frontiers | Frontiers in Audiology and Otology

TYPE Review
PUBLISHED 30 January 2026
DOI 10.3389/fauot.2026.1748554

OPEN ACCESS

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RECEIVED 18 November 2025
REVISED 29 December 2025
ACCEPTED 07 January 2026
PUBLISHED 30 January 2026

CITATION
Elased RK, Marshall ZS, Bomback MJ, Alter IL and Lalwani AK (2026) Music perception and enjoyment with hearing loss: what hearing aids and cochlear implants can—and cannot—do. *Front. Audiol. Otol.* 4:1748554. doi: 10.3389/fauot.2026.1748554

Music perception and enjoyment with hearing loss: what hearing aids and cochlear implants can—and cannot—do

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Music is a complex auditory stimulus characterized by spectral and temporal elements that is a fundamental part of the human experience across cultures. Music perception and enjoyment are distinct yet related experiences of music that can be assessed using a variety of standardized survey instruments, qualitative interviews, and neuroimaging studies. Hearing loss significantly diminishes music perception and enjoyment, and current hearing devices can only partially restore these qualities. In cochlear implant users especially, technological limitations of devices uniquely compromise their experience of music, but the wide variability in individual outcomes suggests that multiple listener and device-related factors contribute to music perception and enjoyment. Ongoing research into music modification, device programming, and music-based training aim to improve music outcomes in people using hearing devices.

KEYWORDS

cochlear implants, hearing aids, hearing loss, music enjoyment, music perception

1 Aspects of music

Music is a form of sound that can be described with three core groups of physical elements—spectral, temporal, and combined spectral-temporal (Figure 1; Prevoteau et al., 2018). The spectral category is related to the frequencies of a sound wave. This mechanical wave is typically described in Hertz, or the number of oscillations per second. Pitch refers to the perceptual correlate of a sound's fundamental frequency, or the vibration that the instrument produces that allows a listener to perceive a note that is high (high frequency) or low (low frequency). Pitch perception relies in part on temporal fine structure, which refers to the rapid oscillatory patterns within the sound waveform. Melody is the variation of pitch over time, coming together to form a musical phrase. Harmony occurs when two pitches are played at the same time and is typically described in terms of the relationship between the simultaneous pitches (Hamm and Hughes, 2021).

The temporal aspect of music traditionally includes rhythm, tempo, and meter. Tempo marks the pace of a piece of music. Rhythm, like pitch, is hierarchical, meaning the length of time taken for each note is relative to the other notes. Meter organizes rhythm into an emphatic pattern that defines the flow of a piece of music, such as the distinctive feel of a waltz in 3/4 time (Gotham et al., 2021).

The pattern of volume change over time is a micro-temporal aspect of music that can also be measured and is captured by the temporal envelope. The attack time of an

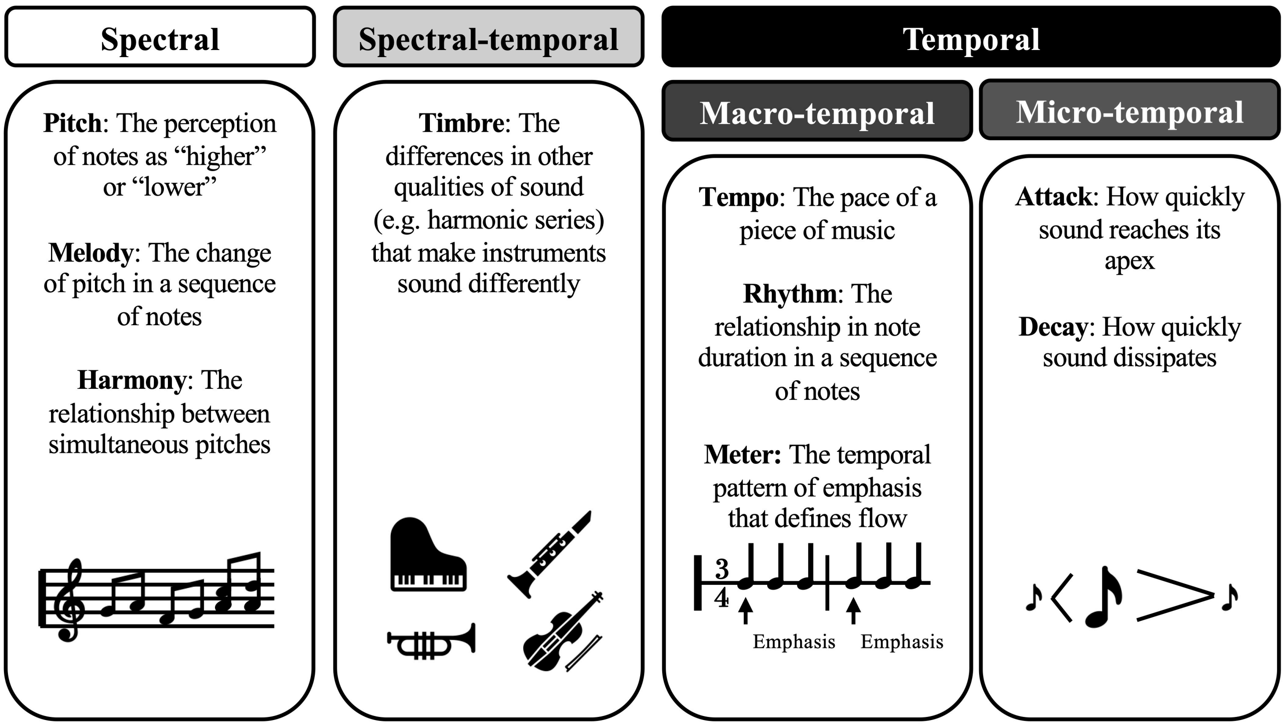

FIGURE 1
Spectral aspects of music involve the relationship between notes with different frequencies. Macro-temporal aspects involve the perceived "beat" of music, while micro-temporal aspects have to do with the timing of sound within single notes. Finally, the spectral-temporal aspect of timbre involves both spectral and temporal qualities that combine to define an instrument's particular sound.

instrument describes how quickly the sound reaches its apex. Agostini et al. (2003) used attack time to separate instruments in two categories—pizzicati (fast attack) and sustained (slow attack). Pizzicati instruments included piano, harp, and other plucked string instruments, and sustained included bowed string instruments, woodwinds, and brass. Decay time measures how long it takes for sound to dissipate. This is a quantitative description of reverberation, which is created by sound waves reflecting off of other surfaces (McAdams, 2013). Larger spaces (i.e., cathedrals, concert halls) tend to have longer decay times and more reverberation because the walls of reflection are much further away from the sound source as compared to smaller spaces (i.e., practice rooms); the types of surfaces reflecting sound waves also contribute to the reverberation (e.g., an echoey marble bathroom vs. a carpeted room).

The combined spectral-temporal aspect of music, also known as timbre, covers the other qualities of sound that make one instrument sound different from another (Agostini et al., 2003). This can be seen in the variation of harmonic series. Most instruments do not deliver only one "fundamental" frequency when a note is played, but a whole spectrum of frequencies that resonate above the fundamental at varying amplitudes. These frequencies are called harmonics or formants, and each instrument has a distinct set of harmonics that comprise its unique timbre (McAdams, 2013). These other frequencies also add a richness to the sound of music and can change throughout the length of a single note on an instrument (Grey, 1977).

1.1 Music perception vs. enjoyment

Hearing begins when sound waves travel through the external ear, down the ear canal, and vibrate the tympanic membrane. This, in turn, vibrates the ossicles (malleus, incus, and stapes), which amplify the sound and push on the oval window of the cochlea, in turn transmitting the waves into the perilymph and ultimately the endolymph. Within the cochlea, sound waves push down on very specific sections of the basilar membrane, stimulating nerve fibers of the vestibular-cochlear nerve and leading to the neural perception of pitch (Houtsma, 1997; Schneider, 2018). As mentioned above, the temporal envelope carries information about the slow changes in volume over time and the temporal fine structure captures the rapid oscillations that are related to pitch.

In research about music, perception and enjoyment must be defined independently. Perception is related to a person's ability to differentiate attributes of music, such as pitch and timbre. Enjoyment, on the other hand, describes an individual's subjective and emotional experience of listening to music. Quantifying the two requires different methodology, which will be discussed in a forthcoming section. Studies have found that there may be some relationship between a person's music perception and their enjoyment, but the relationship is not direct (Duerksen, 1968; Lassaletta et al., 2007; Zatorre and Salimpoor, 2013; Salimpoor et al., 2015; Prevoteau et al., 2018; Buechner et al., 2020; Hwa et al., 2021; Vuust et al., 2022).

1.2 Music and quality of life

A growing body of evidence suggests that music contributes positively to overall quality of life (QoL) and wellbeing. As a non-invasive, generally enjoyable option, music can be used in clinical care for therapeutic effects, especially in anxiety and depression (Wakim et al., 2010; Aalbers et al., 2017; McCrary et al., 2022; Luo et al., 2025), and has been found to help improve cognition and neuropsychiatric symptoms in patients with dementia, as compared to non-music therapy (Lin et al., 2023). Music is also often used as a form of emotional regulation, whether through the social connections with shared music listening or through an increase in mood from the music itself (Saarikallio, 2011; Schäfer et al., 2013; Zatorre and Salimpoor, 2013; Dingle et al., 2021; Granot et al., 2021; Hennessy et al., 2021; Groarke et al., 2022). It is especially beneficial for older adults (Lee et al., 2010; Krause and Davidson, 2021), and it can even make exercise more enjoyable (Miller et al., 2010; Stork et al., 2015). Even beyond the substantial empirical research, the widespread personal and cultural significance of music—reflected in its omnipresence in seminal life events such as weddings and funerals—underscores its centrality to the human experience. The loss or impairment in music perception or enjoyment should therefore be considered a serious concern, with potential implications for quality of life and emotional wellbeing.

2 How music is investigated

An ever-growing body of research has expanded our understanding of how music is presented, perceived, and evaluated across both normal-hearing (NH) individuals and those with hearing loss (HL), including those using hearing aids (HAs) and cochlear implants (CIs). Traditionally, music perception studies have been conducted in controlled laboratory environments, such as sound-attenuated booths, to minimize acoustic variability (Yoon et al., 2023). However, there is a growing emphasis on ecological validity, with researchers increasingly incorporating home-based assessments to better reflect real-world listening environments (Timmer et al., 2015; Wu et al., 2015; Hey et al., 2022). Halliwell et al. (2015) compared a laboratory experiment with a take home trial and found that CI users had different preferences for various pre-processing strategies of music in each setting. In addition, Gfeller et al. (2000) explored natural listening settings and found that music enjoyment varied significantly depending on the listening environment.

Both open-field loudspeakers and direct streaming (e.g., via Bluetooth) are commonly used to present music to participants in music-focused studies. Loudspeakers are favored for spatial discrimination tasks, as they allow sound to be presented from various angles, helping to evaluate binaural and directional hearing abilities (Kühnle et al., 2013; Brown et al., 2015). Direct streaming, on the other hand, transmits the audio signal wirelessly and directly into a hearing device, bypassing environmental noise and room acoustics (Chen et al., 2021). This makes it especially useful for evaluating perceived sound quality under controlled, everyday listening conditions. Some studies, on the other hand, use headphones instead of sound field presentation, which differs from direct device streaming and may influence perceived sound quality and spatial cues (Zelechowska et al., 2020). In addition, distance of source to listener has been shown to impact music perception; Eurich et al. (2019) found that CI users preferred smaller source-to-sound distances compared to larger ones.

The selection of musical stimuli is critical and often tailored to the objectives of the study. Familiar music, such as popular songs or culturally recognizable melodies, can engage emotional and memory-related pathways, while unfamiliar or newly composed pieces allow researchers to focus on perceptual mechanisms without confounds from prior knowledge (Pereira et al., 2011; Jagiello et al., 2019). This distinction is meaningful because familiarity, emotional salience, and prior exposure can significantly shape how listeners perceive music. This is particularly relevant for individuals with HL, who may rely on memory to fill in gaps in music perception (Yüksel et al., 2019; Hsiao and Gfeller, 2012). Researchers can also vary the complexity of musical excerpts, contrasting single-instrumental with multi-instrumental stimuli, and including or excluding vocals depending on whether linguistic processing is a variable of interest (Sallavanti et al., 2016; Fucci et al., 1996; Avila et al., 2012; Brattico et al., 2011). These choices are not merely aesthetic but can profoundly influence task difficulty, listener engagement, and perceptual accuracy.

To quantify music perception, several standardized tools have been developed and validated (Table 1). The Montreal Battery for the Evaluation of Amusia (MBEA) remains one of the most widely used, assessing rhythm, melodic contour, and memory (Nunes-Silva and Haase, 2012). However, new tools such as the Profile of Music Perception Skills (PROMS) and the University of Washington Clinical Assessment of Music Perception (UW-CAMP) can provide finer resolution by isolating specific perceptual domains, such as pitch discrimination, melody contour, rhythm synchronization, and timbre identification, using adaptive or graded-difficulty tasks (Kang et al., 2009; Strauss et al., 2024). These measures yield more detailed performance profiles and are better suited for listeners with HL, particularly CI recipients, because they accommodate the limited spectral and fine temporal resolution of implant-mediated hearing and reduce confounds from complex or linguistically loaded stimuli (Kang et al., 2009; Strauss et al., 2024). The MuSIC battery, specifically designed for CI users, further expands this toolkit by incorporating timbre and tuning components adapted to the auditory limitations of this group (Brockmeier et al., 2011; Bruns et al., 2016).

Music enjoyment is a more subjective yet equally important dimension of auditory experience. It is typically assessed through self-report tools that rate qualities such as naturalness, pleasantness, musicality, clarity, richness, emotional impact, and overall satisfaction. Likert-type scales and visual analog scales are commonly used, along with more specialized tools like the Music Engagement Questionnaire (MusEQ) and the Music Perception Questionnaire (MPQ), both of which capture multiple domains of listening enjoyment and participation (Vanstone et al., 2016; Alter et al., 2025a; Blasco-Magraner et al., 2025). Other instruments, such as the Music Quality Rating Test (MQRT), have been used to evaluate attributes like fidelity, balance, and timbral realism, particularly in CI and HA research (Looi et al., 2011).

TABLE 1 Methods of investigating music.

Tool/Instrument	Primary purpose	Domains or subtests measured	Population/Setting
Montreal Battery for the Evaluation of Amusia (MBEA)	Quantitative assessment of music perception	Melody, rhythm, pitch, contour, meter, memory	Normal-hearing and hearing-loss populations; laboratory testing
Profile of Music Perception Skills (PROMS/Micro-PROMS)	Rapid multidomain assessment of perceptual acuity	Pitch discrimination, melody contour, rhythm synchronization, timbre identification	Normal-hearing, hearing-aid, and cochlear-implant users; online or clinical administration
University of Washington Clinical Assessment of Music Perception (UW-CAMP)	Clinical evaluation of music perception	Pitch discrimination, melody identification, timbre recognition	Primarily cochlear-implant recipients
MuSIC Perception Battery	Cochlear-implant–specific assessment of music perception	Pitch, timbre, tuning, melody; adapted to limited spectral resolution	Cochlear-implant users
Music Engagement Questionnaire (MusEQ)	Self-report of music enjoyment and participation	Enjoyment, engagement, listening frequency, social use	Adults with hearing loss, hearing aids, or cochlear implants
Music Perception Questionnaire (MPQ)	Self-report of enjoyment and musical profile	Pleasantness, naturalness, clarity, richness, emotional impact	Music education and hearing-research contexts
Music Quality Rating Test (MQRT)	Evaluation of perceived sound quality	Fidelity, balance, timbral realism	Hearing-aid and cochlear-implant users; comparison of processing strategies
Music-Related Quality of Life Scale (MuRQoL)	Assessment of music-specific quality of life	Impact of music on daily activities, emotional wellbeing, participation	Hearing-aid and cochlear-implant users; rehabilitation outcome tracking
Cochlear Implant Quality of Life (CIQOL)	Evaluation of hearing-related quality of life including entertainment domain	Enjoyment, social interaction, listening satisfaction	Cochlear-implant users; complements MuRQoL
Neurophysiologic Methods (EEG/fMRI)	Objective assessment of neural responses to music	Event-related potentials (e.g., mismatch negativity), cortical activation, emotion-related circuitry	Normal-hearing and cochlear-implant participants; cognitive-neuroscience research
Qualitative Interviews and Focus Groups	Exploration of subjective and emotional experiences with music	Wellbeing, identity, social connection, community participation	Musicians and listeners with hearing loss, hearing aids, or cochlear implants

Some studies also differentiate between active and passive listening contexts. Active listening involves intentional, focused engagement with the music, often through attention, emotional involvement, or selection of preferred pieces, whereas passive listening refers to hearing music incidentally or as background sound without directed attention (Friston et al., 2021). Salimpoor et al. (2009); Lynar et al. (2017) reported that active listening, to self-selected music in particular, elicits stronger subjective pleasure and physiological arousal (e.g., chills, elevated heart rate and galvanic skin response) than neutral background music. On the other hand, Gold et al. (2013) found that passive listening is consistently associated with lower levels of enjoyment and engagement.

An additional important and frequently studied outcome related to music listening is that of emotion evoked by music. In examining the emotional impact of music, researchers often adopt the valence-arousal framework, which conceptualizes emotional responses along two core dimensions: valence (ranging from unpleasant to pleasant or happy to sad) and arousal (ranging from calm to excited; Picou et al., 2018; Hofbauer and Rodriguez, 2023). This model provides a continuous scale to assess emotional reactions beyond binary labels and is broadly applicable across both NH individuals and those with HL.

Quality of life (QoL) is an essential endpoint in music and hearing research, reflecting how musical engagement contributes to social, emotional, and cognitive wellbeing. Instruments like the Music-Related Quality of Life scale (MuRQoL) have been adapted for CI and HA users to assess the impact of musical activities on everyday life (Dritsakis et al., 2017, 2025; Frosolini et al., 2024; Akbulut et al., 2025). In addition, the Cochlear Implant Quality of Life (CIQOL) questionnaire includes domains related to entertainment and listening enjoyment, providing insight into how music contributes to perceived wellbeing among CI users (McRackan et al., 2019). Together, these instruments offer a framework for evaluating the broader psychosocial benefits of music engagement in individuals with hearing impairment.

Electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) have significantly advanced our understanding of how music is processed in the brain, particularly regarding perceptual, cognitive, and emotional dimensions. EEG, with its high temporal resolution, is uniquely suited to capturing the brain's real-time response to musical structure. Studies frequently employ event-related potentials (ERPs) such as the mismatch negativity (MMN) to investigate the detection of unexpected changes in melody or rhythm—an important mechanism for understanding musical pattern recognition, especially in individuals with auditory processing disorders (Koelsch, 2014). While EEG captures rapid neural responses, fMRI provides the spatial resolution needed to localize the brain regions activated during music listening. fMRI studies have consistently shown that music engages not only auditory cortex but also a network of emotion-related structures such as the amygdala, ventral striatum, and orbitofrontal cortex (Koelsch et al., 2006). Koelsch et al. (2006) found that whether the music stimulus was pleasant or unpleasant led to activation of different brain regions;

however, in both conditions, activations increased as the stimulus duration increased, indicating that effects of emotion processing have temporal dynamics. Although primarily used in cognitive neuroscience, these techniques offer valuable complementary insights for audiology and music perception research.

Finally, qualitative research has provided meaningful insight into how music is experienced by individuals with HL, particularly those using CIs. Among the most common methodologies are semi-structured interviews, focus groups, and open-ended questionnaires, which allow participants to articulate nuanced emotional and social responses that quantitative tools often overlook (Vaisberg et al., 2019; Sanfilippo et al., 2020; Vidas et al., 2024). Within these studies, frequently investigated outcomes include wellbeing and mental health, social connection and community building, and personal growth and self-efficacy (Tamplin et al., 2014; Wilson and MacDonald, 2019; Perkins et al., 2020; Kapa et al., 2025). This research underscores the importance of integrating music-focused perspectives into hearing healthcare, highlighting music not only as an auditory stimulus but also as a meaningful contributor to emotional wellbeing, social connection, and personal identity.

3 Music, hearing loss, and hearing aids

3.1 Hearing loss and music perception

Hearing loss has a clear impact on both music perception and enjoyment. Music perception in participants with HL is affected by the symmetry and severity of HL, as well as their familiarity with music (Cai et al., 2016). Individuals with HL are less able to recognize changes in harmony and have trouble distinguishing melodies from a background of music, especially when the melodies and harmonic spectrum are higher in pitch (Kirchberger and Russo, 2015). Those with mild HL can often compensate for these deficits through the increased volume provided by HAs, but when HL becomes more severe, there tend to be greater issues with pitch discrimination (Moore, 1996; Kirchberger and Russo, 2015; Looi et al., 2019; Madsen et al., 2025).

3.2 Hearing loss and music enjoyment

Worsening HL is associated with worse active and self-rated music enjoyment (Chern et al., 2022, 2023). Those with HL described music in one study as more “unnatural, unpleasant, and indistinct” after developing HL (Meehan et al., 2017). Many say they listen to music less after developing HL, with the sound sometimes confounded by tinnitus (Alter et al., 2025a; Meehan et al., 2017; Chern et al., 2023). As found in a study by Looi et al. in 2019, individuals with HL tend to prefer music with male singers and lower pitched instruments, with the preferences being stronger for more severe HL; this is hypothesized to be due to the well-established pattern of higher frequencies being preferentially affected by age-related HL (Looi et al., 2019; Škerková et al., 2021; Lough and Plack, 2022; Lin, 2024; Mishra et al., 2025).

3.3 Hearing aids and music perception

HAs are frequently used by those with HL to aid in music perception and enjoyment. HAs can increase volume, but they cannot compensate for the loss of higher frequency perception with damaged inner hair cells, synapses, or other neuronal issues (Cai et al., 2013). In addition, multichannel compression can make it difficult to distinguish one instrument or voice from a background of music, and systems for reducing feedback can have undesirable side effects (Figures 2A, B; Moore, 2016). HA users (compared to NH individuals) have trouble with rhythm, melody, pitch and timbre discrimination (Uys and van Dijk, 2011), though some studies have found that timbre discrimination is the most impacted single aspect of music perception for HA users (Choi et al., 2018). HAs themselves can also cause linear and non-linear distortions. Linear distortions are fixed frequency amplifications, which can change the harmonic spectrum, or natural timbre, of instruments. Non-linear distortions occur when the HAs mistakenly add harmonics to a sound because of a rapid change in volume (Chasin and Russo, 2004). These effects can be compounded by peak limiting, when devices are made to only amplify sounds below a certain volume, usually around 85 dB for older devices. Some newer devices have the option to increase the peak limit to 105 dB, so that compression does not occur at too low of a volume (Chasin and Russo, 2004; Chasin and Hockley, 2014).

3.4 Hearing aids and music enjoyment

Studies have suggested that HAs have the potential to increase music enjoyment for those with HL (Chern et al., 2022, 2023; Holman et al., 2023, p. 202). but they do not return enjoyment to pre-HL levels (Meehan et al., 2017). Music listening habits also may be preferentially negatively affected for individuals who previously particularly enjoyed music prior to their HL (Alter et al., 2025a). Some people find music through HAs “too bright or shrill” (Feldmann and Kumpf, 1988; Madsen and Moore, 2014), and while others have described music after hearing loss and without HAs as “muddy,” “muffled,” and “distant,” the addition of HAs shifted descriptors to “harsh” and “tinny,” suggesting that listening to music with HAs increases clarity, but also harshness and distortion (Chasin and Hockley, 2014; Bannister et al., 2024). HA users have also expressed other subjective issues with their HAs. The bass at loud, in-person music events has been described as “unbearable,” requiring the removal of HAs. Even when the bass is unbearably loud, HA users say they are still unable to understand the words (Greasley et al., 2020). One HA user in a study by Greasley et al. (2020) said, “I can no longer go to concerts or listen to any record/CD collection with any pleasure.”

3.5 Predictors of music outcomes in hearing aid users

While there do exist general trends in music perception and enjoyment in HA users, both with and without the use of their

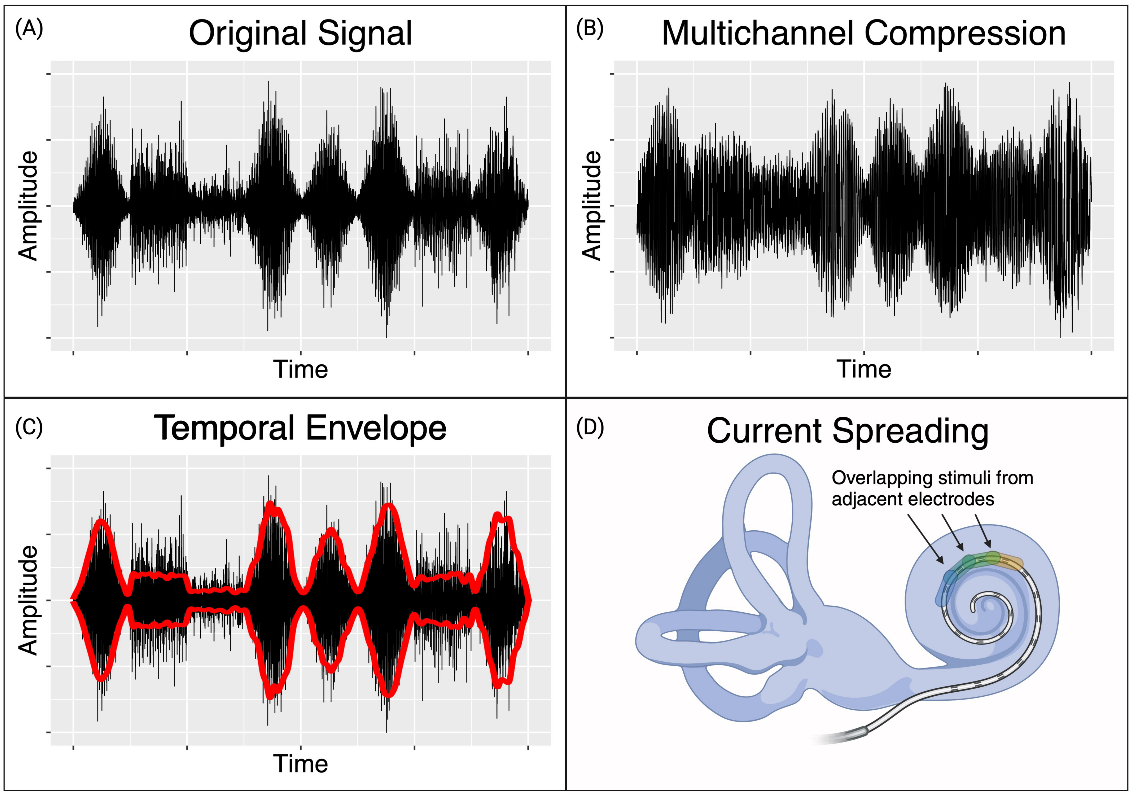

FIGURE 2
Technological limitations of hearing aids and cochlear implants in music. **(A)** An illustrative example of an auditory signal. **(B)** In hearing aids and cochlear implants, multi-channel compression increases amplification of quiet, low amplitude signals and decreases amplification of low, high amplitude signals. **(C)** Cochlear implants transmit the broad temporal envelope of auditory signals (red line), but not the temporal fine structure. **(D)** Cochlear implants exhibit current spread, causing stimuli from adjacent electrodes to overlap. [Created in BioRender. Elased (2026); https://BioRender.com/kl41gqx].

HAs, there also exists significant interparticipant variation. Some of this variation can be attributed to severity of hearing loss, type of HA and compression settings, as well as the participant's prior experience with music (Chern et al., 2022, 2023; Looi et al., 2019; Alter et al., 2025a). Participants who rated their enjoyment of music higher before HL were more likely to experience greater dissatisfaction in music enjoyment with HAs (Alter et al., 2025a). Overall, despite worsening HL over time, music enjoyment stays relatively stable for HA users, and the original satisfaction or dissatisfaction with the listening experience is the most predictive factor for music enjoyment (Alter et al., 2025a).

3.6 Improving music outcomes in hearing aid users

As part of the ongoing efforts to innovate and improve HA quality, there are now specific music programs or settings that purport to improve music perception and enjoyment (Table 2; Leek et al., 2008). For example, the "Live Music Plus" program described by Hockley et al. (2010) includes "ChannelFree compression," which allows level differences in harmonic spectra to be maintained, preserving the inherent timbre of live instruments. This program also increases the dynamic range of amplification, allowing volumes up to 115 dB to be preserved. Additionally, while everyday conversational clarity is improved with "adaptive directionality" (a feature of new HAs that amplifies sound only in the direction of a person's gaze), this can sometimes impair music enjoyment and thus is often turned off for many music listening programs. Some subjective experiences of these music programs have been quite positive. For example: "The audiologist set one of my hearing-aid programs to have no feedback so that it does not attenuate very loud sounds. This enables me to enjoy as much as is possible, for example, the full dynamic range of a Mahler symphony" (Greasley et al., 2020). Others say they don't want to be bothered to switch to a new program, or find that the difference is not obvious (Vaisberg et al., 2019). There have been no objective studies that compare the music enjoyment of those using specific music programs to those who do not. Finally, there could be a role for music re-engineering in improving music outcomes for HA users. Benjamin and Siedenburg (2023) described a preference for sound mixes with more prominent lead vocals in HA vs. NH users. However, the effect of changes to other aspects of music have not been reported and merits further investigation.

TABLE 2 Directions toward improving music outcomes for those with hearing loss using hearing devices.

Intervention or strategy	Cochlear implant users	Hearing aid users
Device programming	Anatomy-based fitting with personalized tonotopic maps (Noble et al., 2014; Jiam et al., 2019; Creff et al., 2024; Heitkötter et al., 2024a; Lassaletta et al., 2024; Berg et al., 2025)	Preserving level differences in harmonic spectra (Moore, 2016; Leek et al., 2008) Increasing dynamic range of amplification (Chasin and Russo, 2004; Chasin and Hockley, 2014) Deactivating "adaptive directionality" while listening to music (Hockley et al., 2010)
Music re-engineering	Increasing vocal and bass prominence (Nemer et al., 2017; Hwa et al., 2021) Decreasing instrument number (Kohlberg et al., 2016) Reducing reverberation time (Certo et al., 2015) Minimizing harmonics (Nemer et al., 2017)	Increasing vocal prominence (Kirchberger and Russo, 2015)
Music training	Attentive listening training (Firestone et al., 2020) Practicing identifying aspects of music (Driscoll, 2012; Smith et al., 2017; Cheng et al., 2018) Increasing music exposure (Gfeller et al., 2008) Formal and informal musical training (Yucel et al., 2009; Chen et al., 2010; Good et al., 2017)	*Has not been explored to date*

4 Music and cochlear implants

CIs rehabilitate hearing of those with moderate to profound hearing loss. Unlike HAs, which directly amplify sound, CIs translate auditory stimuli into electric stimuli that directly activate the cochlear nerve via stimulation within the cochlea. Though CIs can improve speech understanding tremendously in pre- or post-lingually deafened individuals, CI users frequently struggle with music perception and enjoyment (Carlson, 2020; Sharma et al., 2020).

4.1 Limitations of cochlear implants in music

CIs are fundamentally limited in spectral aspects of music by several technological components. Firstly, CIs deliver impulses through a limited number of electrodes distributed along the length of the cochlea. The native cochlea has a tonotopic organization, in which basal areas are designed to transmit higher pitches and apical areas transmit lower pitches. Through ∼3,500 inner hair cells in the native cochlea, this results in a nearly continuous tonotopy that CI technology struggles to replicate. Current CIs have up to 22 electrodes, though one study presented a theoretically feasible 32-electrode design (Shin et al., 2021). Though current arrays are largely sufficient for speech understanding, increasing electrode number has been proposed as a theoretical means of delivering more spatially precise stimulation. One estimate suggests that up to 64 or more electrodes would be required to properly perceive complex music with multiple instruments (Shannon, 2005). In practice, however, studies to date have only demonstrated benefits to increasing the number of active electrodes or independent channels from very low counts (1–4) to moderate levels, with improvements limited to specific aspects of music perception, such as musical sound quality or high-frequency melody recognition, under certain conditions (Singh et al., 2009; Berg et al., 2019). Incremental benefits beyond these ranges have not been consistently demonstrated, and any potential benefit of higher electrode number is further limited by current spread. Current spread, or the propagation of stimulus from the electrode beyond the direct area where it is stimulating, causes signals between nearby electrodes to overlap (Figure 2D). This means that the number of independent electrodes is lower and that precise stimulation of adjacent but distinct areas of the cochlea is challenging. Additionally, (Donnelly et al., 2009) showed that CI users often demonstrate perceptual fusion, in which they perceive superimposed tones as a single-pitch unit. Such a phenomenon is problematic for music perception where not only are tones layered to create chords within a single instrument or group of instruments, but often many instruments or tracks play simultaneously, adding further complexity. Finally, the most common CI coding strategies primarily transmit auditory information through temporal envelope cues—the large amplitude changes in sound waves—and largely fail to transmit temporal fine structure, or the rapid oscillations in waveforms (Figures 2A, C; Moon and Hong, 2014). While temporal envelopes transmit sufficient information for speech intelligibility and tempo or rhythm perception, temporal fine structure is critical for pitch discrimination and timbre perception, and its limited encoding contributes to impaired music perception in CI users (Shannon et al., 1995; Heinz et al., 2001; Moore et al., 2006; Heng et al., 2011). As such, the technological limitations that impair pitch and timbre perception form the basis for challenges in music perception in CI users.

4.2 Cochlear implants and music perception

Consistent with these signal-processing limitations, CI users show characteristic patterns in musical perception. Temporal aspects of music, such as tempo discrimination and rhythm, have been found to be reliably transmitted by CIs. (Kong et al., 2004) found that CI users performed similarly to NH controls in discriminating tempos between 60 and 120 bpm and in identifying rhythmic patterns. In addition, (Kim et al., 2010) found that CI users and NH controls exhibited similar internal rhythmic clocking, or the ability to determine beats as on- or off-rhythm.

However, CI users struggle in perceiving spectral aspects of music. On average, CI users can discriminate an estimated interval of 1.8–7.6 semitones, while estimates for NH non-musicians range between 0.25 and 1.1 semitones, depending on the pitch and timbre of the stimulus and age of participants (Kang et al., 2009; Gfeller et al., 2002; Mary Zarate et al., 2012; Stalinski et al., 2008; Berg et al., 2025; Wagner et al., 2021; Wang et al., 2011). Similarly, CI users require larger intervals to identify musical contours and are less accurate in interval perception than NH (Galvin et al., 2007; Spitzer et al., 2021; Landsberger et al., 2022). Harmonically, CI users have been shown to have impaired ability to distinguish between consonant and dissonant harmonies and have decreased association between the consonance of harmony and pleasantness of music (Gilbert et al., 2025). Timbre perception is also impaired; CI have significantly diminished ability to identifying instruments (Looi et al., 2008; Prentiss et al., 2016). Collectively, these findings highlight the substantial limitations CI users face in accessing the rich spectral information fundamental to music perception.

4.3 Cochlear implants and music enjoyment

Beyond the diminished perception of music, CI users have also been shown to suffer from reduced enjoyment of music compared to NH controls (Landsberger et al., 2020; Akbulut et al., 2025; Alter et al., 2025c). CI users also tend to experience a decrease in music enjoyment after implantation (Mirza et al., 2003; Lassaletta et al., 2008). However, some CI users can show improvement in music appreciation and enjoyment, such as unilaterally deafened users (Migirov et al., 2009; Yang et al., 2024).

The pattern of reduced enjoyment may be due in part to difficulty in identifying emotions associated with music—Alter et al. (2025c) found that bilateral CI users had significantly higher error rates in identifying musical valence than NH controls, and Ambert-Dahan et al. (2015) found that CI users had impaired emotional judgments of happy, scary, and sad music. Similarly, Caldwell et al. demonstrated that the presence of consonant vs. dissonant chords did not significantly impact whether melodies were considered pleasant or unpleasant (Caldwell et al., 2016). Multiple studies have also reported similar results in children, with school-age children using either bilateral or unilateral CIs performing significantly worse than NH controls but better than chance at distinguishing happy and sad music (Hopyan et al., 2011; Stabej et al., 2012; Volkova et al., 2013). Errors in identifying emotion in music may stem from the fact that CI users depend more heavily on tempo to identify emotion instead of tonality (Caldwell et al., 2015). CI users also have a constricted range of arousal in response to music, which can contribute to limited enjoyment even if the musical valence be identified correctly (Alter et al., 2025c).

4.4 Contribution of modality of cochlear implant usage

An important driver of CI user experience of music is the modality of hearing—whether patients have a CI in both ears (bilateral), a CI in one ear and an HA in the other (bimodal), or one CI with normal hearing in the other ear, known as single-sided deafness (SSD). Notable differences have been found between CI users' experience of music based on differences in modality, such as Gfeller, Oleson, Knutson, Breheny, Driscoll and Olszewski (2008) finding that bimodal CI users were more likely to recognize familiar music without lyrics than bilateral CI users. Akbulut et al. (2025) showed that SSD CI users had a statistically significant decrease in the frequency of engagement with music compared to bilateral CI users as measured by the MuRQoL.

On the other hand, binaural input, even with discordant input types, may benefit the music listening experience. Binaural summation (increased perceived loudness with both ears), improved localization of sound, and binaural squelch (improved masking of noise), may all play a role (Avan et al., 2015). Several studies have demonstrated that in SSD and bimodal CI users, the binaural experience of music is not significantly different, or may even be improved, compared to either ear alone for outcomes including enjoyment, perception accuracy, or emotional response (Landsberger et al., 2020; El Fata et al., 2009; Alter et al., 2025b; Kong et al., 2005; Alter et al., 2025d). This counters a previous hypothesis that unilateral CI-degraded signals would detract from the binaural listening experience; it is the better hearing ear that determines and dominates level of music enjoyment, perception and emotional response under binaural listening conditions. Analogous work investigating speech quality perception in individuals with SSD has also found that although speech quality is worsened by a CI in the implanted ear, this does not meaningfully impact binaural listening when compared to the NH ear alone (Kelly et al., 2025). (Duret et al., 2021) also described bimodal stimulation improving or not significantly impacting several qualities compared to either ear alone.

4.5 Predictors of music outcomes in cochlear implant users

Many of the aforementioned studies describing trends in music perception and enjoyment in CI users have noted large individual differences between participants. Several factors have been hypothesized to predict music perception and enjoyment in CI users. Importantly, as discussed previously music perception and enjoyment are not correlated with each other, and CI users can enjoy music despite impaired perception (Wright and Uchanski, 2012; Drennan et al., 2015; Bruns et al., 2016).

Some studies found that those who were deafened pre-lingually and implanted as adults report higher music appreciation and engagement despite similar or worse music perception to post-lingually deafened CI users, suggesting that their lack of musical memory or familiarity may enable them to enjoy the CI-mediated experience of music more (Bruns et al., 2016; Fuller et al., 2019; Akbulut et al., 2025). This contrasts with other studies that report no significant difference between the pre-lingually and post-lingually deafened CI users in amount of music listening or music enjoyment, though these studies do not specifically isolate those pre-lingually deafened individuals implanted as adults (Migirov et al., 2009; Moran et al., 2016). One study indicated that following implantation, younger post-lingually deafened adults experience smaller decreases in music listening habits, enjoyment, and perception of certain musical qualities compared to older adults (Chung et al., 2022).

Technical aspects of the CI implantation may also contribute to music outcomes. Berg et al. (2019, 2025) found that a full scala tympani insertion, straight arrays, larger distances from the electrode to the modiolus of the cochlea, and a shallower insertion depth were associated with improved music perception and that CI users with straight arrays were associated with improved sound quality ratings than those with pre-curved arrays. On the other hand, Roy et al. (2016) found that deeper arrays contributed to improved sound quality discrimination, and Heitkötter et al. (2024b) reported no significant impact of implantation depth on music perception. While speech perception also benefits from a full scala tympani insertion, speech performance has been associated with pre-curved arrays, closer electrode-modiolus proximity, and greater angular insertion depth (Wanna et al., 2014; Vohra et al., 2024; Holder et al., 2019; Sharma et al., 2022; O'Connell et al., 2016; Chakravorti et al., 2019; Helbig et al., 2018; Canfarotta et al., 2025). Berg et al. (2019, 2025) suggested the discrepancy may be due to higher rates of translocation impacting music perception disproportionately in pre-curved vs. straight arrays in their sample. Further investigation is warranted to better understand if there should be differences in implantation approach for patients that prioritize music perception.

Traditionally, speech recognition is expected to improve in the 6–24 months after implantation before reaching a plateau (Lenarz et al., 2012; Massa and Ruckenstein, 2014; Ma et al., 2023). Similar plateaus may exist in music perception, although some long-term improvements have been reported. Gfeller et al. (2010) showed that musical performance generally remained stable at 2 years post-implantation compared to 1 year except for performance in familiar melody recognition and musical excerpt recognition of items with lyrics, which improved. Ahn et al. (2019) found that in patients that had poor music performance ~1.5 years post-implantation, pitch discrimination and timbre identification but not melody identification had improved ~2 years later. Berg et al. (2025) found that increased CI wear time by datalogging was associated with improved pitch discrimination but not melody or timbre performance. However, there is a need for studies investigating music performance over even longer periods of time, as some CI users have continued to demonstrate improvements in speech perception up to 5 years after implantation (Tyler et al., 1997; Cusumano et al., 2017). These cases of long-term improvements may suggest that device programming, technological advances, and targeted rehabilitation may have a role even in experienced CI users in enhancing music outcomes as they do for speech outcomes (Schumann et al., 2015; Moberly et al., 2018; de Quillettes et al., 2024; Holden et al., 2025).

In contrast, the Akbulut et al. (2025) study found no relationship between MuRQoL with duration of auditory rehabilitation or HA usage prior to implantation. Additionally, Migirov et al. (2009) found that none of age at implantation, duration of deafness, duration of CI use, type of CI device, or speech perception abilities were associated with music enjoyment or frequency of listening to music. Berg et al. (2025) also did not find age, onset of deafness, or length of CI use were associated with music perception. The contrasting findings indicate that further work is needed to better understand individual predictors for music outcomes, which is likely multifactorial involving demographics, pattern of HL, and implantation factors.

4.6 Improving music outcomes in cochlear implant users

Despite well-known challenges in music perception and enjoyment among CI users, some interventions—focused on either the implantees themselves or on musical stimuli—may improve outcomes (Table 2). Pre-implantation musical training as well as increased music exposure and rehabilitation post-implantation have been associated with improved music recognition and enjoyment, suggesting a role for active rehabilitation to improve outcomes (Gfeller et al., 2008; Smith et al., 2017). Music training yielding benefits included individualized piano lessons but also home-based attentive listening training and practice identifying pitch relationships, melodic contours, or musical instruments (Yucel et al., 2009; Chen et al., 2010; Driscoll, 2012; Good et al., 2017; Smith et al., 2017; Cheng et al., 2018; Firestone et al., 2020). Online platforms like Meludia show promise as a form of musical rehabilitation and as a tool to evaluate the effects of such training on performance over time (Boyer and Stohl, 2022; Calvino et al., 2025). A meta-analysis by Shukor et al. (2023) found that CI users across ages who participated in post-implant musical training showed improvement in pitch and rhythm performance but not harmony or timbre discrimination. An additional meta-analysis by the same group found that bilateral CI users benefitted more from musical training than bimodal users (Shukor et al., 2021).

Furthermore, innovations in personalized programming methods have shown promising results in music perception. Anatomy-based fitting, also known as image-guided programming, leverages CT imaging of the cochlea to calculate personalized tonotopic maps and programs electrodes accordingly. Such strategies can optimize place-pitch mapping, minimize overlapping stimulation, and have been associated with improved musical perception (Noble et al., 2014; Jiam et al., 2019; Creff et al., 2024; Heitkötter et al., 2024a; Lassaletta et al., 2024; Berg et al., 2025). Music engineering has also been used to alter existing music, or create novel musical stimuli, to better fit within the limitations of CI technology. For example, reducing reverberation time, minimizing harmonics, decreasing instrument number, and increasing the prominence of vocals and bass have all been shown to improve music enjoyment in CI users generally (Buyens et al., 2014; Certo et al., 2015; Kohlberg et al., 2016; Nemer et al., 2017). A user-directed music re-engineering tool allowing participants to adjust treble and bass frequencies, percussion emphasis, and reverberation time also improved music enjoyment (Hwa et al., 2021). In addition, presenting music with stereo sound has also been associated with increased enjoyment for bilateral CI users (Buechner et al., 2020).

5 Conclusion

Individuals with HL suffer from diminished music perception and enjoyment. Hearing devices have been optimized for speech perception rather than the experience of music, leaving limited tools to improve music outcomes. As highlighted throughout this review, these limitations affect both the accuracy of musical perception and the emotional resonance that music typically provides, contributing to wide variability in outcomes across individuals. Because music plays a meaningful role in wellbeing, identity, and social connection, difficulties in accessing it represent more than a technical challenge; they constitute a significant quality-of-life concern. Given the important role of music in society and the variability in music outcomes, there is room for advances in understanding predictors of music outcomes.

Future work identifying the listener-, device-, and environment-level factors that best predict successful music engagement will be essential for guiding personalized clinical care and informing next-generation device design. Emerging methods to make music more accessible to those with HL are promising and include re-engineering music to simplify stimuli, re-programming devices to accommodate signals in music outside typical speech parameters, and goal-directed musical training. Together, these approaches reflect a growing commitment to treating music as a rehabilitative priority rather than an optional supplement to speech-focused interventions. Continued innovation in these areas has the potential to restore a valued dimension of human experience for individuals with hearing loss.

Author contributions

RE: Writing – original draft, Writing – review & editing. ZM: Writing – review & editing, Writing – original draft. MB: Writing – original draft, Writing – review & editing. IA: Writing – original draft, Writing – review & editing. AL: Supervision, Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. The contributions of RKE, ZSM, and MJB were supported by the National Institute on Aging of the National Institutes of Health under Award Number T35AG044303.

Conflict of interest

AKL is the founder and equity owner of Haystack Medical.

The remaining author(s) declared that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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