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Music enjoyment with cochlear implantation

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ABSTRACT

Since the advent of cochlear implant (CI) surgery in the 1960s, there have been remarkable technological and surgical advances enabling excellent speech perception in quiet with many CI users able to use the telephone. However, many CI users struggle with music perception, particularly with the pitch-based and melodic elements of music. Yet remarkably, despite poor music perception, many CI users enjoy listening to music based on self-report questionnaires, and prospective studies have suggested a disassociation between music perception and enjoyment. Music enjoyment is arguably a more functional measure of one's listening experience, and thus enhancing one's listening experience is a worthy goal. Recent studies have shown that re-engineering music to reduce its complexity may enhance enjoyment in CI users and also delineate differences in musical preferences from normal hearing listeners.

1. Historical background

During the late eighteenth and nineteenth centuries, the first electric stimulations to enable hearing were developed [1,2]. These early techniques utilized gross extra-auricular electrical stimulation by a battery connected to probes placed within the external auditory canals bilaterally, inducing a "jolt," warmth, and the sensation of "crackling," "buzzing," and "ringing". By the early twentieth century, researchers began experimenting with auditory nerve stimulation by an electrode. In 1957, In Paris, the first electrode was implanted intra-auricularly by André Djourno and Charles Eyriès, introduced in contact to the auditory nerve in humans, to electrically stimulate [3].

The first true cochlear implant (CI), in which the device was introduced through the cochlea to stimulate the auditory nerve, was implanted in 1961 by the American otologist William House in collaboration with neurosurgeon John Doyle [2,4]. This first device involved the implantation of a bare induction coil with five electrodes, and enabled patients to discriminate basic frequencies and identify words in closed sets. This development inspired a wealth of physiological research to understand pathways of hearing and optimize technology, which led to the implantation of the first multichannel cochlear implant in 1964. Since then, there have been continued advances in CI technology, including the development of a percutaneous button to contain the induction coil of the CI, miniaturization of electronics components, development of new surgical plastics, and improvements in surgical technique. In addition, there have been many advances in CI hardware. For example, recently developed processing strategies including HiRes 120, Fine Structure Processing (FSP), and high-definition continuous interleaved sampling (HDCIS), enable enhanced temporal resolution and pitch differentiation (First

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et al., 2009, Otol Neurotol; Looi et al., 2011, International Journal of Audiology; Roy et al. 2015, Ear and Hearing).

2. Speech perception

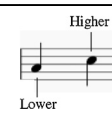
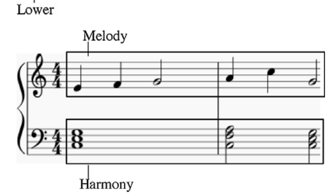
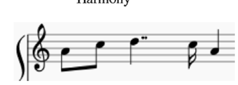
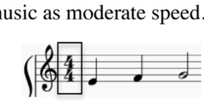
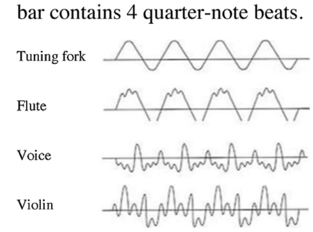
While there were low expectations for the performance of the first CI, which was created as an aid for lip reading in patients with profound sensorineural hearing loss, CI hearing outcomes have improved dramatically over the last thirty years, particularly with regards to speech perception. In 1995, the National Institute of Health issued a consensus statement reporting hearing outcomes of approximately 12,000 implanted patients, with most individuals achieving scores above 80% on high-context sentence tests without visual cues [5]. Notably, a study by Gifford et al. [1] demonstrated that many patients achieve at least 90% on standardized tests of sentence intelligibility in quiet, with 28% achieving 100% on the HINT (Hearing in Noise Test) sentences test. This ceiling effect made it difficult to adequately assess hearing outcomes in CI users. Thus, more difficult speech recognition tests including the Consonant Nucleus Consonant (CNC), AzBio Sentences, Bamford-Kowal-Bench Sentences in Noise (BKB-SIN), were identified as better measures for speech perception performance and are currently components of the Minimum Speech Testing Battery. Using these more rigorous measures for CI users, many studies have reported significant improvements in speech perception following implantation [6–8]. In addition, many CI recipients are able to use the telephone [9]. Of note, speech perception in noise remains difficult for most CI recipients [10–12], likely due to the increased complexity of the acoustic waveform, inferior quality output of speaker telephones, and the poor spectral detail of current CI devices [13].

3. Music perception

Despite remarkable advances in speech perception in quiet, the perception of music remains difficult for most CI recipients compared to normal hearing listeners [14,15]. The authors have chosen to focus this review on music perception and enjoyment in post-lingually deafened CI adults. Before discussing studies of music perception, it is important to first define fundamental elements of music.

A useful method to classify musical features is to divide them into *spectral*, *temporal*, and *combined spectral-temporal*

Table 1
Classification and definitions of musical elements.

Category	Musical element	Definition	Example
Spectral	Pitch	Quality that allows a listener to classify a musical sound as relatively high or low; often quantified as a frequency.	
	Melody	Succession of several pitches in sequence to form a musical phrase.	
	Harmony	Multiples pitches played simultaneously.	
Temporal	Rhythm	Composed of temporal patterns of musical sounds.	
	Tempo	Rate or speed of a musical piece, in beats per minute.	 In this example, the tempo is set at 80 quarter note beats per minute. Allegretto is another tempo marking that describes the music as moderate speed.
	Meter	Recurring pattern of accents, with stressed and unstressed beats that divide each bar. Often classified by the number of beats per measure, or the time signature.	 In this example, the 4/4 time signature demonstrates that each bar contains 4 quarter-note beats.
Spectral-temporal	Timbre	Sound characteristic that enables a listener to distinguish one instrument from another, even when played at the same pitch and loudness.	

elements [16] (Table 1). Among the spectral elements are pitch, melody, and harmony. Pitch is a quality that allows a listener to classify a musical sound as relatively high or low. Pitch may be quantified as a frequency, but pitch is not a purely objective physical property; it is a subjective psychoacoustical attribute of sound. It is determined by the lowest frequency of the note called the fundamental frequency (F0). Melody is a succession of several pitches in sequence to form a musical phrase, and is perceived by the listener as a single entity. Harmony consists of multiple pitches played simultaneously, or the vertical organization of pitches to form chords. Next, temporal elements include rhythm, tempo, and meter. Rhythm is composed of temporal patterns of musical sounds. Tempo is the rate of a musical piece, measured in beats per minute. Meter is the overall pulse of the musical piece, or the recurring pattern of accents, with stressed and unstressed beats that divide each bar. Finally, combined spectral-temporal elements include timbre, which is a sound characteristic that enables a listener to distinguish one instrument from another, even when played at the same pitch and loudness. Timbre is thus one of the more complex musical elements, composed of multiple parameters including the envelope (overall amplitude structure) and spectrum (range of frequencies) of a sound. Altogether, these musical parameters make up the tremendous complexity of music and encompass a larger range of frequencies, rhythms, timbral wave forms, and varied types of sound production (i.e. reed, percussion, bowed, etc.) compared to the spoken voice.

Many studies have shown that the perception of the temporal features of music, such as rhythm [17,18], tempo [19], and meter [17], are preserved in CI users and they are able to achieve similar perceptual performance as normal hearing (NH) adults [15,17,20–22]. However, many cochlear implantees have difficulty with spectral and combined spectral-temporal features of music including the perception of pitch [15,17,20–22], harmony [23], melody [19,24,25], and timbre [26–30]. Kang et al. [31] demonstrated that CI users had a pitch direction discrimination ability ranging from 1 to 8.0 semitones (3.0 ± 2.3, mean ± s.d. for all values) compared to 1 semitone (1.0 ± 0.3) for NH adults. In the same study, CI users correctly identified only 45.3% of musical instruments, compared to 94.2% for NH individuals.

This difficulty to perceive pitch-based elements may be at least partially attributed to the low resolution of the CI and skewed mapping of transmitted frequencies [16]. For example, in contrast to 3500 inner hair cells of healthy normal hearing (NH) individuals, CI users rely on at most 22 electrodes to convey tonotopic pitch information, resulting in grossly imprecise and broad auditory nerve stimulation by each electrode [16,32]. Moreover, while in NH listeners, pitch is encoded by the stimulation of specific locations in the cochlea (place-pitch) spanning from the basal to most apical regions, CI electrodes do not reach or stimulate the most apical regions due to limitations of the array itself [33,34]. Notably, studies have demonstrated wide variability in CI performance on music perception tasks, although it is unclear which predictor variables are associated with better or worse music perception. For example, in one study, while some CI listeners were able to discriminate notes spaced by one semitone reliably, others required a two-octave interval to detect a difference in pitch [25].

While the specific listener characteristics associated with better music perception are unknown, several studies have shown that music training can improve music perception and enjoyment for cochlear implant users [35–38]. Gfeller et al. [37] worked with 24 CI adults, 12 of which participated in a training program for 12 weeks. Training sessions included listening

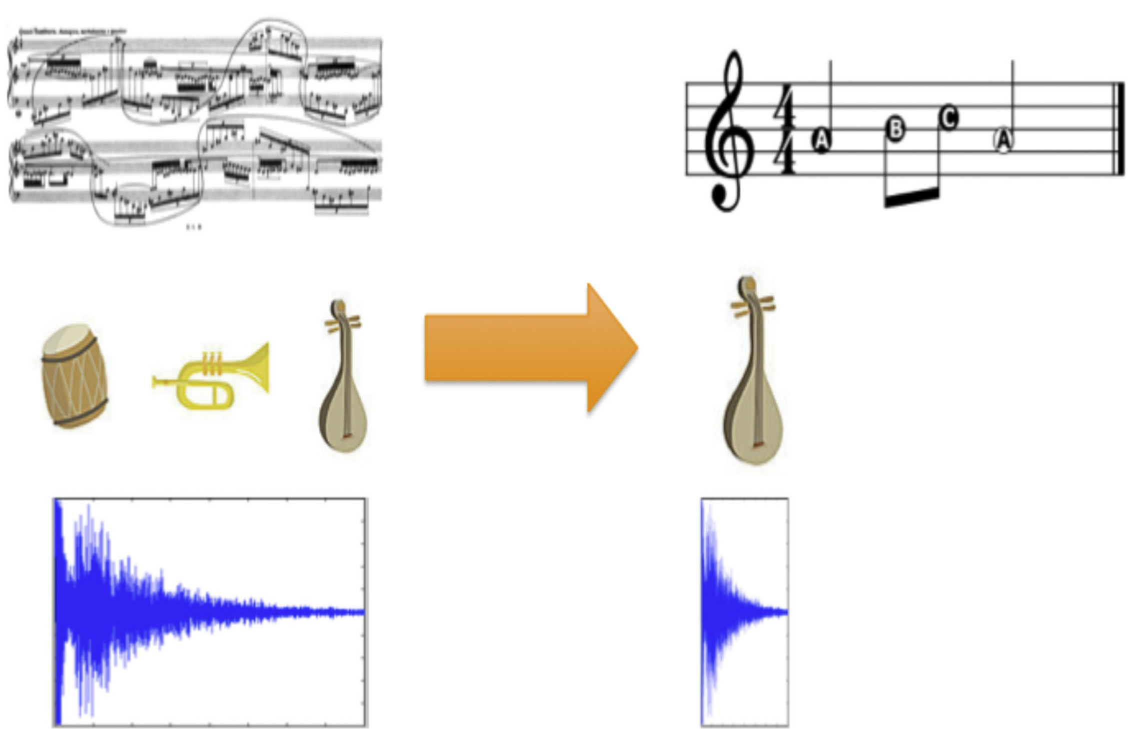


Fig. 1. Goal of re-engineering music for a CI patient. The hypothesis is that reducing the complexity of music may enhance the listening experience for CI listeners.

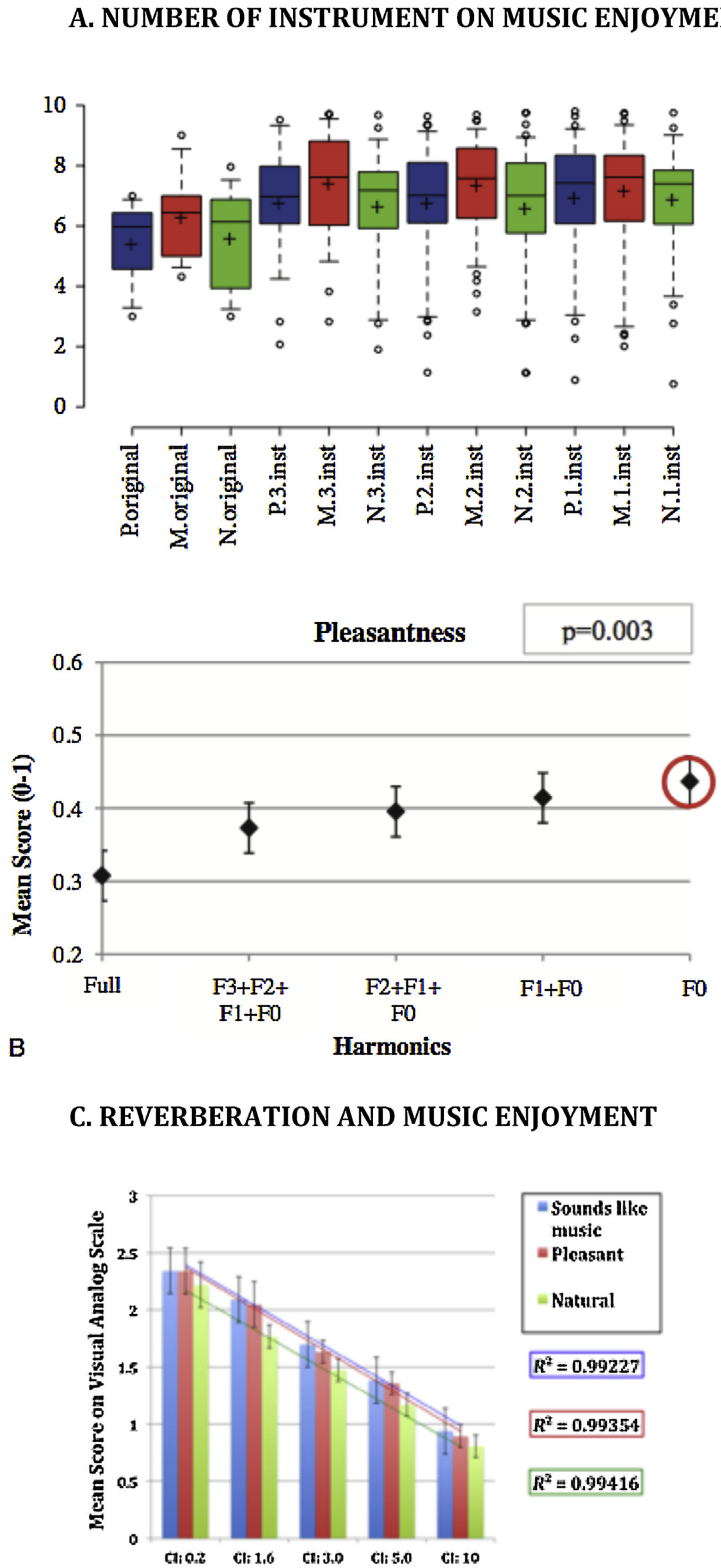


Fig. 2. Preference of cochlear implantees for number of instruments, harmonics and reverberation.
A. Number of instruments on music enjoyment. In general, the CI listeners preferred fewer instruments. The graph shows that CI listeners preference for modified segments of music comprised of a single instrument, two instruments, or three instruments compared to the original music sample containing **X** instruments. The Y-axis corresponds to a rate between 0 and 10 on VAS scale. *P: pleasant, N: natural, M: sounds like music* [14].
B. Harmonics and music enjoyment. CI recipients preferred reduced harmonics. The graph shows the mean score on the visual analog scale for pleasantness (Y-axis)

exercises for melodies and timbre, interactive computer software that conveyed strategies for optimizing one's listening environment. By the end of the study, CI users who underwent training demonstrated a clear enhancement of recognition and appraisal of melody and timbre compared to those without training. More recently, researchers have found that music-based training enhances not only music perception and enjoyment but also speech perception [39,40]. They hypothesize that the fine-tuned frequency discrimination required to perceive music likely translates to heightened perceptual skills of complex speech tasks such as vocal inflection, speech perception in noise, and speaker identification [39,40].

4. Music enjoyment

Despite poor music perception among the majority of CI users, 38–73.6% of CI users enjoy listening to music and 30.2%–37% report that they would undergo implantation again just to be able to listen to music [41,42]. There is also patient variability regarding the degree of enjoyment and listening habits post-implantation. In a questionnaire study of 53 CI users by Migirov et al. [42], self-report surveys assessing music enjoyment pre-deafness and post-implantation demonstrated that enjoyment ratings were similar in 22.6% of patients pre- and post-implantation, higher for 26.4% of patients post-implantation, and worse for 50.9% of patients after implantation. Similarly, a survey-based study of 35 CI patients by Mirza et al. [43] reported that 69% of patients were disappointed by how music sounded after implantation, yet 46% of CI users continued to listen to music. The same study reported mean ratings for music enjoyment of 8.7 on a 10-point visual analog scale (VAS) prior to hearing loss, compared to 2.6 using the CI.

In addition, multiple prospective studies have assessed the relationship between music perception and enjoyment, and have reported no association between the two [44–46]. Drennan et al. [46] administered both the Iowa Musical Background Questionnaire (IMBQ) questionnaire and the Clinical Assessment of Music Perception (CAMP) to 145 CI patients. The IMBQ is a self-report questionnaire assessing music enjoyment, musical training and listening habits pre- and post-implantation. The CAMP is a validated tool that assesses music perception including pitch, melody, and timbre recognition. There was little to no relationship between IMBQ and CAMP results in CI users, suggesting that music perception and enjoyment are independent and disparate subjects. While the unnatura-natural enjoyment scale correlated with CAMP scores, this relationship was weak at best ($r = 0.35$, Spearman), and thus unlikely to be clinically significant. Moreover, in a study by Wright et al. in which they assessed the relationship between music enjoyment and multiple music perception tests (AMICI, MBEA, MCI, CAMP), there was no relationship between music perception and appraisal in CI users [45]. Thus, it is important to study music enjoyment separately. Additionally, people often listen to music for pleasure, and therefore mere perception or accuracy in identifying specific components in music is not sufficient for implant benefit or improved quality of life. In fact, studies have suggested that the enhancement of music enjoyment is a better functional measure of music experience, and can improve the quality of life of CI patients [47–49].

There are several factors that determine a listener's enjoyment of music. Music is diverse and complex, encompassing a wide range of genres, instrument combinations, sounds, and rhythms. It is therefore useful to approach music enjoyment by examining both the subjective and objective complexity of music [47,50]. Subjective complexity is dependent on past listening experiences, listening conditions, music preferences, and other listener characteristics such as musical training and auditory sensitivity. Some studies suggest that certain characteristics including age, cognitive factors, and the presence of residual hearing may contribute to differences in music enjoyment outcomes [44,50]. In addition, environmental circumstances can also influence enjoyment, with enhanced experiences when listening in a quiet, non-reverberant room with good sound equipment [50]. Objective complexity is determined by individual musical elements and the acoustic waveform, including features such as the melody, rhythm, and structural redundancy.

Most music appraisal studies are conducted using subjective psychometric measures, such as a visual analog scale (VAS) [51–53] or Likert scale [45]. For example, upon listening to a musical excerpt, participants rate how pleasant–unpleasant [45,51–53], natural–unnatural [51–54], thin–full [37], dull–brilliant [37], like–dislike [27,37], clear–unclear [54], or music-like-not-music-like [51–53] the excerpt sounds. Other studies have utilized self-report questionnaires to assess CI users' subjective music experiences and listening habits, often utilizing a Likert scale for responses [47,55–57].

4.1. Emotional response to music

Another quantifiable aspect of music enjoyment is a listener's emotional response to music, given that music may stimulate strong emotions in NH listeners. It is also arguably one of the main purposes of music, and thus warrants investigation in CI users. In a study by Ambert-Dahan et al. [58] of 13 NH and 13 CI adults, all listeners were instructed to rate 4 different emotions (fear, happiness, sadness and peacefulness) on a VAS scale of 0–100 after listening samples of music. Results differed between both groups, with CI

across all instruments for actual CI rated samples as a function of harmonic level reduction. Ratings exhibited a positive linear relationship between harmonic level reduction and pleasantness. CI listeners show a preference for maximal harmonic series reduction. *CI indicates cochlear implant; LME, linear mixed effect* [53].
C. Reverberation and music enjoyment. CI recipients prefer minimal reverberation. The graph shows the mean score on the visual analog scale for "sounds like music," "pleasant," and "natural" across all instruments for CI simulation samples as a function of RT60 as well as the linear regression and coefficients of determination. CI samples with RT60 = 0.2 s were rated most musical, most pleasant, and most natural. *RT60 (reverberation time): time it takes for the intensity of a sound to be reduced by* 60 dB [51].

patients demonstrating less accuracy and greater variability for three of the emotions (fear, happiness and sadness) compared to NH listeners. However, ratings were similar across music stimuli with respect to how peaceful the stimuli sounded for NH and CI listeners. Although a small study, these results suggest that emotional judgments may be altered but also vary widely after cochlear implantation. Future studies should investigate music and emotional responses using a larger sample size and assess predictor variables for certain emotional responses. For example, emotional responses may correlate with certain objective and subjective measures, and would enable us to better understand how CI patients respond to the music that they hear.

5. Music re-engineering to enhance music enjoyment

To improve music enjoyment for CI listeners, there are two general approaches. The first is to improve the technological aspect of the CI itself, by developing enhanced sound processing strategies and CI hardware [59–63], or modifications in surgical technique such as variations in insertion angle or depth [64]. The second is to focus on the music itself by identifying specific features of music that are more enjoyable for CI patients, with the ultimate goal of re-engineering music to be more enjoyable based on these findings (Fig. 1).

Kohlberg et al. [52] studied the impact of a noise reduction algorithm (NRA) on music enjoyment in 9 CI users and 16 NH listeners with CI simulation. Upon listening to each of the 21 music samples, listeners rated how pleasant, music-like, and natural the clip sounded using a 10-point VAS. While there was no difference in enjoyment ratings of music with and without NRA, decreasing the number of instruments was significantly associated with enhanced pleasantness and naturalness. In another study by Kohlberg et al. [14] in which CI users listened to different arrangements of "Milk Cow Blues," modified versions containing only 1–3 instruments were more enjoyable to CI users compared to the original song (Fig. 2a). Of note, only versions played by 1 instrument alone or 3 instruments were significantly more enjoyable than the original version, with no statistically significant difference in 2-instrument versus the original song. Similarly, Looi et al. [65] demonstrated that CI users rated music played by single instruments as more pleasant and enjoyable than excerpts played by multiple instruments. Thus, reducing the complexity of music may enhance music enjoyment for CI users.

Similarly, other features of music were studied to identify how to decrease the complexity of music for a more enjoyable listening experience for cochlear implant users. Certo et al. [51] assessed the effect of different durations of reverberation, based on published reverberation times of actual concert venues and listening environments, on the enjoyment of music stimuli in 20 NH listeners with cochlear implant simulation. From this study, music stimuli with the least amount of reverberation time were rated as most enjoyable under implant conditions (Fig. 2b). These findings were supported by other studies demonstrating that reverberant conditions decrease music enjoyment [50,66], possibly due to the temporal and spectral smearing of reverberation, and resulting distortion of the original sound [67,68].

In another study, Nemer et al. [53] investigated the effect of harmonic reduction on music enjoyment. Harmonics are often described in terms of the sum of several distinct frequencies. The lowest frequency is called the fundamental frequency (F0); harmonics are whole number multiples of the fundamental frequency, and contribute to the richness of sound produced by a musical instrument. In the study by Nemer, 20 NH adults and 8 CI users listened to recordings of "Happy Birthday" by 7 different instruments, with five levels of harmonic reduction. They reported that NH adults had rated original, unprocessed stimuli as the most pleasant and natural at the first four harmonic levels. In contrast, NH adults listening to stimuli processed with CI simulation in addition to CI users rated stimuli with only the first harmonic alone as the most pleasant (Fig. 2c). Therefore, the reduction of complexity, with respect to the harmonic series, similarly resulted in enhanced music enjoyment.

Several studies have also demonstrated patterns of timbral enjoyment in CI users. Gfeller et al. [28] investigated the effect of different musical instruments on music appraisal in 20 NH and 51 CI adults. Participants listened to excerpts of the same short melody played by 8 different instruments and rated each excerpt on a VAS of three enjoyment measures: thin–full, dull–brilliant, like–dislike. CI listeners rated higher frequency instruments (violin, flute, piano played in the upper register) as noisier and less music-like compared to NH listeners. In comparison, NH non-musicians preferred music played by the violin over the clarinet, brass, and piano. These findings suggest that limited high frequency perception in CI users may be responsible for reduced enjoyment of higher frequency instruments [69]. Nemer et al. [53] also demonstrated variations in timbral enjoyment between NH and CI listeners, with CI listeners rating plucked violin as the least musical and natural compared to trumpet, piano, and marimba. In another study by Buyens et al. [70], cochlear implant subjects preferred the bass/drum track to be louder than the other instrument tracks. Altogether these studies suggest that CI users have different timbral preferences compared to NH listeners, and future studies investigating the re-engineering of music to sound more "percussive" or with lower frequency components may enhance music enjoyment for CI users.

6. Conclusions

Most cochlear implantees are able to achieve excellent speech perception in quiet. However, due to the greater complexity of music, many CI users have difficulty with music perception and enjoyment. While the perception of certain temporal elements such as rhythm and tempo are preserved, spectral or melodic elements including pitch, harmony, and timbre are difficult for most CI users. Yet despite poor music perception, most CI users report that they enjoy listening to music, with recent studies demonstrating that re-engineering music to reduce its complexity may enhance their enjoyment of listening to music. Further research to identify more enjoyable features of music, predictor variables for enjoyment, and the association of enjoyment with the emotional response to music should be explored. Altogether, a better understanding of these elements will enable further advancements in the overall music listening experience for CI users.

Conflicts of interest and sources of funding

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