Music Perception in Cochlear Implant Users

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Introduction

The last few decades have brought rapid advancements in cochlear implant technology. As basic language perception is now routinely achieved in properly selected candidates, the perception of other listening conditions, such as ambient sounds and music, has recently received a great deal of attention.

While music fundamentally differs from speech, music does share several similarities to spoken language (*see Figure 1)*. In both speech and music, sounds of varying frequency, duration, and timbre unfold over time to communicate a message, whether concrete (speech) or abstract (music). Both convey prosodic information that significantly affect their respective interpretations, such as inflection and phrasing. Perception of timbre is involved in both the recognition of a familiar voice or the identification of a musical instrument. Like language, music communicates, conveying important affective and expressive messages. However, unlike spoken language, music is ultimately abstract and its interpretation is highly subjective, depending on factors such as musical training, music listening habits, and cultural background.

Cochlear implant users face multiple difficulties in the perception and subsequent enjoyment of music. Implant users generally lack extensive exposure to music as a result of their hearing difficulties prior to implantation. Furthermore, following implantation many users report only minimal or incidental exposure to music. Since implants are primarily designed to convey speech discrimination, current technology remains limited when applied to musical stimuli.

Enjoyment and Recognition of Music

Musical enjoyment and listening habits vary significantly among implant users. Many implant users describe music as unpleasant or difficult to follow. Although most implant users report their daily music listening habits decline substantially following implantation, some users report they still enjoy listening music after implantation (Lassaletta, Castro *et al.*, 2007). Surveys of cochlear implant users' music listening habits indicate that a quiet listening environment and pre-existing familiarity with the music correlate with an increased enjoyment of music. One such study correlated the amount to time spent listening to music to the subjective judgment of music as pleasant (Gfeller, Christ *et al.*, 2000). While intriguing, it is difficult to ascertain if implant users who better perceive music tend to listen to music more frequently or if frequent musical listening practice facilitates improvements in music perception.

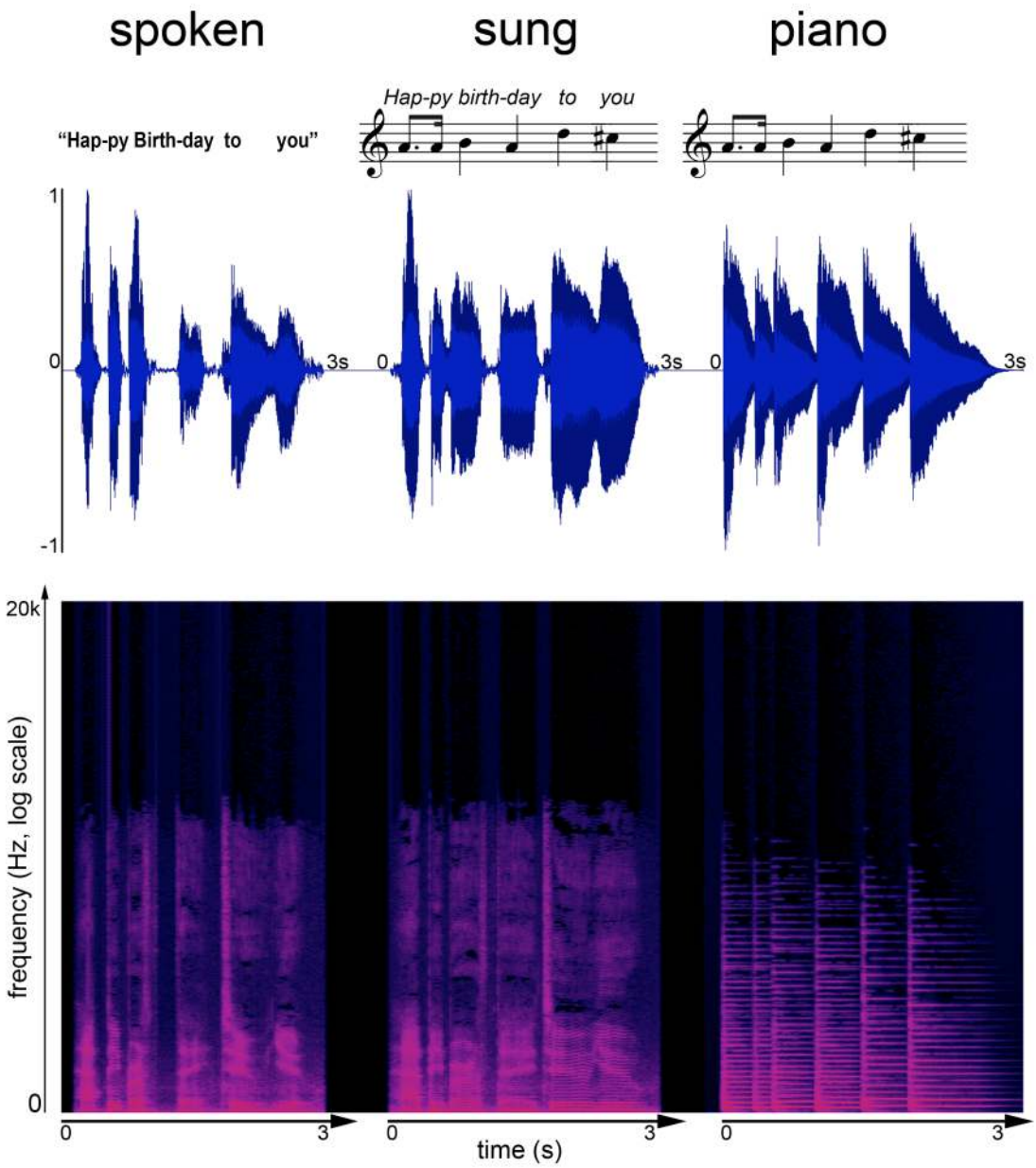


FIGURE 1. (a) The words "Happy Birthday" recited in a normal speaking voice; (b) the same words sung to the familiar melody; (c) the same melody played by a solo piano.

One major difference in speech and music is the distribution of spectral energy. In human speech, the spectral energy is often distributed over many frequencies and their respective harmonic partials. However in music, the spectral energy of a pitched musical note emphasizes the fundamental and its harmonic partials.

For many individuals, enjoyment of music is closely linked to the recognition of a familiar song or melody. For this reason, the ability to identify familiar melodies is one of the most common assessments of cochlear implant-mediated music perception. When post-lingually deafened cochlear implant users are presented with previously familiar, melodies, such as nursery rhymes or folk songs, cochlear implant recipients are consistently impaired when compared to normal hearing subjects. This impairment is reduced with the addition of vocal lyrics and musical accompaniment (Fujita and Ito, 1999; Leal, Shin, *et al.*, 2003). Congenitally deaf implanted children also more readily recognize a melody with lyrics and show an even greater deficit in the ability to recognize instrumental versions of melodies (Nakata, Trehub, *et al.*, 2005; Vongpaisal, Trehub, *et al.*, 2006; Mitani, Nakata, *et al.*, 2007). These results consistently demonstrate the importance of linguistic cues in the cochlear implanted-mediated recognition of a musical melody.

One large-scale study of seventy-nine CI users examined the ability to recognize a melody across several musical genres. The subjects showed significant deficits compared to the normal hearing control population and were most accurate in identifying country and pop music and least accurate in identifying classical music (Gfeller, Olszewski, *et al.*, 2005). A similar study assessed the subjective rankings of 'preference' and 'complexity' of music from these three genres. On average, implant subjects slightly preferred pop and country to classical music in contrast with the normal hearing group's strong preference for classical music. In addition, implant subjects ranked classical music as significantly more complex than did the normal hearing group (Gfeller ,Christ, *et al.*, 2003).

Rhythm

Numerous studies investigating cochlear implant-mediated perception of music implicate that rhythmic information – above all other music aspects – is the most readily perceived by implant listeners. Rhythm generally describes the temporal features of music that typically occur on the order of seconds, as opposed to the fine scale temporal features that occur on the order of milliseconds that are crucial in the perception of pitch and timbre. Research shows that macroscopic temporal cues are critically important to cochlear implant-mediated recognition of song. In other words, rhythmic patterns can often frame a musical passage yielding basic perception in spite of poor or erroneous perception of pitch, timbre, or other music aspects.

Several studies indicate that rhythm is crucial to the recognition of a familiar song and, at times, can be of greater importance than pitch cues alone. In one familiar song recognition study of 49 cochlear implant users, investigators found that two-thirds of the correctly identified melodies had a highly memorable rhythmic line, as opposed to a sequence of notes or equal duration (Gfeller, Turner, *et al.*, 2002). A similar study presented several familiar songs each in two forms. In the first version the melody was presented with both the original rhythmic and melodic information present while in the second the note length was equalized between songs, effectively removing any potential rhythmic cues. While normal hearing subjects achieved near perfect scores for both conditions, cochlear implant users were able to correctly identify almost two-thirds of the melodies with rhythmic information but were completely impaired in ability to recognize

any melodies with the rhythm removed (Kong, Cruz, *et al.* 2004). Another related study presented four different nursery tune melodies with similar rhythmic patterns all played by the same instrument in a uniform tempo. Cochlear implant users were only able to correctly identify the tune at chance levels (Fujita and Ito, 1999), further indicating the reliance of temporal cues over pitch cues by cochlear implant listeners.

In another study assessing the rhythmic perception of 29 cochlear implant subjects, subject heard pairs of rhythms in which one of the musical lines might differ in duration or intensity of the notes. Subjects were asked to identify if the pair was the 'same' or 'different' (discrimination task) and to determine the point of change (identification task). 59% and 41% of the subjects were able to discriminate and identify, respectively, all of the subtests. In addition, the authors found a correlation between performance in these rhythm tasks and speech perception scores. Two-thirds of the subjects who performed well in the rhythmic tasks achieved greater than 90% performance in a speech perception task (Leal, Shin, *et al.*, 2003).

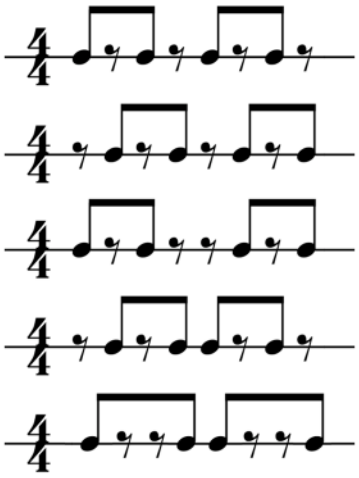


FIGURE 2. Several different rhythmic permutations of four eighth notes and four eighth note rests within a single measure.

While cochlear implant recipients often perceive broad, periodic rhythms rather well, research has only recently begun to investigate the ability to perceive subtle differences, changes, and variations in rhythm.

In one unique study, Kong *et al*. tested the ability of cochlear implant recipients to discriminate subtle changes in tempo. The stimuli consisted of pairs of rhythmic patterns in which one was played at one of four standard tempos of 60, 80, 100, 120 beats per minute and the other was played at a slightly faster tempo. The authors found that while mean thresholds for tempo discrimination were slightly lower (improved) for normal hearing individuals, there was no statistically significant difference between the two groups and no significant difference based on speed of the tempo (Kong, Cruz, *et al.* 2004). In the same study, the authors also tested the ability of cochlear implant subjects to identify a presented rhythm from one of seven notated rhythmic patterns. Subjects heard a four-beat rhythmic pattern in which the second note was comprised of permutations of quarter note into eighth and sixteenth notes while the remaining beats were all quarter notes. While the normal hearing controls responded with nearly 100% accuracy, the results of cochlear implant subjects varied from nearly perfect responses down to around 75% accuracy (Kong, Cruz, *et al.* 2004).

Pitch and Melody

Pitch processing is fundamental to the perception, identification, and enjoyment of music. Pitch describes the absolute frequency of a musical note framed within the context of a musical scale. A musical phrase, or melody, is created when a series of pitches are sequentially and temporally organized into patterns of varying musical contour and interval. The perception of melody requires the fine discrimination of changes in pitch, including both the direction of change (up or down) and the degree of change (interval size). While numerous studies have identified difficulties in the recognition and identification of melodies, more recent investigations have begun to isolate cochlear implant-mediated perception of pitch.

Pitch Discrimination

In the pitch discrimination task, subjects listening to two pitches must decide if this second is higher or lower than the first. Early investigations revealed that cochlear implant subjects vary widely in their ability to identify pitch changes using synthesized tones, ranging from those who could discriminate changes of 4 semitones or more to those who could not identify changes of an octave (Fujita and Ito, 1999). A more recent study compared pitch discrimination ability at 1 and 6 semitones using ‘real-world’ stimuli of sung vowels sounds. Cochlear implant subjects were severely impaired compared to normal hearing subjects and had a mean score of 60.2% for the 6 semitone change condition and 49% accuracy in the 1 semitone change condition. In addition the cochlear implant subjects frequently confused the direction of pitch change (Sucher and McDermott, 2007).

Another study investigated interval discrimination in 8 normal hearing individuals and 46 cochlear implant recipients using synthesized piano tones. While normal hearing subject averaged a mean minimum threshold of 1.13 semitones, cochlear-implant subjects averaged 7.56 semitones or about three-quarters of an octave. Of the cochlear implant subjects who scored above 30% on a related song recognition task, the average pitch discrimination threshold was 4.11 semitones (Gfeller, Turner, *et al.*, 2002). This correlation between ability to recognize melody and pitch discrimination threshold underscores the importance of accurate pitch perception to song recognition and to enjoyment of music in general.

In a simplified version of the pitch discrimination task, subjects need not identify the direction of change but must only decide if the second tone is a different pitch than the first. One large scale study investigating pitch discrimination included 101 implant users, 13 implant users with low-frequency residual hearing in the contralateral ear, and 21 normal hearing subjects. The investigators found that implant users with residual hearing (A+E group), compared to implant users without residual hearing, more accurately identified changes of pitch both as a function of interval size and across the range of frequencies tested (131 to 1048 Hz). Furthermore the accuracy of the A+E subject group declined in comparison to the normal implant users in the higher frequency ranges, emphasizing the importance of preserving low-frequency residual acoustic hearing (Gfeller, Turner, *et al.*, 2007).

Explicit Pitch Coding

Difficulties in the accuracy of cochlear-implanted perception of pitch arise from inherent ambiguities in mapping a fixed number of electrode contracts in evenly spaced positions along the tonotopic gradient of the cochlea. *Pitch placement* relies upon the tonotopic placement of the electrode along the cochlea. One study of six implant users compared predicted pitch perception of stimulated pitch of a single electrode (according to Greenwood's function) against acoustic tones presented to the contralateral ear with residual hearing. The authors found that electrically stimulated pitch may differ by up to two octaves from the acoustically stimulated pitches (Boēx, Baud, 2005). *Pitch rate*, on the other hand, describes the effects of varying rates of electrical stimulation alone (at a single electrode site) on pitch perception. Several experimental studies have shown that varying the rate of stimuli of a single electrode leads to the perception of changing pitch, suggesting that temporal cues alone may be exploited to provide pitch perception in implanted individuals, despite the fact that this approach differs fundamentally from normal processing of pitch within the cochlea (Limb, 2006).

Melodic Contour

The ability to detect the direction and interval in changes of pitch is crucial in identifying melodic contours (*see Figure 3)*. An intriguing study by Galvin and Fu tested the identification of melodic contour shape in 9 normal hearing and 11 cochlear implant users. Subjects heard various 5-note melodic contours and were asked to identify the contour shape from 9 visual choices. The normal hearing subjects achieved a mean performance of about 95% accuracy but the cochlear implant users' performance varied drastically from 14 to 90%. The implant users performed slightly worse in the lower frequency musical range. In addition, implant users' performance was significantly lower for contours involving intervallic changes of one or two semitones compared to those contours with five semitone changes between notes. Furthermore implant subjects more often correctly identified "flat" (no pitch change) contours and least often identified "falling" (descending) contours (Galvin, Fu, *et al.*, 2007).

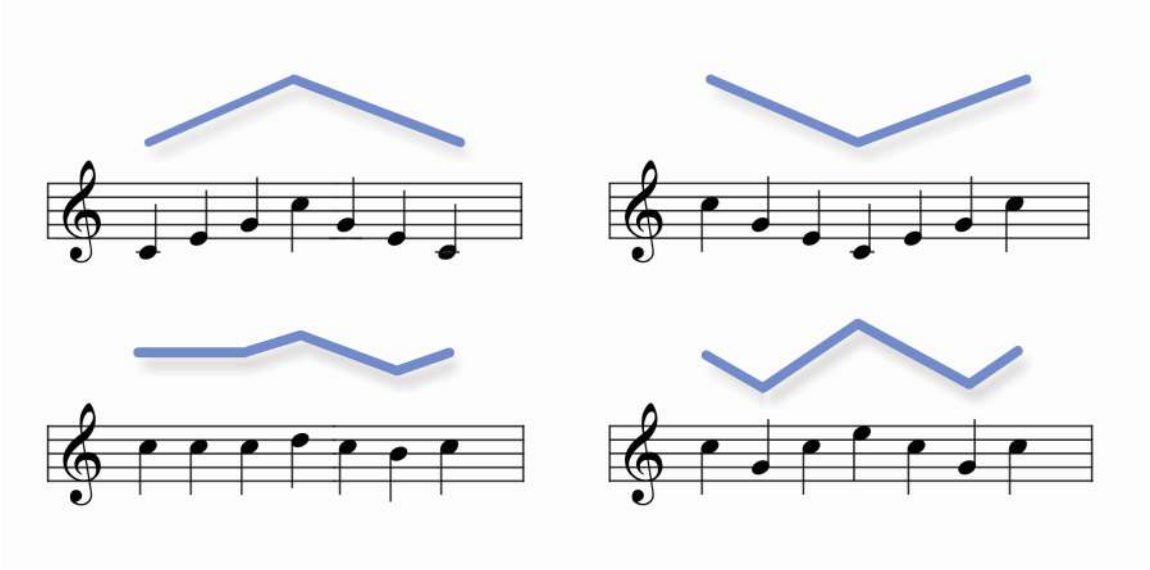


FIGURE 3. Several simple melodies and the shape of their respective melodic contour. The perception of change in pitch direction is crucial to the comprehension of a melody. Cochlear implant recipients often have greater difficulty perceiving small pitch intervals, such as those in the lower left-hand melody, as well as difficulty perceiving changes in pitch direction, such as those in the lower right-hand melody.

Timbre

Another fundamental feature of music is timbre, or tone-color. Derived from the acoustic properties of spectra (the ratios of the harmonics to the fundamental frequency) and timing (envelope) of each harmonic constituent, the psychoacoustic property of timbre permits us to differentiate between two musical instruments playing at the same pitch and volume level (*see Figure 4*). Because cochlear implant users must interpret these subtle acoustic properties of timbre through a device designed to code linguistic cues, the recognition and identification of musical instruments remains one of the more challenging aspects of cochlear implant-mediated perception of music.

Numerous studies have investigated the ability to discriminate between the timbres of different musical instruments (Gfeller and Lansing, 1991; Fujita and Ito, 1999; Leal, Shin, *et al.*, 2003). Normal hearing subjects more often mistake one instrument for another in the same instrument family (e.g., a trumpet for a trombone). Implant users, however, consistently show a more diffuse error pattern that is often unrelated to instrument family (Gfeller, Knutson, *et al.*, 1998; Gfeller, Witt, *et al*., 2002a). Implant users also show a greater deficit in identifying instrumental timbres in higher musical registers compared to those in lower registers (Gfeller, Witt, *et al*., 2002a). Cochlear implant subjects show greater ability to identify percussive instruments, such as the piano, in comparison to woodwind or brass instruments (Gfeller, Knutson, *et al.*, 1998; Gfeller, Witt, *et al*., 2002a; Gfeller, Witt, *et al.*, 2002b). Such results imply that the distinctive attack associated with percussive instruments serves as a valuable temporal cue in the cochlear implant-mediated identification of instrumental timbre.

Effects of Training

While the ability cochlear implant users to perceive music often correlate to levels of music exposure prior to implantation, several studies have demonstrated that training can improve music perception after implantation. One such study investigated the effects of training on six implant users on a melodic contour identification task for periods ranging from 1 week to 2 months with individual practice varying from 30 minutes to 3 hours per day. All patients showed marked improvement in the ability to recognize semitone distance and this improvement increased as the training period continued. Follow-up testing on two of the users performed at 2 months after training ceased showed a slight performance decrease compared to performance immediately following the training period but performance levels remained significantly improved over pre-training levels (Galvin, Fu, *et al.*, 2007). In a study of training effects on timbre recognition, 12 users trained for 12 weeks while a control group received no training. Although the two groups showed similar response patterns prior to training, following the training period the training group significantly outperformed the control group and showed a less diffuse error pattern compared to their own performance prior to training (Gfeller, Witt, *et al.*, 2002a). The results of these and similar studies continue to demonstrate the important and beneficial effects of long-term training on cochlear implant-mediated perception of music.

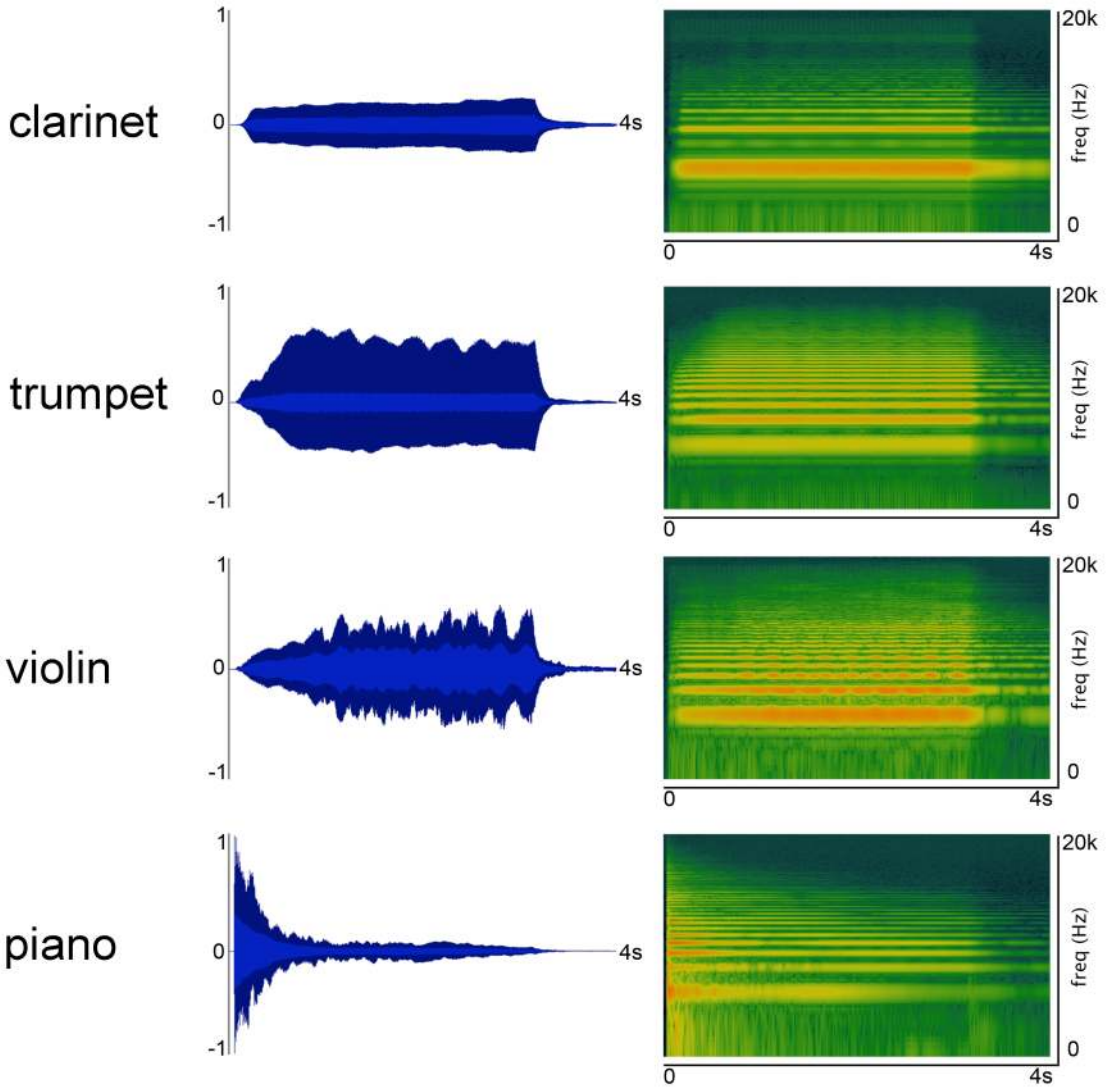


FIGURE 4. Comparison of a single note (middle C, 261.6 Hz) played by different instruments, representing each of the four primary instrument families: woodwinds, brass, strings, and percussion, respectively. The left column represents the acoustic waveform for each instrument, where the y-axis represents amplitude proportional to the voltage level of the resulting audio output. The right column is a log-based spectrogram of this waveform.

Conclusion

Music remains an extremely challenging category of auditory stimuli for implant users. While clinical investigations of cochlear implant-mediated perception of music must deconstruct music into its fundamental elements, such as melody, rhythm, and timbre, these individual aspects of music do not fully represent the complex challenges and difficulties faced by implant users while listening to music in most settings. Although cochlear implants are designed for language perception, the perception of music is now viewed as a viable possibility and is increasingly recognized as an important goal of cochlear implant and processing strategy design. Continual improvements in electrical-to-cochlear pitch mapping, pitch processing strategies, and the ability to preserve residual hearing in the implanted ears, together with an increased recognition of the importance of training should ultimately lead to major improvements in the ability of cochlear implants to convey musical information.

References

Boëx C, Baud L, Cosendai G, Sigrist A, Kós MI, Pelizzone M. Acoustic to Electric Pitch Comparisons in Cochlear Implant Subjects with Residual Hearing. Journal of the Association for Research in Otolaryngology 2006; 7: 110-124.

Fujita S, Ito J. Ability of nucleus cochlear implantees to recognize music. Ann Otol Rhinol Laryngol 1999; 108: 634-40.

Galvin JJ, Fu QJ, Nogaki G. Melodic contour identification by cochlear implant listeners. Ear and Hearing 2007; 28: 302-319.

Gfeller K, Christ A, Knutson J, Witt S, Mehr M. The effects of familiarity and complexity on appraisal of complex songs by cochlear implant recipients and normal hearing adults. J Music Ther 2003; 40: 78-112.

Gfeller K, Christ A, Knutson JF, Witt S, Murray KT, Tyler RS. Musical backgrounds, listening habits, and aesthetic enjoyment of adult cochlear implant recipients. J Am Acad Audiol 2000; 11: 390-406.

Gfeller K, Knutson JF, Woodworth G, Witt S, DeBus B. Timbral recognition and appraisal by adult cochlear implant users and normal-hearing adults. J Am Acad Audiol 1998; 9: 1-19.

Gfeller K, Lansing CR. Melodic, Rhythmic, and Timbral Perception of Adult Cochlear Implant Users. Journal of Speech, Language and Hearing Research 1991; 34: 916-920.

Gfeller K, Olszewski C, Rychener M, Sena K, Knutson JF, Witt S, et al. Recognition of" Real-World" Musical Excerpts by Cochlear Implant Recipients and Normal-Hearing Adults. Ear and Hearing 2005; 26: 237-250.

Gfeller K, Turner C, Oleson J, Zhang X, Gantz B, Froman R, et al. Accuracy of Cochlear Implant Recipients on Pitch Perception, Melody Recognition, and Speech Reception in Noise. Ear and Hearing 2007; 28: 412-423.

Gfeller K, Witt S, Adamek M, Mehr M, Rogers J, Stordahl J, et al. Effects of training on timbre recognition and appraisal by postlingually deafened cochlear implant recipients. J Am Acad Audiol 2002; 13: 132-45.

Gfeller K, Witt S, Woodworth G, Mehr MA, Knutson J. Effects of frequency, instrumental family, and cochlear implant type on timbre recognition and appraisal. Ann Otol Rhinol Laryngol 2002; 111: 349-56.

Gfeller K, Woodworth G, Robin DA, Witt S, Knutson JF. Perception of rhythmic and sequential pitch patterns by normally hearing adults and adult cochlear implant users. Ear and Hearing 1997; 18: 252–260.

Kong YY, Cruz R, Jones JA, Zeng FG. Music perception with temporal cues in acoustic and electric hearing. Ear Hear 2004; 25: 173–185.

Lassaletta L, Castro A, Bastarrica M, Pérez-Mora R, Madero R, De Sarriá J, et al. Does music perception have an impact on quality of life following cochlear implantation? Acta Oto-Laryngologica 2007; 99999: 1-5.

Leal MC, Shin YJ, Laborde M, Calmels M, Verges S, Lugardon S, et al. Music Perception in Adult Cochlear Implant Recipients. Acta Oto-Laryngologica 2003; 123: 826-835.

Mitani C, Nakata T, Trehub SE, Kanda Y, Kumagami H, Takasaki K, et al. Music recognition, music listening, and word recognition by deaf children with cochlear implants. Ear and Hearing 2007: 29S-33S.

Nakata T, Trehub SE, Mitani C, Kanda Y, Shibasaki A, Schellenberg EG. Music Recognition by Japanese Children with Cochlear Implants. J Physiol Anthropol Appl Human Sci 2005; 24: 29-32.

Pijl S. Labeling of musical interval size by cochlear implant patients and normally hearing subjects. Ear and Hearing 1997; 18: 364-72.

Sucher CM, McDermott HJ. Pitch ranking of complex tones by normally hearing subjects and cochlear implant users. Hear Res 2007; 230: 80-87.

Vongpaisal T, Trehub SE, Schellenberg EG. Song Recognition by Children and Adolescents With Cochlear Implants. Journal of Speech, Language, and Hearing Research 2006; 49: 1091.