially affected by IHC/synaptic/neural dysfunction is sensitivity to "temporal fine structure" (TFS). The output of each auditory filter can be thought of as an envelope, the slow changes over time in the amplitude of the vibration of the BM, superimposed on the TFS, the rapid fluctuations in instantaneous amplitude (Moore, 2014). The TFS is reflected in neural phase locking; the nerve spikes are synchronized to a specific phase of the waveform on the BM, at least for frequencies up to 4-5 kHz. When the number of neurons conveying phase-locking information is reduced, this may impair the ability of the central auditory system in the brain to "decode" the TFS information. In addition, OHC dysfunction can change the tuning of a given place on the BM in such a way that the patterns of TFS information become distorted (Henry and Heinz, 2012), making it harder to discriminate speech sounds, especially in background noise (Moore, 2014). Information about TFS may also be important when trying to focus on one talker in a multitalker background (Hopkins and Moore, 2009). Finally, TFS information can be compared across ears, which contributes to the ability to localize sounds and to understand speech in the presence of spatially distributed interfering sounds. This ability worsens with increasing age and increasing hearing loss (Moore, 2021).

Near-complete IHC/synaptic/neural dysfunction results in a “cochlear dead region” (DR) (Moore, 2001). No information is sent to the brain from a DR. However, a sinusoid that produces maximum BM vibration in a DR may be detected if the sinusoid produces sufficient vibration in an adjacent functioning region, something called “off-frequency” or “off-place” listening. A hearing loss of 70 dB or more at a given frequency is often associated with a DR at the place on the BM tuned to that frequency, but a DR cannot be reliably diagnosed from the audiogram (Vinay and Moore, 2007). An extensive DR is associated with a very poor ability to understand speech, even in quiet situations, and is also associated with a limited benefit from hearing aids (Vickers et al., 2001; Baer et al., 2002).

How Hearing Aids Work

Hearing aids usually contain the following components (Moore and Popelka, 2016):

(1) One to three microphones to pick up the sound;
(2) Each microphone is connected to a preamplifier followed by a low-pass filter;
(3) An analog-to-digital converter that periodically samples the voltage at the output of each filter and converts it into a numerical value. The number of samples per second (sampling frequency) needs to be at least double the highest frequency that it is desired to transmit (i.e., the low-pass filter cutoff frequency). In modern hearing aids, the sample frequency is usually about 20,000 samples per second;
(4) A miniature computer that processes the digitized sound;
(5) A miniature loudspeaker, confusingly called a “receiver,” that converts the digital output of the computer to sound;
(6) A battery; and
(7) A casing to accommodate the components that fits behind the ear or in the ear canal.

Styles of Hearing Aids

Figure 3 shows the common hearing aid styles. When all of the components are housed in a single case, this is called in the ear (ITE) if the case is partly in the bowl of the pinna (**Figure 3A**) or completely in the canal (CIC) if the case fits completely in the ear canal (**Figure 3B**). The most common style is behind the ear (BTE) (**Figure 3C**), where the case is placed behind the pinna. For this style, the microphones are just above the pinna. In the “receiver-in-the-ear” (RITE) style, the case is also behind the pinna, but the receiver is inside the ear canal (**Figure 3D**). The RITE style does not generally require a custom-made earmold or shell, whereas the ITE and CIC styles usually, but not always, involve a custom-made shell.

Figure 3. *Illustration of the main styles of hearing aids.* ***a:*** *In the ear;* ***b:*** *completely in the canal;* ***c:*** *behind the ear;* ***d:*** *receiver in the ear canal. From Moore and Popelka (2016), with permission of Springer Cham.*

What Do Hearing Aids Do?

Compensation for Threshold Elevation and Loudness Recruitment

Hearing aids incorporate signal processing to compensate for reduced sensitivity to soft sounds and loudness recruitment. Usually, this is done by filtering the sound into several frequency bands or “channels” and applying independent automatic gain control (AGC) to the signal in each channel (Kates, 2005). This allows for the fact that the amount of hearing loss of an individual varies with frequency, often being greater at high than at low frequencies. With AGC, weak sounds are strongly amplified to restore their audibility, but the amplification is progressively reduced as the sound level increases. This partially compensates for the effects of loudness recruitment.

The amplitude compression produced by the active mechanism in a normally functioning cochlea is very fast acting (Cooper and van der Heijden, 2016), in that the amplification changes rapidly with changes in the input sound level. It might be expected that the AGC in hearing aids would be most effective if it was also fast acting. However, despite many research studies, there is no clear consensus as to whether fast or slow compression is preferable (Moore, 2008). Indeed, based on the subjective judgments of hearing-impaired people, it appears that slow AGC is slightly preferred over fast AGC for listening to music but preferences for speech are less clear (Moore and Sęk, 2016).

Multichannel AGC does not compensate fully for the effects of threshold elevation and loudness recruitment. The amplification of soft sounds is usually not sufficient to fully restore their audibility, and slow-acting AGC does not compensate adequately for rapid fluctuations in level, such as can occur in music. Hence, dynamic changes in music can appear exaggerated, and users of hearing aids still complain that some sounds are too loud (Madsen and Moore, 2014).

The number of compression channels does not have a strong influence on the ability to understand speech in quiet or in noise (Salorio-Corbetto et al., 2020). However, the filtering of the input signal into channels is also used for other forms of signal processing, such as noise reduction, as described in the section ***Partial Compensation for Reduced Frequency Selectivity and Other Deficits***. For such processing, it can be beneficial to have many channels. The filtering is often done using the fast Fourier transform (FFT) to process the signal in short overlapping time frames (Allen, 1977). The longer the time frame, the greater the sharpness of filtering. However, long time frames involve greater time delays and if the delay is greater than about 10 ms, it can have deleterious effects on speech production and perception (Stone et al., 2008). In practice, the time delay of modern hearing aids is in the range 0.5 to 10 ms. This limits the sharpness of the filtering that can be achieved and also limits the number of channels.

Partial Compensation for Reduced Frequency Selectivity and Other Deficits

Hearing aids do not compensate directly for reduced frequency selectivity or for the effects of IHC/synaptic/neural dysfunction. At best, they achieve partial compensation for these effects by improving the speech-to-background ratio. This is done in two main ways: (1) using directional microphones and (2) using noise-reduction algorithms (NRAs).

Directionality is often achieved using the two microphones within one hearing aid. The signal picked up by one microphone is delayed and combined with the signal from the other microphone. Manipulation of the delay leads to different patterns of directionality (Launer et al., 2016). In addition, signals can be transmitted wirelessly between bilaterally fitted aids, and all four microphones of the two hearing aids can be used to create high directional selectivity (Launer et al., 2016). Such systems are called binaural beamformers, by analogy with a beam of light that is pointed at an object of interest.

Usually, it is assumed that the user of hearing aids will face toward the target so the beamformer is pointed toward the front. However, people do not always want to listen to someone directly in front of them and so some beamformers can steer the beam in different directions. Additionally, because background sounds and targets can move, *adaptive* beamformers have been developed that change their directionality patterns, usually so as to select the most prominent talker (Launer et al., 2016; Kollmeier and Kiessling, 2018). Adaptive directional systems improve speech understanding and/or ease of listening in a range of situations, but the benefits vary depending on the type of environment, the technical implementation, the type of background, and the auditory skills of the individual (Best et al., 2015).

NRAs are most effective when the background is dominated by noise (e.g., from ventilation or machinery) rather than by people talking. NRAs attempt to estimate the signal-to-noise ratio (SNR) in each channel using information such as the amount or pattern of amplitude modulation of the channel signal (Launer et al., 2016; Kollmeier and Kiessling, 2018). In one approach, the gain is maintained for channels with a high estimated SNR but is reduced for channels with a low SNR (Holube et al., 1999). Alternatively, the estimated noise signal is subtracted from the speech plus noise in each channel (Kollmeier and Kiessling, 2018). Such NRAs have been shown to make the sound more pleasant, but they have not been clearly shown to improve speech intelligibility.

Applications of Deep Learning

NRAs are currently being transformed by advances in machine learning, based on deep neural networks (DNNs). DNNs require training. For example, if it is desired to improve the SNR, the DNN is trained by providing as input many samples of noisy speech and the corresponding clean speech (without noise). The clean speech is the "training target." After training, the DNN can process noisy speech to extract clean speech. To ensure that the DNN is effective in practice, it must be trained using many talkers, types of background, and SNRs. DNNs have been shown to be effective for speech in noise (Healy et al., 2013; Keshavarzi et al., 2018), speech in the presence of a single competing talker (Healy et al., 2017; Bramsløw et al., 2018), and even for separating talkers in a multitalker background in reverberant environments (Lesica et al., 2021). Of course, in multitalker environments, it would also be necessary to select the target talker, and this is a difficult task. Although much current research is aimed at "cognitively controlled" hearing aids, where the target talker is selected based on sound-evoked brain electrical potentials, this research is still far from practical application.

The DNNs used in many laboratory studies require more memory storage and processing power than is currently available in hearing aids, and some involve time delays exceeding 10 ms. For implementation in current hearing aids, the architecture must be simplified and the time delay reduced. We are aware of only one manufacturer that incorporates a DNN to process speech in noise in some of their hearing aids. This DNN was trained to attenuate nonspeech background sounds while preserving speech sounds from all directions (Andersen et al., 2021).

Sound Classification

Many hearing aids incorporate methods of classifying the sound environment, for example, speech in quiet, speech in noise, music, or low reverberation versus high reverberation. In some cases, this is done via simple DNNs. The signal processing in the hearing aid is then adapted to suit the specific environment. For example, an extended low-frequency response may be beneficial for listening to music (Moore et al., 2016), whereas a highly directional response with strong noise reduction may be beneficial for listening to speech in a noisy situation. The benefits of such classification methods require further evaluation.

Dealing with Acoustic Feedback

When a person has a hearing loss that requires considerable amplification, the sound output from the hearing aid may be picked up by the microphones, leading to a squealing sound called acoustic feedback. Nearly all hearing aids incorporate systems for reducing acoustic feedback (Kates, 1999), but these can degrade sound quality and introduce artifacts of various kinds (Madsen and Moore, 2014; Zheng et al., 2022). A DNN for reducing such artifacts has been described but has not yet been implemented in hearing aids (Zheng et al., 2022).

Other Features of Modern Hearing Aids

Bluetooth streaming of sound from mobile phones, remote microphones, or TVs to hearing aids is becoming more frequent. This can be beneficial in delivering a relatively clean signal to the hearing aids, with little background noise or reverberation.

Most modern hearing aids provide sufficient amplification to partially restore audibility for frequencies up to about 5 kHz for people with mild-to-moderate hearing loss (Moore et al., 2001). However, for severe hearing losses, the maximum audible frequency can be much lower. For this reason, some hearing aids shift the high frequencies of the input to lower frequencies where the user's hearing thresholds are lower (Launer et al., 2016; Salorio-Corbetto et al., 2017). The lower frequency components of the input signal remain intact. Although frequency lowering of various types is an option in many hearing aids, evaluations of its benefits have given conflicting results.

Summary of What Hearing Aids Do

In summary, hearing aids partially compensate for threshold elevation and loudness recruitment, but they only compensate indirectly and to a limited extent for the other perceptual effects of hearing loss. Thus, hearing aids help, but they by no means restore hearing to "normal" and they have not yet solved the cocktail party problem. This may be one of the reasons why less than 20% of those with hearing difficulties in the United States regularly use hearing aids (Humes, 2023). Other reasons for the limited uptake include cost, perceived stigma, the "bother" of looking after hearing aids (e.g., the receivers can get clogged with wax), and discomfort produced by the part in the ear canal.

Recent Developments

The incorporation of biosensors into hearing aids is blurring the boundary between hearing aids and other gadgets used in everyday life. Some hearing aids can count your steps, track your heart rate and even detect a fall and send an alert to a close contact. These features are changing public perception about hearing health and hearing aids. Current hearing aids are being integrated into modern lifestyles as an additional way of promoting health and well-being. This phenomenon is further promoted by the approval of over-the-counter instruments in some countries, including the United States and Japan, and by the use of "hearables" as hearing aids.

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