Contribution of Hearing Aids

to Music Perception by Cochlear Implant Users

Nathaniel Peterson and Tonya R. Bergeson

Indiana University School of Medicine

Author Note

Tonya R. Bergeson, Department of Otolaryngology – Head and Neck Surgery, Indiana University School of Medicine; Nathan Peterson, Department of Otolaryngology – Head and Neck Surgery, Indiana University School of Medicine.

Nathan Peterson is now at Department of Otolaryngology – Head and Neck Surgery, Loma Linda University.

Correspondence concerning this article should be addressed to Tonya Bergeson, Department of Otolaryngology – Head and Neck Surgery, Indiana University School of Medicine, Indianapolis, IN 46202. E-mail: tbergeso@indiana.edu.

Abstract

Modern cochlear implant (CI) encoding strategies represent the temporal envelope of sounds well but provide limited spectral information. This deficit in spectral information has been implicated as a contributing factor to difficulty with speech perception in noisy conditions, discriminating between talkers and melody recognition. One way to supplement spectral information for CI users is by fitting a hearing aid (HA) to the non-implanted ear. In this study 14 postlingually deaf adults (half with a unilateral CI and the other half with a CI and an HA (CI+HA)) were tested on measures of music perception and familiar melody recognition. CI+HA listeners performed significantly better than CI-only listeners on all pitch-based music perception tasks. The CI+HA group did not perform significantly better than the CI-only group in the two tasks that relied on duration cues. Recognition of familiar melodies was significantly enhanced for the group wearing an HA in addition to their CI. This advantage in melody recognition was increased when melodic sequences were presented with the addition of harmony. These results show that, for CI recipients with aidable hearing in the non-implanted ear, using a hearing aid in addition to their implant improves perception of musical pitch and recognition of real-world melodies.

Keywords: cochlear implant, hearing aid, electroacoustic hearing, music perception

Contribution of Hearing Aids to Music Perception by Cochlear Implant Users

Historically, speech-encoding strategies for cochlear implants (CIs) explicitly encoded frequency-based information (Teig et al., 1992). More modern strategies, however, have focused on conveying temporal information at the expense of the spectral information within the temporal envelope (Grantham, Ashmead, Ricketts, Haynes, & Labadie, 2008). Studies with CI recipients and normal hearing individuals listening to CI simulations (i.e., vocoders) have shown that a lack of spectral information is a contributing factor to difficulty with speech perception in noisy listening environments as well as perception of music (Dorman, Gifford, Spahr, & McKarns, 2008; Dunn, Tyler, & Witt, 2005; Gifford, Dorman, McKarns, & Spahr, 2007). Fundamental frequency, a low-frequency spectral cue, has been shown to be important in identification of voice gender, a component of talker identification and discrimination (Mullenix, Johnson, Topcu-Durgun, & Farnsworth, 1995) as well as perception of music (Gfeller et al., 2012; Looi, 2008; McDermott, 2004).

Several methods for supplementing spectral information not provided by a cochlear implant are theoretically possible. Novel encoding strategies that rely on the presence of virtual channels could be developed to allow better distinction of frequency-based information (Firszt, Koch, Downing, & Litvak, 2007). Tests of this concept have led to promising results in some CI recipients, with the number of virtual channels theoretically possible increasing from 22 (the number of channels physically present on a CI electrode array) to well over 100. Such an increase could aid in the development of strategies to convey more fine-grained spectral information to the auditory system. Other encoding strategies that have been tested rely on explicit encoding of specific spectral cues, such as the fundamental frequency of a talker's voice (Milczynski, Wouters, & van Wieringen, 2009). However, all encoding strategies using methods

designed to substantially increase frequency-based information are strictly research tools at this time, and none are currently available for widespread use.

Another method for increasing the spectral information presented to the auditory system is the use of a hearing aid in addition to a cochlear implant (Dorman et al., 2008; Dunn et al., 2005; Gifford et al., 2007). This can be accomplished in two different ways: use of a hybrid device, or use of a conventional hearing aid (HA) in the ear contralateral to the implanted ear. Both methods rely on residual hearing to provide spectral information. Though the level of residual hearing may not be sufficient to independently provide meaningful audition (such as speech understanding), it can enhance the auditory capabilities of a cochlear implant user (Turner, Gantz, Vidal, Behrens, & Henry, 2004). Of these two methods of combining acoustic and electric hearing, the use of a conventional aid is the less restricted option, as hybrid devices are implanted only in implant candidates with hearing loss meeting certain criteria: hearing loss of less than 60 dB at 250 Hz, steeply sloping to severe/profound loss by 2000 Hz (Turner, Gantz, & Reiss, 2007). Additionally, placing the HA in the ear contralateral to the CI may provide some of the advantages of binaural hearing, such as sound localization (Ching, Incerti, & Hill, 2004; Ching, Incerti, Hill, & van Wanrooy, 2006) and speech perception in noisy listening environments (Ching et al., 2004; Luntz, Shpak, & Weiss, 2005).

Since many aspects of musical perception are based on musical pitch (frequency), a spectral cue, it would be reasonable to expect bimodal hearing to be superior to electrical hearing for perception of music. Indeed, studies using hybrid devices have shown that music appreciation, song recognition, instrument recognition, and pitch discrimination are all improved as compared to traditional long-electrode cochlear implants (Gantz, Turner, & Gfeller, 2006; Gfeller, Olszewski, Turner, Gantz, & Oleson, 2006; Gfeller et al., 2007). Dorman et al. (2008)

showed that in addition to improvements in speech perception, CI recipients who also relied on an HA in everyday use were more accurate in identifying melodies using both their CI and HA than when listening with only their CI. Two additional studies have reported better melody recognition when listeners use CIs and HAs as compared to CIs alone (El Fata, James, Laborde, & Fraysse, 2009; Kong, Stickney, & Zeng, 2005). These studies assume that the benefit of the low frequency hearing from the HA on music recognition is pitch perception. However, only one study that we are aware of has tested the perception of pitch and rhythm separately from song recognition, although they tested acoustic hearing and electric hearing in individual groups. When comparing a group of people using CIs versus HAs, (Looi, McDermott, McKay, & Hickson, 2008) found that the HA users had better pitch discrimination and song recognition than the CI users. The two groups performed similarly on tests of rhythm perception and instrument recognition.

The aim of the present study was to determine whether the use of an HA in addition to a CI provides CI recipients with some advantage in perception of specific musical features: perception of musical scale, melodic contour, pitch interval, rhythm, meter, and melodic memory. Additionally, we examined the benefit that binaural/bimodal hearing provides over electric hearing for the recognition of familiar melodies. We presented postlingually deaf adults (half of whom used a CI alone; the other half of whom used a CI and an HA in the contralateral ear) a series of tests including the *Montreal Battery for Evaluation of Amusia* and a melody recognition task. Based on the results of the studies presented above, we hypothesized that the group who used both CIs and HAs would perform better on tests involving pitch and melody perception, but that the two groups would perform similarly on tests involving rhythm and meter perception. We also hypothesized that the poorer performance on pitch and melody perception

would adversely affect memory for familiar melodies as well as newly learned melodies in the CI-only group as compared to the CI+HA group.

Method

Participants

We recruited fourteen postlingually deaf adults with postlingual deafness who received a CI at the Department of Otolaryngology—Head and Neck Surgery at the Indiana University School of Medicine. Seven study participants were unilateral cochlear implant users (CI-only group), and seven used a cochlear implant and a conventional hearing aid in the ear contralateral to the cochlear implant (CI+HA group). All participants were native English speakers who had used their current mode of amplification for a minimum of one year. All participants took part in a larger study at this center examining speech perception, vowel identification, dialect identification, and talker discrimination (unpublished data and Hay-McCutcheon, Peterson, Rosado, & Pisoni, 2014). Informed consent was obtained from all participants at the time of entry into this study.

Age, years of device use, pre-implant better-ear pure-tone average (PTA) and pre-implant better-ear low frequency pure-tone average (LF-PTA) of the two groups are shown in Table 1. PTA was calculated as the mean value of the levels of hearing loss (in dB) as measured by pure-tone audiometry at 500, 1000, and 2000 Hz in the better ear at the last clinic appointment prior to implantation. LF-PTA was calculated because some authors have argued that the primary benefit of a hearing aid in addition to a CI is from the addition of low-frequency information(Mok, Grayden, Dowell, & Lawrence, 2006). LF-PTA was determined in the same manner as PTA, except that the frequencies at which hearing loss was measured were 250, 500 and 1000 Hz. Differences between the two groups were not statistically significant for age, PTA and LF-PTA.

The CI group had significantly more CI use (mean = 9.6 years, SD = 5.9) than the CI+HA group

(mean = 2.8 years, SD = 1.1), $t(12) = 2.99$, $p = .011$.

Music Perception Tasks

To evaluate music perception, the *Montreal Battery for Evaluation of Amusia* (MBEA)

was used (Peretz, Champod, & Hyde, 2003). The MBEA is a series of six subtests initially

developed for identification and classification of musical disorders in normal-hearing people. It

has been validated on over 160 normal-hearing adults and has demonstrated good test-retest

reliability. The normal-hearing mean score is 86 – 90% correct for each subtest. Each of the six

subtests assesses perception of a different aspect of music: scale, contour, interval, rhythm,

meter, and memory. We presented the subtests in this order. Throughout the testing, each study

participant was seated in a sound-attenuated booth with a single loudspeaker at zero degrees

azimuth. All stimuli were presented at 65 dB SPL.

In the first four subtests (scale, contour, interval, rhythm), the participant heard a warning

signal followed by two short melodic sequences, separated by 2 seconds of silence. After

listening to the two melodic sequences, the participant selected one of two buttons displayed on a

computer monitor (one marked "same," the other labeled "different"), indicating whether (s)he

judged the two melodies to be same or different. If the two melodies were different, they varied

by a single note; the altered note was never the first or last note in the melody. Each subtest

consisted of approximately 30 pairs of melodies presented in random order; the correct answer

for half the pairs was "same," and the correct answer for half the pairs was "different." All

melodic sequences were presented using a synthetic piano tone.

For the melodic pairs that were different, the changed note was altered in a systematic

fashion according to the subtest being taken. In the scale subtest, the note was varied so that it

was not from the same scale as the rest of the tune; it would sound "out of tune" to a normal-hearing listener. The contour subtest altered notes so that the melodic contour would be changed, moving up instead of down or vice versa. Notes that were different in the interval subtest were of a larger or smaller step size from the preceding and following notes, but the general direction (up or down) of the note change remained the same as in the first melody. All pitches were unchanged between the two melodies in the rhythm subtest, but in the "different" pairings, the duration of one of the notes was lengthened or shortened (Peretz et al., 2003).

The final two tasks of the MBEA presented the listener with a single melody and asked him/her to make a judgment regarding that melody. In the meter subtest, the participant heard a melody with harmony present and was asked to judge whether the tune had 2 or 3 beats per measure. They indicated their choice by selecting one of two buttons displayed on a computer monitor: one marked "march," the other labeled "waltz." This was the only subtest in which harmony was used, and it was included to make the meter of each melody more apparent. Throughout the testing, the same set of melodies was used for the first melody in each pair. In the final MBEA task (memory), the participant heard a single melody and was asked to indicate whether they had heard the melody in the previous tests; buttons displayed on the computer screen were labeled "yes" and "no." Participants were not told of the memory task prior to testing (Peretz et al., 2003).

Melody Recognition Tasks

A melody recognition task based on the Gfeller et al. (2002) study was given to each participant in the current project. Common American melodies such as familiar patriotic, folk and nursery songs were presented to each listener. Melodies were classified as either rhythmic or arrhythmic according to whether they contained distinctive rhythmic features, such as dotted

eighth notes or triplets (e.g., The Star-Spangled Banner). Arrhythmic melodies were composed

of mostly quarter notes with a sustained note at the end of each phrase (e.g., Twinkle, Twinkle

Little Star). Arrhythmic melodies, therefore, did not contain significant duration-based cues to

help the listeners identify the tune.

In addition to the actual melodies, 5 foils were composed. These were designed to

investigate the probability that CI listeners with or without hearing aids would misidentify a

novel melodic sequence as a similar one with which they were familiar. Each foil was

rhythmically identical to one of the melodies, but the pitches were different. Table 2 below is a

list of the songs used in the melody recognition task; an "(f)" after a song title indicates that a

foil that was rhythmically identical to that song was also composed and presented to the listeners.

Melodies were presented in random order using a synthesized piano tone at 65 dB SPL

over a single loudspeaker located at zero degrees azimuth. After listening to each melody, the

participant attempted to verbally identify the name of the song for the examiner. Emphasis was

on demonstrating recognition, not correct naming. Thus, alternative names were accepted. If a

study participant stated (s)he recognized the song but was unable to remember the name, (s)he

was asked what was associated with the song (e.g., at what occasion the song would be sung). If

the listener could not identify the tune but was certain (s)he recognized it, (s)he was given the

opportunity to hum it back to the examiner. This was only used as an option of last resort.

The familiar melody recognition task was administered in two conditions: a melody-only

condition and a melody-plus-harmony condition. Foils were included only in the melody-only

condition. Thus, a total of 16 tunes were presented in the melody-only condition, followed by 11

songs in the melody-plus-harmony condition. We calculated the total percent of tunes correctly

identified for both the melody-only and melody-plus-harmony conditions. Percent of rhythmic

tunes correctly identified and percent of arrhythmic tunes correctly identified was also determined. We also calculated the percent of foils misidentified as their rhythmically identical song within the melody-only condition.

Results

Music Perception

The results for each subtest of the MBEA are presented in Figures 1 and 2. The subtest name is listed on the horizontal axis of the box plots, and the percentage of items in each subtest answered correctly is on the vertical axis. The box extends vertically from the 25th to the 75th percentile of the scores. The solid line within each box is the median score, and the dashed line within each box is the mean of the scores for each task. Scores below the 25th percentile or above the 75th percentile are plotted as individual data points. White boxes are unilateral CI recipients' results, and gray boxes represent test scores for the CI+HA group. The horizontal line at 50% correct indicates the level of chance performance on these tasks. Figure 1 shows the scores for the first three subtests of the MBEA (scale, contour and interval, all pitch-based tasks) and Figure 2 displays results for the remaining three subtests of the MBEA (rhythm, meter and memory).

The mean scores of the musical pitch-based based tests in Figure 1 are all well below the NH mean value of approximately 90% for each subtest. In the Scale subtest, there was no significant difference between the CI-only and CI+HA groups. The CI+HA group did perform significantly better than the CI-only group on the Contour (CI mean = 55%, SD = 7.3%; CI+HA mean 73%, SD = 8.3%), $t(12) = 4.31$, $p = 0.001$, and Interval subtests of the MBEA (CI mean = 53%, SD = 4.5%; CI+HA mean = 66%, SD = 9.8%), $t(12) = 3.27$, $p = 0.007$.

Figure 2 is a series of box plots representing the scores on the final three tests of the MBEA. In both the Rhythm and Meter subtests, there is no significant difference between the CI-only and CI+HA groups. On the MBEA test of melodic Memory, the CI+HA group performed significantly better than the CI-only group (CI mean = 56%, SD = 11%; CI+HA mean = 73%, SD = 7.3%), $t(12) = 2.49$, $p = 0.029$.

Comparison of subtest scores within each group was also performed. One-way ANOVAs conducted on all subtests for the CI-only group revealed that there was a statistically significant difference between subtest scores, $F(5, 41) = 7.6$, $p < 0.001$. Subsequent multiple pairwise comparison by the Holm-Sidak method showed that mean scores for both the Rhythm and Meter subtests were significantly higher than mean scores on the Scale, Contour, Interval, and Memory subtests for the CI-only group. Similar use of one-way ANOVAs among the individual subtests for the CI+HA group indicated statistically significant differences among mean scores, $F(5, 41) = 3.4$, $p = 0.012$. Subsequent pairwise comparisons within the CI+HA group showed that the mean Rhythm subtest score was significantly better than performance on the Scale subtest. All other pairwise comparisons were not statistically significant.

Melody Recognition

Scores on the Melody Recognition task are in Figures 3 – 5. As for the MBEA results, the Melody Recognition results are shown as box plots. Each box extends from the 25th to 75th percentile of scores (shown as percent correct on the vertical axis); whiskers, if present, extend outward from the box to the 10th and 90th percentiles; data outside the range covered by the box and whisker plot are shown as individual data points. Solid horizontal lines in each box indicate the median score, and dashed horizontal lines are at the mean score. The type of song – total score, rhythmic, arrhythmic, or foil – is on the horizontal axis. Score for each portion of the task

is on the vertical axis. For the categories total score, rhythmic and arrhythmic, the score is the percent of songs correctly identified. For the category foil, the score is the percent of foils that were incorrectly identified as the rhythmically identical melody. The total score is the combination of the scores for the rhythmic and arrhythmic melodies; it does not include the score for the foils. Whiskers are present in Figure 3 but not in Figures 4 or 5 because Figure 3 compares scores across conditions for all study participants, but Figures 4 and 5 display each group separately, reducing the number of data points represented by any one box. With fewer data points, calculation of multiple percentile levels is unreliable, thus 10th and 90th percentiles were not computed.

Figure 3 shows the aggregate results for both groups (CI-only and CI+HA) on the melody recognition task. The first box (filled with vertical lines) in each pair of boxes corresponds to scores for the melody-only condition; the second box in each pair (filled with diamonds) represents scores for the melody-plus-harmony condition. No foils were included in the melody-plus-harmony condition.

As seen in Figure 3, the conglomerate scores on the Melody Recognition task exhibited wide variation, with total score ranging from 0 to 91% (0 to 10 out of 11 melodies) correctly identified. Similarly, recognition scores for both the rhythmic and arrhythmic melodies are widely distributed. On average, one out of five foils (20%) was misidentified as the rhythmically identical melody. The decrease in mean scores between rhythmic and arrhythmic melodies was not statistically significant. The addition of harmony had no significant effect on the overall scores or the recognition of either song type, as means and score distributions were almost identical in the melody-only and melody-plus-harmony conditions.

Figure 4 shows the results of the Melody Recognition task for each group. As with the MBEA box plots, the scores for the CI-only and CI+HA groups are represented by white and gray boxes, respectively. CI+HA listeners identified songs in the melody-only condition with significantly greater accuracy than CI-only listeners (CI mean = 17%, SD = 14% CI+HA mean = 57%, SD = 31%,), $t(12) = 3.13$, $p = 0.009$. For the subset of melodies that contained distinctive rhythmic features, the difference between the CI-only (mean = 19%, SD = 14%) and CI+HA (mean = 69%, SD = 35%) Melody Recognition scores was also significant, $t(12) = 3.45$, $p = 0.005$. However, in arrhythmic melodies, the difference in mean scores between groups approached, but did not attain, significance (CI mean = 14%, SD = 19%; CI+HA mean, 43%, SD = 31%), $t(12) = 2.06$, $p = 0.062$. CI+HA listeners were as likely as CI-only listeners to mistakenly identify a foil as its rhythmically identical counterpart melody (CI mean = 17%; CI+HA mean = 14%), *ns*.

Figure 5 is a series of box plots depicting the results of the Melody Recognition task when administered with both melody and harmony. In the melody-plus-harmony condition, CI+HA users were significantly more accurate than CI-only listeners in identifying familiar American melodies either with or without distinctive rhythmic characteristics. (Rhythmic songs: CI mean = 17%, SD = 17%; CI+HA mean = 69%, SD = 33%, $t(12) = 3.79$, $p = 0.003$; Arrhythmic songs: CI mean = 11%, SD = 16%; CI+HA mean = 46%, SD = 25%, $t(12) = 3.07$, $p = 0.010$.) The total Melody Recognition score for CI+HA listeners was also significantly better than the mean total score for the CI-only group (CI mean = 14%, SD = 12%; CI+HA mean = 58%, SD = 27%), $t(12) = 3.95$, $p = 0.002$.

We performed one-way ANOVAs to investigate differences among total score, rhythmic melody recognition, and arrhythmic melody recognition for each group in each test condition.

No differences among total, rhythmic and arrhythmic melody recognition scores were significant.

Discussion

Results from the *Montreal Battery for Evaluation of Amusia* revealed that in all but one of the pitch-based subtests (Scale), the addition of a hearing aid to a cochlear implant increased performance significantly. In fact, the performance of the 25th percentile of the CI-only group was at chance performance across the pitch-based subtests. Keep in mind as well that the CI-only group in this study had significantly more CI experience (9.6 years) than the CI+HA group (2.8 years). It seems clear that CI experience did not contribute to the music perception results.

It is interesting that the CI+HA group perceived the Contour and Interval changes but not Scale changes, which are a arguably a different type of change compared to Contour and Interval. That is, Scale changes the tonal quality or "feel" of music from major to minor or "in tune" to "out of tune," whereas Contour changes a series of notes from moving up or down and Interval changes the specific distance from one note to another. Moreover, there were smaller changes in pitch (often only one half-step) in the "different" melody pairs in the Scale subtest as compared to the other MBEA subtests, which made much larger changes in pitch in the second melodic sequence when it was different from the first melody in the pair. Research by Galvin et al. (Galvin, Fu, & Nogaki, 2007) has shown that increasing step size between notes increases the accuracy of melodic contour identification by CI recipients. In any case, this finding is worth additional exploration in future studies.

We should note that even with the addition of the HA, the CI+HA group still did not reach the normal-hearing normed averages on the MBEA (90%) for all pitch-related subtests

(scale, contour, interval and memory). In other words, hearing loss in general still had effects on music perception in this group of adults that the HA could not resolve.

CI-only listeners also performed significantly better on the rhythm and meter subtests than on all other subtests of the MBEA, and their CI+HA peers performed just as well. This is in agreement with other studies showing that CI listeners perceive rhythmic information much better than musical pitch, and that there are no differences between CI-only and CI+HA listeners in conditions of musical rhythm (Dorman et al., 2008; Drennan & Rubinstein, 2008; El Fata et al., 2009; Gfeller et al., 2012; Kong et al., 2005; Looi et al., 2008).

Melody recognition was widely variable for the group as a whole, with scores ranging from 0 to 10 out of 11 melodies correctly identified in both the melody-only and melody plus harmony conditions. Addition of harmony to the melodic structure appeared to neither decrease recognition (due to the "noise" of the harmony) nor to increase recognition (due to increased cues). In fact, the addition of harmony had almost no effect on any aspect of the distribution of scores – the means, medians, minima, and maxima of each component of the melody recognition task were essentially the same in both conditions.

Listening with a hearing aid in the ear contralateral to the CI was almost universally beneficial across the subjects in this study in correctly recognizing common American tunes. Total score for melody recognition in both the melody-only and the melody-plus-harmony conditions was significantly better for CI+HA listeners than it was for the CI-only group. The same was true for both types of melodies (rhythmic and arrhythmic) in the condition with harmony, and for rhythmic songs in the melody-only condition.

Interestingly, the greatest difference between the CI-only and the CI+HA groups was found in the songs with distinctive rhythmic features when they were played in the melody-only

condition. In this component of the melody recognition task, the best CI-only score was not as good as the worst CI+HA score. This is in contrast to the results in the more structured MBEA, in which CI-only and CI+HA groups were not statistically distinguishable on the rhythm subtest. Additionally, neither group of participants scored statistically better on one melody type (rhythmic vs. arrhythmic) than on the other. This indicates that although both groups – and especially CI-only listeners – score higher on rhythmic tests than on pitch-based tests, they do not appear to use this information well in identifying real-world melodies.

Conclusions

Cochlear implants using modern speech encoding strategies do not adequately convey pitch-based information needed for music perception or melody recognition. Although CI users can objectively discriminate between rhythmically different melodic sequences, they still struggle to identify familiar real-world melodies with distinct rhythms. Acoustic amplification of residual hearing in the non-implanted ear of a CI recipient is one way to improve music perception and recognition of melodies.

References

Ching, T. Y., Incerti, P., & Hill, M. (2004). Binaural benefits for adults who use hearing aids and cochlear implants in opposite ears. *Ear and Hearing, 25*(1), 9-21.

Ching, T. Y., Incerti, P., Hill, M., & van Wanrooy, E. (2006). An overview of binaural advantages for children and adults aho use binaural/bimodal hearing devices. *Audiology and Neurotology, 11*(Suppl 1), 6-11.

Dorman, M. F., Gifford, R. H., Spahr, A. J., & McKarns, S. A. (2008). The benefits of combining acoustic and electric stimulation for the recognition of speech, voice and melodies. *Audiology & Neurotology, 13*(2), 105-112.

Drennan, W. R., & Rubinstein, J. T. (2008). Music perception in cochlear implant users and its relationship with psychphysical capabilities. *Journal of Rehabilitation Research & Development, 45*(5), 779-789.

Dunn, C. C., Tyler, R. S., & Witt, S. A. (2005). Benefit of wearing a hearing aid on the unimplanted ear in adult users of a cochlear implant. *Journal of Speech Language and Hearing Research, 48*(3), 668-680.

El Fata, F., James, C. J., Laborde, M. L., & Fraysse, B. (2009). How much residual hearing is 'useful' for music perception with cochlear implants? *Audiology & Neuro-otology, 14*, 14-21.

Firszt, J. B., Koch, D. B., Downing, M., & Litvak, L. (2007). Current steering creates additional pitch percepts in adult cochlear implant recipients. *Otology and Neurotology, 28*(5), 629-636.

Galvin, J., Fu, Q. J., & Nogaki, G. (2007). Melodic contour identification by cochlear implant listeners. *Ear and Hearing, 28*(3), 302-319.

Gantz, B. J., Turner, C., & Gfeller, K. E. (2006). Acoustic plus electric speech processing: preliminary results of a multicenter clinical trial of the Iowa/Nucleus Hybrid implant. *Audiology & Neuro-otology, 11*, 63-68.

Gfeller, K., Jiang, D., Oleson, J. J., Driscoll, V., Olszewski, C., Knutson, J. F., . . . Gantz, B. (2012). The effects of musical and linguistic components in recognition of real-world musical excerpts by cochlear implant recipients and normal-hearing adults. *Journal of Music Therapy, 49*, 68-101.

Gfeller, K., Olszewski, C., Turner, C., Gantz, B., & Oleson, J. J. (2006). Music perception with cochlear implants and residual hearing. *Audiology & Neuro-otology, 11*, 12-15.

Gfeller, K., Turner, C., Mehr, M., Woodworth, G., Fearn, R., Knutson, J., . . . Stordahl, J. (2002). Recognition of familiar melodies by adult cochlear implant recipients and normal-hearing adults. *Cochlear Implants International, 3*(1), 29-53.

Gfeller, K., Turner, C., Oleson, J. J., Zhang, X., Gantz, B., Froman, R., & Olszewski, C. (2007). Accuracy of cochlear implant recipients on pitch perception, melody recognition, and speech reception in noise. *Ear & Hearing, 28*, 412-423.

Gifford, R. H., Dorman, M. F., McKarns, S. A., & Spahr, A. J. (2007). Combined electric and contralateral acoustic hearing: word and sentence recognition with bimodal hearing. *Journal of Speech Language and Hearing Research, 50*(4), 835-843.

Grantham, D. W., Ashmead, D. H., Ricketts, T. A., Haynes, D. S., & Labadie, R. F. (2008). Interaural time and level difference thresholds for acoustically presented signals in post-lingually deafened adults fitted with bilateral cochlear implants using CIS+ processing. *Ear and Hearing, 29*(1), 33-44.

Hay-McCutcheon, M. J., Peterson, N. R., Rosado, C. A., & Pisoni, D. B. (2014). Identification of acoustically similar and dissimilar vowels in profoundly deaf adults who use hearing aids and/or cochlear implants: Some preliminary findings. *American Journal of Audiology, 23*, 57-70.

Kong, Y.-Y., Stickney, G. S., & Zeng, F.-G. (2005). Speech and melody recognition in binaurally combined acoustic and electric hearing. *Journal of the Acoustical Society of America, 117*, 1351-1361.

Looi, V. (2008). The effect of cochlear implantation on music perception: A review. *Otorinolaryngologia, 58*, 169-190.

Looi, V., McDermott, H., McKay, C., & Hickson, L. (2008). Music perception of cochlear implant users compared with that of hearing aid users. *Ear & Hearing, 29*, 421-434.

Luntz, M., Shpak, T., & Weiss, H. (2005). Binaural-bimodal hearing: concomitant use of a unilateral cochlear implant and a contralateral hearing aid. *Acta Otolarygologica, 125*(8), 863-869.

McDermott, H. J. (2004). Music perception with cochlear implants: A review. *Trends in Amplification, 8*, 49-81.

Milczynski, M., Wouters, J., & van Wieringen, A. (2009). Improved fundamental frequency coding in cochlear implant signal processing. *Journal of the Acoustical Society of America, 124*(4), 2260-2271.

Mok, M., Grayden, D., Dowell, R. C., & Lawrence, D. (2006). Speech perception for adults who use hearing aids in conjunction with cochlear implants in opposite ears. *Journal of Speech Language and Hearing Research, 49*(2), 338-351.

Mullenix, J. W., Johnson, K. A., Topcu-Durgun, M., & Farnsworth, L. M. (1995). The perceptual representation of voice gender. *Journal of the Acoustical Society of America, 98*(6), 3080-3095.

Peretz, I., Champod, S., & Hyde, K. (2003). Varieties of musical disorders: the Montreal Battery for Evaluation of Amusia. *Annals of the New York Academy of Sciences, 999*, 58-75.

Teig, E., Lindeman, H. H., Flottorp, G., Tvete, O., Hanche-Olsen, S., & Arnsten, O. (1992). Patient performance with two types of multiple electrode intracochlear implant. *Scandinavian Audiology, 21*(2), 93-99.

Turner, C. W., Gantz, B. J., & Reiss, L. (2007). Integration of acoustic and electric hearing. *Journal of Rehabilitation Research & Development, 45*(5), 769-778.

Turner, C. W., Gantz, B. J., Vidal, C., Behrens, A., & Henry, B. A. (2004). Speech regognition in noise for cochlear implant listeners: benefits of residual acoustic hearing. *Journal of the Acoustical Society of America, 115*, 1729-1735.

Table 1.

Demographic information for research participants

		Unilateral CI	Bimodal (CI+HA)
n		7	7
age (yr)	mean ± SD	57 ± 11	63 ± 12
	range	48 – 80	39 – 72
duration of use (yr)	mean ± SD	9.6 ± 5.9	2.8 ± 1.1
	range	3.9 – 18.4	1.5 – 4.1
PTA (dB HL)	mean ± SD	106 ± 9	97 ± 10
	range	92 – 120	83 – 113
LF-PTA (dB HL)	mean ± SD	102 ± 12	88 ± 19
	range	83 – 120	60 – 108

Note. Mean, standard deviation, maximum and minimum are shown for each demographic variable.

Table 2.

Songs used in the melody recognition task

Rhythmic melodies	Arrhythmic melodies
America (My country, 'tis of thee)	Down in the valley
For he's a jolly good fellow	Frere Jacques (f)
Happy birthday (f)	On top of old smoky
Row, row, row your boat (f)	Twinkle, twinkle little star (f)
Star spangled banner	Yankee doodle
Wedding march (Here comes the bride) (f)	

Note. Songs are categorized by presence of distinct rhythmic features.
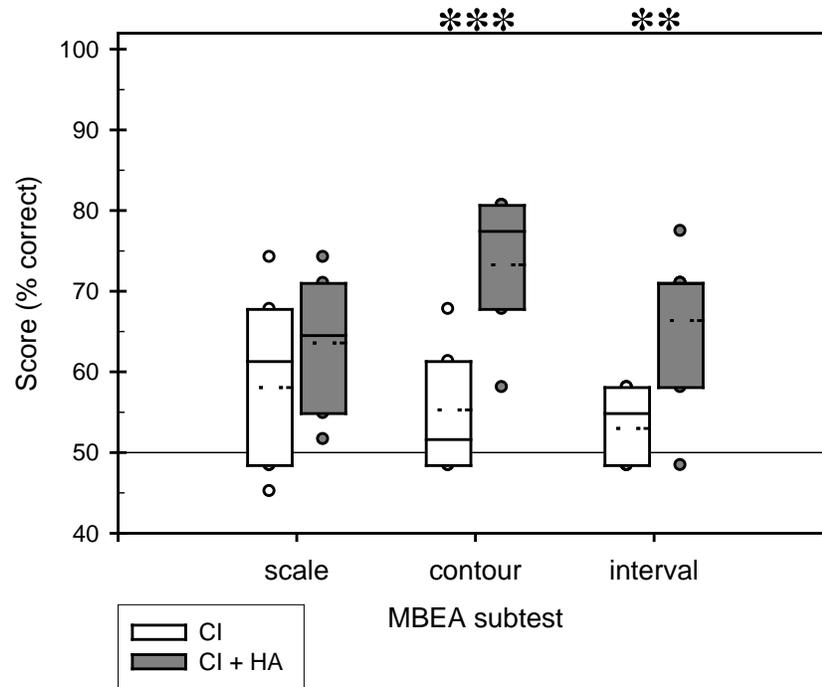
Figure 1: Scores for scale, contour and interval subtests of the MBEA. White boxes are the CI-only group, and gray boxes are the CI+HA group. Chance performance is 50% correct. Significant differences between CI-only and CI+HA groups are indicated: **, $p < 0.01$; ***, $p < 0.001$.
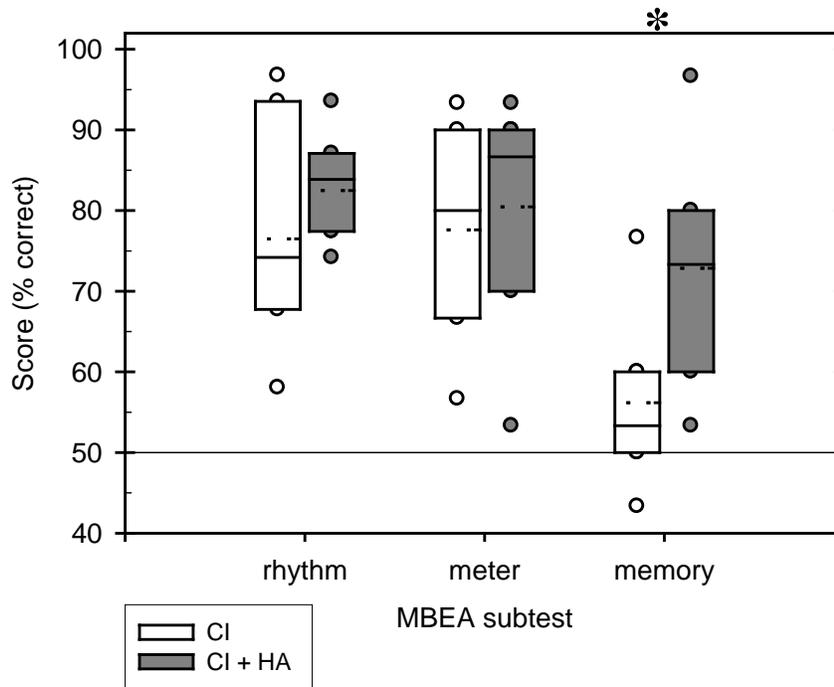
Figure 2. Scores for rhythm, meter and memory subtests of the MBEA. White boxes are the CI-only group, and gray boxes are the CI+HA group. Chance performance is 50% correct. Significant differences between CI-only and CI+HA groups are indicated: *, $p < 0.05$.
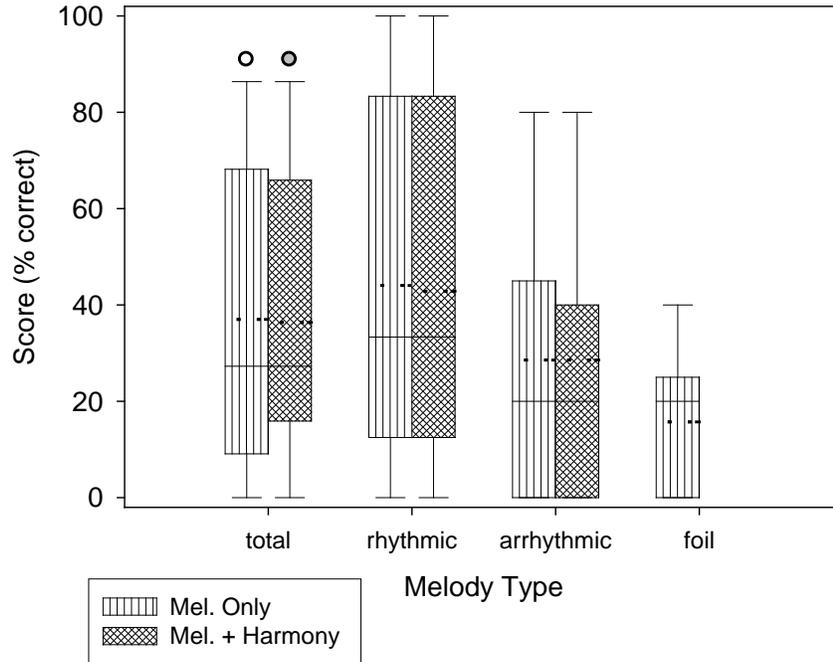
Figure 3: Aggregate results on melody recognition task. Total score, score on rhythmic and arrhythmic melodies, and percent of foils misidentified are shown for the melody-only (vertical lines) and melody plus harmony (diamonds) conditions.
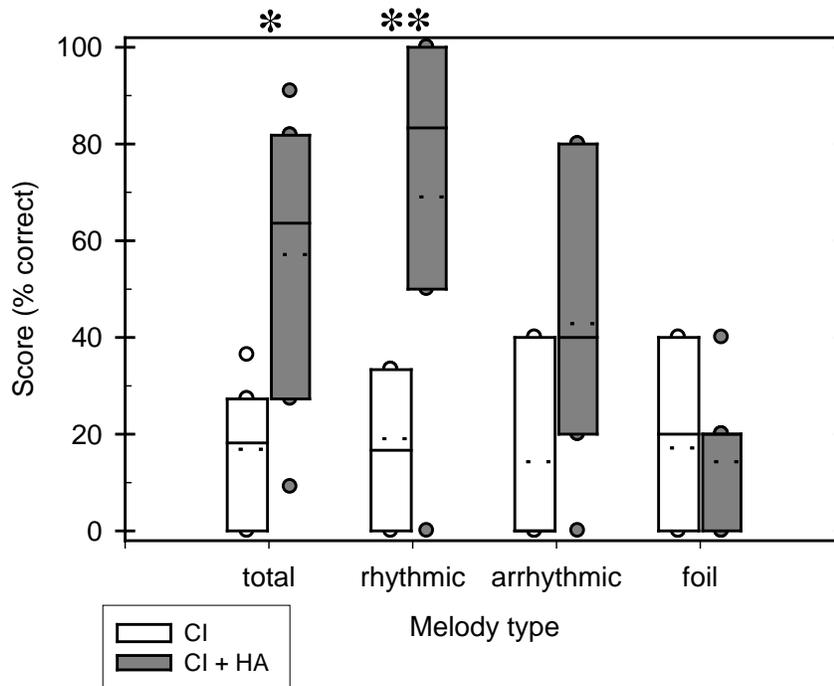
Figure 4: Familiar melody recognition in the melody-only condition for CI-only and CI+HA groups. White boxes are the CI-only group, and gray boxes are the CI+HA group. Significant differences between CI-only and CI+HA groups are indicated: *, $p < 0.05$; **, $p < 0.01$.
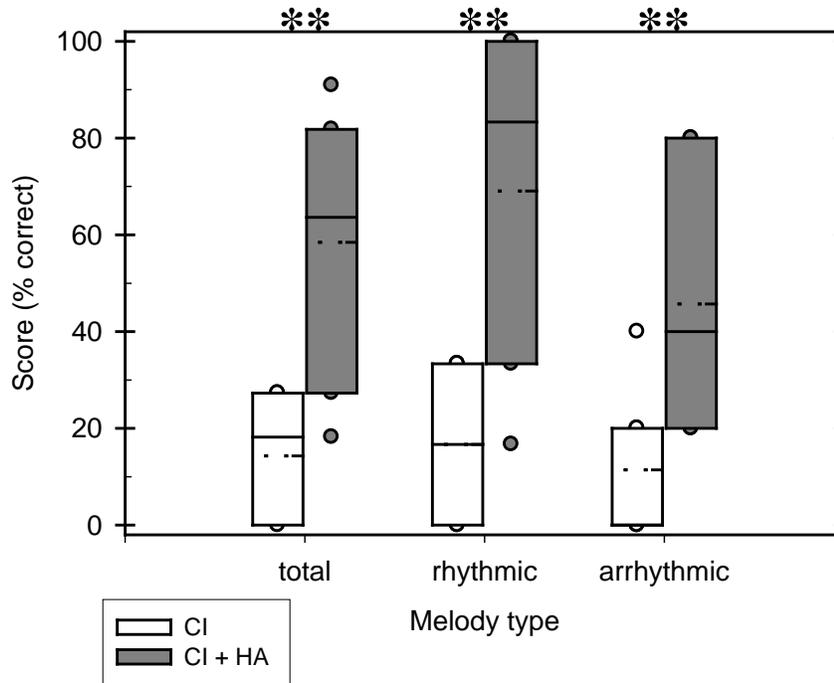
Figure 5: Familiar melody recognition in the melody plus harmony condition for CI-only and CI+HA groups. White boxes are the CI-only group, and gray boxes are the CI+HA group. Significant differences between CI-only and CI+HA groups are indicated: **, p < 0.01.