Published in final edited form as:
Ear Hear. 2008 August ; 29(4): 618–626. doi:10.1097/AUD.0b013e318174e787.

Music Perception by Cochlear Implant and Normal Hearing Listeners as Measured by the Montreal Battery for Evaluation of Amusia

William B. Cooper, **Emily Tobey**, and **Philipos C. Loizou**[a)]
The University of Texas at Dallas

Abstract

Objectives—The purpose of this study was to explore the utility/possibility of using the Montreal Battery for Evaluation of Amusia (MBEA) test (Peretz, Champod, & Hyde, 2003) to assess the music perception abilities of cochlear implant (CI) users.

Design—The MBEA was used to measure six different aspects of music perception (Scale, Contour, Interval, Rhythm, Meter, and Melody Memory) by CI users and normal hearing (NH) listeners presented with stimuli processed via CI simulations. The spectral resolution (number of channels) was varied in the CI simulations to determine: (a) the number of channels (4, 6, 8, 12, 16) needed to achieve the highest levels of music perception and (b) the number of channels needed to produce levels of music perception performance comparable to that of CI users.

Results—CI users and NH listeners performed higher on temporal-based tests (Rhythm and Meter) than on pitch-based tests (Scale, Contour, and Interval) – a finding that is consistent with previous research studies. The CI users' scores on pitch-based tests were near chance. The CI users' (but not NH listeners') scores for the Memory test, a test that incorporates an integration of both temporal-based and pitch-based aspects of music, were significantly higher than the scores obtained for the pitch-based Scale test and significantly lower than the temporal-based Rhythm and Meter tests. The data from NH listeners indicated that 16 channels of stimulation did not provide the highest music perception scores and performance was as good as that obtained with 12 channels. This outcome is consistent with other studies showing that NH listeners listening to vocoded speech are not able to utilize effectively F0 cues present in the envelopes, even when the stimuli are processed with a large number (16) of channels. The CI user data appear to most closely match with the 4- and 6- channel NH listener conditions for the pitch-based tasks.

Conclusions—Consistent with previous studies, both CI users and NH listeners showed the typical pattern of music perception in which scores are higher on tests measuring the perception of temporal aspects of music (rhythm and meter) than spectral (pitch) aspects of music (Scale, Contour, Interval). On that regard, the pattern of results from this study indicates that the MBEA is a suitable test for measuring various aspects of music perception by CI users.

Keywords

Cochlear Implants; Music; Montreal Battery for Evaluation of Amusia; MBEA

a) Address correspondence to: Philipos C. Loizou, Ph.D., Department of Electrical Engineering, University of Texas at Dallas, P.O. Box 830688, EC 33, Richardson, TX 75083-0688, E-mail : E-mail: loizou@utdallas.edu, Phone : (972) 883-4617, Fax : (972) 883-2710, Electronic-mail: E-mail: loizou@utdallas.edu.

Introduction

Music perception by CI users is generally poor (see McDermott, 2004; Zeng, 2004 for reviews). To better understand this problem, researchers have measured aspects of CI user music perception using a variety of tasks including pitch perception (Fearn, 2001, Reference note 1; Fujita and Ito, 1999; Gfeller, Turner, Mehr, et al., 2002), pitch ranking (Vandali, Sucher, Tsang, McKay, Chew, & McDermott, 2005), musical interval recognition (McDermott & McKay, 1997; Pijl, 1997; Pijl & Schwartz, 1995a, 1995b), timbre perception (Fujita & Ito, 1999; Gfeller, Knutson, Woodworth, et al., 1998; Gfeller & Lansing, 1991; Gfeller, Witt, Adamek, et al., 2002; Gfeller, Witt, Woodworth, et al., 2002; Leal, Shin, Laborde, et al., 2003; Schulz & Kerber, 1994), familiar melody recognition (Fujita and Ito, 1999; Gfeller, Turner, Mehr, et al., 2002; Kong, Cruz, Jones, & Zeng, 2004; Kong, Stickney, & Zeng, 2005; Leal et al., 2003; Pijl and Schwartz, 1995a; Schulz & Kerber, 1994) and melodic contour identification tasks (Galvin, Fu & Nogaki, 2007). With the exception of the Primary Measures of Music Audiation (Gfeller & Lansing, 1991,1992; Gfeller, et al., 1997), no standardized music perception tasks have been used. The most common task used to measure CI music perception is the familiar melody identification (recognition) task. However, the use of familiar melody recognition (FMEL) tasks in CI music perception research presents a few problems. First, the reliance of FMEL tasks on a person's memory presents a problem, particularly for CI users who were deaf for a long duration prior to implantation, as it is difficult to verify the level of familiarity a person has had with a given melody. Second, a CI user's ability to recognize a familiar melody provides little information about the individual mechanisms that underlie the melody recognition process. Accordingly, when CI users perform poorly on FMEL tasks, as is often the case, little is learned about *why* the level of performance is low. Third, FMEL tasks have little to no utility toward measuring music perception by *pre-lingually* deafened CI users because FMEL tasks rely on the memory of a familiar melody, memories that were never formed by congenitally-deafened CI users. The Montreal Battery for Evaluation of Amusia (MBEA) test (Peretz, Champod, & Hyde, 2003) assesses a variety of mechanisms that underlie music perception and does not rely on the memory of familiar melodies. It is a measure based on cognitive theories of music perception and neuropsychological evidence (Peretz & Coltheart, 2003). The MBEA test has been shown to have good sensitivity, reliability and validity based on listening tests from 160 normal-hearing listeners (Peretz *et al.*, 2003). It consists of six tests, each of which is designed to assess different aspects of music perception along a melodic dimension (defined by variations in pitch), and a temporal dimension (defined by variations in duration). The MBEA is proposed in this study is a test battery for assessing the musical abilities of CI users. The MBEA can serve as a diagnostic tool for pinpointing the deficiencies in perceiving music via a cochlear implant.

The present study will also use the MBEA test to assess the minimum number of channels needed by NH listeners to obtain maximum performance on this task. The number of channels that CI users need for music perception has been studied previously with CI simulations and NH listeners by varying the number of available channels (Kong, et al., 2004; Smith, Delgutte, & Oxenham, 2002). Smith et al. showed optimal performance on a musical task with 48-64 channels. However, their task was quite challenging as it required subjects to extract the musical signal from either a competing speech signal or another musical signal in the stimulus. Kong et al. showed highest levels of familiar melody recognition performance for 32 and 64 channels. Both studies used performance on FMEL tasks as the dependent variable in their investigations and both studies found highest levels of performance at numbers of channels (i.e. 32 - 64) that are not commonly available to CI users. Whereas it has been determined that the number of channels needed for optimal performance on music perception tasks is beyond that which is currently available to CI users, it is the aim of the present study to understand more fully the music perception abilities of CI users using numbers of channels (i.e. 4 - 16 channels), that are more consistent with the relatively small number of electrodes in a CI device (8 - 24 electrodes) than with high numbers of channels (i.e. 32-64) that are theoretically achievable, but not used in common practice. To accomplish this aim, a test must be used which is sensitive enough to detect aspects of music perception within the range of performance that CI users are capable of demonstrating. The MBEA measures several aspects of music perception for which CI users are known to show variability including pitch perception, rhythm perception, and memory for melodies. By testing the music perception of CI users (and NH listeners who listen to CI simulations), we aim to address the following three questions: 1) Within a range consistent with the number of electrodes available to a CI device, how does spectral resolution (number of channels) affect the six different music perception tests of the MBEA? 2) How do CI users perform on the MBEA task compared to NH listeners presented with stimuli processed via CI simulations? 3) What number of channels with CI simulations best represents the actual performance of CI users on the MBEA?

CI users are known to demonstrate higher levels of performance on rhythm perception tasks than on pitch perception tasks (Fujita & Ito 1999; Gfeller & Lansing, 1991; Gfeller, et al., 1997; Kong, et al., 2004; Schultz & Kerber, 1994). Accordingly, it is predicted that CI users will show higher levels of performance for the Rhythm and Meter tests of the MBEA than for the three pitch-based tests (Contour, Interval, and Scale). The Rhythm and Meter scores are predicted to be in the range of NH listeners. Whereas pitch perception is known to be poor for CI users, it is predicted that among the three pitch tests, CI user scores will be highest for the Contour test (as it has the most exaggerated changes in pitch), followed by the Interval and Scale tests.

Methods

Participants

12 CI users and 30 NH listeners participated in this study. Mean age of CI users was 50 (SD = 12). CI users were screened for their speech perception ability on the Hearing in Noise Test (HINT, Nilsson, Soli, & Sullivan, 1994) in quiet and on consonant-nucleus-consonant (CNC) word recognition (Causey, Hood, Hermanson, & Bowling, 1984). Each CI user scored above 80% on the HINT and 50% on the CNC speech perception measures, in quiet. Table 1 lists the individual CI user characteristics.

NH listeners were students at the University of Texas at Dallas who participated in the study for class credit. Each participant was screened for hearing at six octave audiometric frequencies (250, 500, 1000, 2000, 4000, and 8000 Hz) at 20 and 30 dB HL. All NH listeners met the 30 dB HL cutoff.

Apparatus

Montreal Battery for Evaluation of Amusia (MBEA)—The present study used the MBEA (Peretz, et al., 2003) to assess music perception by CI users and NH listeners presented with CI simulations. The MBEA is composed of six tests (Scale, Contour, Interval, Rhythm, Meter, and Melody Memory). Each test is 10 minutes long, composed of 30 to 31 trials, and preceded by at least two examples with feedback and question answering. No feedback is given during the test. With the exception of the Meter and Melody Memory test, in each task, participants listen to two melodies and indicate whether they are the same or different. Each pair of melodies is preceded by a warning tone. Participants are advised that some differences may be subtle. For the meter test, participants indicate whether the melody is either a march or a waltz. There are four practice items for this test. On the incidental memory test, participants indicate whether the melody was presented in an earlier test (yes/no). In all conditions, participants indicate their response to each trial by marking an “X” on an answer sheet provided.

MBEA Stimuli—Melodies were composed according to the rules of Western tonality by Peretz *et al.* (2003) and "with sufficient complexity to guarantee [their] processing as a meaningful structure rather than as a simple sequence of notes" (Peretz *et al.*, 2003, p. 62). Accordingly, these melodies were composed of musical intervals typical of Western tonality. Rhythmical patterns were varied across melodies. The frequency range of the melodies ranged from 247 Hz (B3) to 988 Hz (B5). The number of notes in a melody ranged from 7 to 21 notes and lasted 3.8 to 6.4 seconds (mean = 5.1 seconds), depending on the tempo (100, 120, 150, 180, and 200 beats per minute). Stimuli for the Meter test were twice as long. Individual note durations varied depending on the rhythm and tempo of each melody and ranged from 150 ms to 1800 ms. Melodies were presented using a synthetic piano sound generated from music production software (Reason, Stockholm, Sweden). Examples of MBEA stimuli can be found in Figure 2 of Peretz et al., (2003).

The three pitch-based tests from the MBEA (Contour, Interval, and Scale) all measure a different aspect of pitch perception. The method used is similar across tests in that it involves the presentation of two melodies that are to be compared. The task is to determine whether the two melodies are the same or differ in some way. The manner in which "different" items differ is what distinguishes these tests. These differences, along with predictions of how CI users will perform on these tests are explained in the remainder of this section. The three pitch-based tests of the MBEA use consistent methodology providing the opportunity to compare three different aspects of pitch perception by CI users.

Contour Test—The Contour test measures the ability of the listener to detect changes to the contour of the melody. This test alters the contour of a melody by changing one note of the melody such that its pitch height, respective to its neighboring notes, is reversed. That is, if a note sequence in the original melody was higher than the neighboring note that preceded it and higher than the note that followed it, the note would be changed to a lower pitch so that it was lower than the note that preceded it and lower than the note that followed it. Of the three pitch-based MBEA tests, CI users are expected to perform highest on the Contour test because the pitch changes made in this test are the most extensive of the three tests. The Contour test alters both the step size between pitches *and* the direction of the pitch change in "different" comparisons.

Interval Test—The Interval test measures the perception of pitch step size (pitch distance) information. In contrast to the Contour test that alters the contour of the melody with a pitch change, the Interval test preserves the contour of the original melody but alters the pitch distance between the changed note and its neighboring notes. The average pitch interval change from the original pitch was 4.2 semitones. The pitch change in the Interval test is more subtle than the pitch change in the Contour test because it alters only the step sizes between notes, rather than both the step size *and* melodic contour. Accordingly, it is expected that CI users will show a lower level of detection for this type of pitch change, as compared to the pitch change in the Contour test. The interval test investigates an aspect of pitch perception that has not been explored in other interval studies (McDermott & McKay, 1997; Pijl & Schwarz, 1995a; Pijl, 1997) with CI users.

Scale Test—The Scale test measures the perception of musical scale information or *tonality*. The "different" comparisons use notes from outside the tonal key that is established by the notes of the melody. The altered notes in the Scale test are in the same pitch range as the altered notes used in the rules of the Contour and Interval tests. In contrast to these two measures, the altered note in the Scale test is not in the correct (same) key. This manipulation provides salient "different" comparisons for most NH listeners because the altered note sounds out of tune. It is important to include the MBEA-Scale test in the present study because this test measures a component of pitch perception (scale) that has not yet been investigated in CI users. It is predicted that CI users will perform worst on the MBEA-Scale because CI users are not expected to perceive tonal pitch. The inability to detect a note that is out of tune will make the Scale task very difficult task for CI users.

The Rhythm test and the Meter test measure the perception of temporal aspects of music. The Rhythm test uses the same melodies as the three pitch-based tests. However, in the different "comparison" melodies, it is the *duration* of two adjacent notes that are altered, rather than the *pitch* of the notes. This manipulation alters the rhythmic grouping of the melodies but does not change the meter or the number of notes (Peretz *et al.*, 2003, p.64).

The Meter test uses the same melodic patterns as the other tests, but the stimuli are presented as two-phrase sequences rather than as one-phrase sequences as used in the earlier tests. The addition of chords adds harmonization to the melodies. Instead of indicating "same" or "different" to the two melody patterns, participants are required to indicate whether the melodic patterns were in either duple or triple meter, using the more familiar terms "march" or "waltz," respectively.

The Melodic Memory test is always given last and uses 15 of the melodies from the previous tests ("old") and 15 previously unheard ("new") melodies, constructed using the same criteria as the "old" melodies. Each melody is presented in a randomized order and the participant is required to indicate whether the melody was presented in the earlier tests by replying "yes" or "no."

NH Simulations of Cochlear Implants

Test material (MBEA stimuli) was first low-pass filtered using a sixth order elliptical filter with a cut-off frequency of 6000 Hz. Filtered sound was passed though a pre-emphasis filter (second order Butterworth filter) with a cut-off-frequency of 2000 Hz. This was followed by band-pass filtering into *N* frequency bands (where *N* varied from 4, 6, 8, 12 and 16) using sixth-order Butterworth filters. The noise band synthesis was performed as described by Shannon *et al.* (1995). The output of each channel was passed through a half-wave rectifier followed by a second order Butterworth low-pass filter with a cut-off frequency of 200 Hz to obtain the envelope of each channel output. The rectified outputs of each channel were used to modulate white noise band-pass filtered with the same analysis filters. The synthesized files were normalized to have the same root-mean-square intensity level and saved on a CD.

Procedure

CI Users—The experimenters measured speech perception abilities of CI users using the HINT and CNC tests. Sound was delivered to CI users at a comfortable level (~ 65 dB SPL) in sound field in a double-walled attenuating booth (Acoustic Systems, Inc). The same method of presentation was used for both speech perception and music perception tasks. After the speech perception tests, the MBEA test was explained to the CI users and they were given an answer booklet. The six tests were then run in a randomized order. Subjects responded after each trial by writing an "x" in the appropriate column (e.g. "same" or "different"). Testing time took approximately 1.5 hours.

NH listeners—The experimenter first ran a hearing screening of the NH subjects in sound field. Subjects were then asked to sit at a table and wear a pair of headphones (Sony MDR-CD280). After establishing a comfortable listening level, subjects engaged in a half-hour warm up session in which they listened to CI simulations of familiar melodies as they monitored the title and lyrics to the melody written out in a notebook in front of them. Subjects warmed up using CI simulations in which the number of channels used was the same as that to be evaluated in the following MBEA test. After the warm up session, directions for the MBEA test were given to the subjects and they took each MBEA test in a randomized order. Each subject took part in only one CI simulation condition and was tested with all six MBEA tests. Accordingly, the same number (6) of NH listeners was used across the number of channels condition.

Experimental Design

For CI users, the experimental design was S × A with "S", corresponding to the subject variable and "A" corresponding to the within-subject independent variable "MBEA Test" with six levels corresponding to each of the tests (Scale, Contour, Interval, Meter, Rhythm, & Memory). The number correct on each MBEA test served as the dependent variable.

For NH listeners, the experimental design was S(A) × B with "S" corresponding to the subject variable and "A", "Number of Channels", serving as a between-subject independent variable with five levels corresponding to each of the channel number conditions (4, 6, 8, 12 and 16-channels). "B" corresponds to the within-subject variable, "MBEA Test" with six levels corresponding to each one of the tests. The number correct on each MBEA test served as the dependent variable.

Results

The group mean (raw) scores for CI users are shown in Figure 1, and the individual CI users's scores are shown in Figure 2. The results for CI users were subjected to a repeated measures analysis of variance (ANOVA) design with MBEA test being a within-subject factor. Results revealed a main effect of MBEA test ($F[5, 55] = 13.05$, $p < .0005$). A *post hoc* comparison of means (Duncan) revealed that scores on the Rhythm test and Meter test were significantly higher than scores on the Scale, Contour, Interval, and Memory tests ($p < .05$). This comparison also revealed that CI users' scores were significantly higher on the Memory test than on the Scale test ($p <0.05$).

The mean (raw) scores for NH users are shown in Figure 3. The results for NH Listeners were treated using a Number of Channels × MBEA Test ANOVA design with Number of Channels (4, 6, 8, 12, and 16) being a between-subject factor and MBEA Test being a within-subject factor. Results revealed significant effect of MBEA test ($F[5, 25] = 29.8$, $p < .0001$), significant effect of number of channels ($F[4,20]=3.3$, $p=0.03$) and non-significant interaction ($F[20,100]=1.0$, $p=0.461$). As shown in Figure 3, scores for the pitch-based tests (Scale, Contour, Interval) were near chance level (15) independent of the number of channels used. Relatively higher scores were obtained with the Rhythm and Meter tests, but performance did not improve significantly as the number of channels increased. The overall effect of number of channels was small.

A *post hoc* analysis of all pair wise comparisons revealed a difference between the Contour and Interval tests of the MBEA with respect to Number of Channels. In the Contour condition, means for the 12-channel group were significantly ($p<0.05$) *higher* than means for the 4-channel group, the 4-, 6-, and 12-channel groups in the Scale condition, and the 4-channel group in the Interval condition. In the Interval condition, means for the 4-channel group were significantly *lower* than means for the 12-channel group in the Interval condition, the 6-, 8-, and 12-channel groups in the Contour condition, and the 12-channel group in the Scale condition. As shown in Figure 3, overall, the 4-channel group (with the exception of the Interval condition) and the 6-channel group (with the exception of the Contour condition) appear to most closely resemble the level of CI user performance on the three pitch-based MBEA tests (Scale, Contour, and Interval).

Discussion

Review of Results

With the use of a single measure, MBEA, the present study demonstrates results that are consistent with previous studies aimed at assessing music perception by CI users. Overall, the results with CI simulations[1] revealed a small effect of number of channels in the pitch-based tests, and no significant effect on the rhythmic-based tests. Small, improvements in music perception scores were obtained when a higher number of channels were used for stimulation in the pitch-based tests. This outcome is consistent with previous studies examining the influence of F0 cues in target segregation in vocoded speech (Qin and Oxenham, 2005;Stickney *et al.*, 2007). Qin and Oxenham (2005) demonstrated that normal-hearing listeners are unable to benefit from F0 differences between competing vowels in a concurrent-vowel paradigm despite the good F0 difference limens (<1 semitone) obtained with 8- and 24-channel vocoder processing. A similar outcome was noted by Stickney *et al.* (2007) with NH and cochlear implant users listening to target and competing sentences with an F0 separation ranging from 0-15 semitones. No benefit was noted in target segregation by NH listeners with any level of F0 separation, despite the 32-channel vocoder processing. It should be noted that the range of F0 values used in the current study (i.e., B3: 247 Hz to B5: 988 Hz) is beyond the range of F0 frequencies considered in the above studies. Consequently, a different mechanism was likely utilized by the NH listeners in the present study for coding F0 information.

Consistent with previous studies, both CI users and NH listeners showed the typical pattern of music perception in which scores are higher on tests measuring the perception of rhythmic aspects of music (rhythm and meter) than pitch aspects of music (Scale, Contour, Interval). The present study demonstrates that the MBEA can be used to assess the music perception abilities of CI users and obtain results that are consistent with those reported in the literature.

The Memory test of the MBEA is a new test in this line of research. Unlike familiar melody tests, which rely on the memory of familiar melodies prior to a person's loss of hearing, the Memory test of the MBEA relies on a relatively short-term memory for melodies presented within the context of the test battery. This Memory test, which, among other things, combines pitch and rhythm information, showed mixed results for CI users and NH listeners. CI users showed a significant difference between the Memory test and both the temporal tests (Rhythm and Meter). There was also a significant difference between the Memory test and one of the three pitch tests, the Scale test. The Scale test uses a pitch change which was predicted to be least perceptible to CI users than the pitch changes made in the other two pitch tests: Contour and Interval. The fact that a significant difference was found between Memory and Scale, but not between Memory and either of the other two pitch tests might indicate that the difference between scores for Memory and Scale were more robust, despite the fact that the CI user scores were not significantly different among the three pitch tests. The lack of a significant difference between the Memory test and the Pitch tests for NH listeners appears to be due to the overall higher level of performance on the pitch tests by NH listeners. The high scores on these tests were obtained in the channel conditions (e.g. 12 Channels) in which NH listeners demonstrate levels of performance higher than those typical of the CI users (e.g. 4- and 6-channels). The lack of significant difference between the three Pitch tests for any number of channels, by both NH and CI users, suggests that the F0 information available in the envelope modulations is not adequate for these tasks, at least for the number of channels tested (maximum number was 16

[1]We should point out that the results obtained with NH listeners listening to vocoded music should be interpreted with caution, as they are based on the premise that the CI simulations model the coding of music in real CI users. Nevertheless, previous studies (Kong *et al.*, 2004Stickney *et al.*, 2007; Kasturi & Loizou, 2007), as well as the present study, indicated that the pattern of results obtained with CI simulations is consistent with the pattern obtained by CI users. The CI simulations (vocoder processing) have proven to be a valuable tool in assessing CI user's performance (on both music and speech recognition tasks) in the absence of confounding factors.

channels). We can not exclude the possibility, however, that channel filter spacing might affect performance. Some studies demonstrated that allocating more filters in the low frequencies might enhance the coding of F0 information and improve pitch perception (Laneau, Moonen & Wouters, 2004) and melody recognition (Kasturi & Loizou, 2007).

Among the pitch-based tests, the highest scoring condition for NH listeners was the 12-channel condition on the Contour test and the lowest scoring condition was the 4-channel condition on the Interval test. The scores by NH listeners in the Contour test were relatively higher than the corresponding scores in the Interval or Scale tests. The high scores on the Contour test are possibly due to the fact that differences between melodies in this test encompass not only a pitch change, but also a change in pitch direction –thereby providing two cues to the listener that a difference exists. Pitch differences between melodies in the Interval test do not encompass a change in pitch direction, so only one pitch cue exists. Pitch differences between melodies in the Scale condition do not incorporate a contour change and the pitch change tends to be very small in magnitude, often only a semitone –enough to render the tone out of key.

The pattern of results wherein NH listeners tended to perform higher on the Contour test than the Scale test indicates that NH listeners perceive pitch changes associated with a change in pitch direction. They tend not to perceive pitch changes that violate scale, particularly in conditions in which only a few channels are available. The fact that CI users performed most consistently with the 4 and 6 channel condition indicates that CI users probably do not perceive musical scale information.

Sources of Variability

An effort was made to control to some degree the variability in CI users' performance by including only CI users performing above a certain threshold value on speech perception tasks in quiet. Individual CI user data showed some inter-subject variability (Figure 2). To examine whether duration of deafness affected performance on any of the six MBEA tests, we ran the correlation (Pearson's) between duration of deafness and the MBEA scores obtained in each of the six tests, but found no significant correlation with any of the six tests.

Another factor that may affect scores on the MBEA is the musicianship (level of musical training) of the participant. Individuals who, prior to deafness, have had moderate to high levels of musical training may demonstrate higher levels of music perception through their CI device than those who have not had training. First, to some extent, the amount of experience a person has with his or device is a predictor of their level of success with the device (e.g. Bassim, Buss, Clark, et al., 2005). Second, training specific to music perception can improve scores on music perception tests (Galvin, Fu, & Nogaki, 2007; Gfeller, Witt, Adamek, et al., 2002; see also McDermott, 2004). For example, Gfeller, Witt, Adamek, et al., (2002) showed that training improves timbre perception (instrument identification) by CI users. Future studies should take into account the level of musicianship of study participants. In addition, future studies should also investigate the effect of musical training on music perception tasks, particularly those related to pitch perception.

Limitations and Future Directions

Though the MBEA has proven effective in demonstrating results that are consistent with the CI music perception literature, the full scope of its utility has yet to be realized. At present, it appears that some aspects of the tests may be too difficult for CI users with the devices and speech-coding strategies currently available. However, slight modifications to the test stimuli (i.e. tone types and frequency range) may allow CI users to demonstrate aspects of pitch perception and melody perception that they are currently unable to demonstrate with the test in its present state.

Though the results from the present study demonstrate that the MBEA is a useful tool for assessing music perception by CI users, this test battery has limitations. One limitation of the MBEA is that the pitch tests appear to be difficult for CI users. However, the high level of test difficulty can be viewed as strength of the MBEA because it allows room for improvement. A test that is too difficult for the population being tested is limited in its utility. First, as is known from many of the familiar melody CI music perception studies, when all the subjects perform at chance (floor level), little is learned about that population and how to improve their performance. Second, with respect to behavioral studies, human participants become discouraged and lose motivation when they consistently fail to perform reasonably well on a test. As new CI devices and strategies are developed, tests will be needed that are sensitive enough to demonstrate improvements to CI devices. Future research will need to refine (fine tune) the MBEA in order to enable CI users to demonstrate the range of music perception of which they are currently capable.

The use of piano tones by the MBEA may contribute to the difficulty of music perception tasks. Piano tones are commonly used in music. Accordingly, piano tones are typically used in music perception tasks because of their ecological validity. However, psychoacoustical studies have shown that CI users demonstrate poor pitch perception for these types of tones (Fearn, 2001, Reference note 1; Fujita & Ito, 1999; Gfeller, Turner, Mehr, et al., 2002) especially when compared to simple harmonic tones. Future research should investigate whether the use of simple harmonic tones instead of piano tones would improve CI user scores on the MBEA.

The use of a relatively low frequency range for the melodic stimuli on the MBEA may also contribute to the difficulty of music perception tasks. The fundamental frequencies of the stimuli in the MBEA range from 247 to 988 Hz. This represents only a fraction of the frequency range available in CI devices. Though 247 Hz corresponds to "middle C" (a relatively middle-ranged frequency for music) it is a relatively low frequency with respect to the frequency range of band-pass filters in most CI devices. In fact, the frequency ranges of some CI devices do not extend that low. In addition, some CI devices and their corresponding strategies process information below 1000 Hz differently from one another. Data from some psychoacoustical studies suggest that CI user place-pitch discrimination is better at high frequencies than low frequencies (Gfeller, Turner, Merh, et al., 2002; Fearn, 2001, Reference note 1). Future research should investigate whether transposing melodies from the MBEA up two octaves to a higher frequency range (1048 – 2960 Hz) will improve CI user performance on the MBEA. Similarly, transposing the melodies to a frequency range below middle C would help us examine the effect of coding F0 using temporal envelope cues rather than place cues.

Lastly, the MBEA test addresses two aspects of music perception, namely rhythm and pitch, but does not address timbre. A different test needs to supplement the MBEA test to assess timbre recognition.

Conclusions

Music perception by CI users and NH listeners can be assessed by the MBEA. The levels of performance on temporal or rhythmic-based tests (Rhythm and Meter) were significantly higher than the levels of performance on pitch-based tests (Scale, Contour, and Interval) by both CI users and NH listeners and demonstrate a pattern of music perception performance that is typical for these groups. A rather small effect of number of channels was observed for the pitch-based tests in CI simulations with NH listeners. The number of channels used did not seem to affect performance on the rhythmic-based tests. Highest scores on pitch-based tests were obtained in the 12-channel condition and lowest scores in the 4- and 6-channel conditions. The condition with the highest number of channels, 16 channels, did not provide the highest music perception scores and performance was as good as that obtained with 12 channels. This outcome is consistent with other studies (Qin and Oxenham, 2005; Stickney *et al.*, 2007) showing that NH listeners listening to vocoded speech are not able to utilize effectively F0 cues present in the envelopes, even when the stimuli are processed with a large number of channels. Future research is needed to explore the role that stimulus characteristics such as tone type and frequency range can have on the music perception performance of CI users and NH listeners.

Acknowledgements

This research was supported by Grant No. R01 DC007527 (awarded to P.C.L) from the National Institute of Deafness and other Communication Disorders, NIH. The authors would like to thank Kalyan Kasturi for all his help with subject testing.

References

Bassim M, Buss E, Clark M, Kolln K, Pillsbury C, Pillsbury H, Buchman C. MED-EL Combi40+ cochlear implantation in adults. Laryngoscope 2005;115(9):1568–1573. [PubMed: 16148696]

Causey G, Hood L, Hermanson C, Bowling L. The Maryland CNC test: normative studies. Audiology 1984;23(6):552–568. [PubMed: 6517748]

Fujita S, Ito J. Ability of nucleus cochlear implantees to recognize music. The Annals of Otology, Rhinology, and Laryngology 1999;108(7 Pt 1):634–640.

Galvin J, Fu Q, Nagaki G. Melodic contour identification by cochlear implant listeners. Ear Hear 2007;28:302–319. [PubMed: 17485980]

Gfeller K, Knutson J, Woodworth G, Witt S, DeBus B. Timbral recognition and appraisal by adult cochlear implant users and normal-hearing adults. Journal of the American Academy of Audiology 1998;9(1):1–19. [PubMed: 9493937]

Gfeller K, Lansing C. Melodic, Rhythmic, and Timbral Perception of Adult Cochlear Implant Users. Journal of Speech and Hearing Research 1991;34:916–920. [PubMed: 1956198]

Gfeller K, Lansing C. Musical perception of cochlear implant users as measured by the *Primary Measures of Music Audiation*: An Item Analysis. Journal of Music Therapy 1992;29(1):18–39.

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

Gfeller K, Witt S, Adamek M, Mehr M, Rogers J, Stordahl J, Ringgenberg S. Effects of training on timbre recognition and appraisal by postlingually deafened cochlear implant recipients. Journal of the American Academy of Audiology 2002;13(3):132, 145. [PubMed: 11936169]

Gfeller K, Witt S, Woodworth G, Mehr M, Knutson J. Effects of frequency, instrumental family, and cochlear implant type on timbre recognition and appraisal. The Annals of Otology, Rhinology, and Laryngology 2002;111(4):349–356.

Gfeller K, Woodworth G, Robin D, Witt S, Knuston J. Perception of rhythmic and sequential pitch patterns by normally bearing adults and adult cochlear implant users. Ear and Hearing 1997;18(3): 252–260. [PubMed: 9201460]

Kasturi K, Loizou P. Effect of frequency spacing on melody recognition: Acoustic and electric hearing. Journal of Acoustical Society of America 2007;122(2):EL29–EL34.

Kong Y, Cruz R, Jones J, Zeng F. Music perception with temporal cues in acoustic and electric hearing. Ear and Hearing 2004;25(2):173–185. [PubMed: 15064662]

Kong Y, Stickney G, Zeng FG. Speech and melody recognition in binaurally combined acoustic and electric hearing. Journal of the Acoustical Society of America 2005;117(3):1351–1361. [PubMed: 15807023]

Laneau J, Moonen M, Wouters J. Relative contributions of temporal and place pitch cues to fundamental frequency discrimination in cochlear implantees. J Acoust Soc Am 2004;106(6):3606–3619. [PubMed: 15658711]

Leal M, Shin Y, Laborde M, Calmels M, Verges S, Lugardon S, Andrieu S, Deguine O, Fraysse B. Music perception in adult cochlear implant recipients. Acta Otolaryngology 2003;123(7):826–835.

McDermott H. Music perception with cochlear implants: a review. Trends in Amplification 2004;8(2): 49–82. [PubMed: 15497033]

McDermott H, McKay C. Musical pitch perception with electrical stimulation of the cochlea. Journal of the Acoustical Society of America 1997;101(3):1622–1631. [PubMed: 9069629]

Nilsson M, Soli SD, Sullivan JA. Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. Journal of the Acoustical Society of America 1994;95(2):1085–1099. [PubMed: 8132902]

Peretz I, Champod A, Hyde K. Varieties of musical disorders: The Montreal Battery of Evaluation of Amusia. Annals of the New York Academy of the Sciences 2003;999:58–75.

Peretz I, Coltheart M. Modularity of music processing. Nature Neuroscience 2003;6(7):688–691.

Pijl S. Labeling of musical interval size by cochlear implant patients and normal hearing subjects. Ear and Hearing 1997;18(5):364–372. [PubMed: 9360860]

Pijl S, Schwarz DW. Melody recognition and musical interval perception by deaf subjects stimulated with electrical pulse trains through single cochlear implant electrodes. Journal of the Acoustical Society of America 1995a;98(2 Pt 1):886–895. [PubMed: 7642827]

Pijl S, Schwarz D. Intonation of musical intervals by musical intervals by deaf subjects stimulated with single bipolar cochlear implant electrodes. Hearing Research 1995b;89(12):203–211. [PubMed: 8600127]

Qin M, Oxenham A. Effects of envelope-vocoder processing on F0 discrimination and concurrent-vowel identification. Ear Hear 2005;26:451–460. [PubMed: 16230895]

Schulz, E.; Kerber, M. Music perception with the MED-EL implants. In: Hochmair-Desoyer, I.; Hochmair, EC., editors. Advances in Cochlear Implants. Vienna, Austria: Manz; 1994. p. 326-322.

Shannon R, Zeng FG, Kamath V, Wygonski J, Ekelid M. Speech recognition with primarily temporal cues. Science 1995;270:303–4. [PubMed: 7569981]

Smith Z, Delgutte B, Oxenham A. Chimaeric sounds reveal dichotomies in auditory perception. Nature 2002;416(6876):87–90. [PubMed: 11882898]

Stickney G, Assmann P, Chang J, Zeng FG. Effects of implant processing and fundamental frequency on the intelligibility of competing sentences. J Acoust Soc Am 2007;122(2):1069–1078. [PubMed: 17672654]

Vandali A, Sucher C, Tsang D, McKay C, Chew J, McDermott H. Pitch ranking ability of cochlear implant recipients: A comparison of sound-processing strategies. Journal of the Acoustical Society of America 2005;117(5):3126–38. [PubMed: 15957780]

Zeng F. Trends in cochlear implants. Trends in Amplification 2004;8(1):1–34. [PubMed: 15247993]

Reference notes

1. Fearn, R. Unpublished doctoral dissertation. University of New South Wales; Australia: 2001. Music and Pitch Perception of Cochlear Implant Recipients.

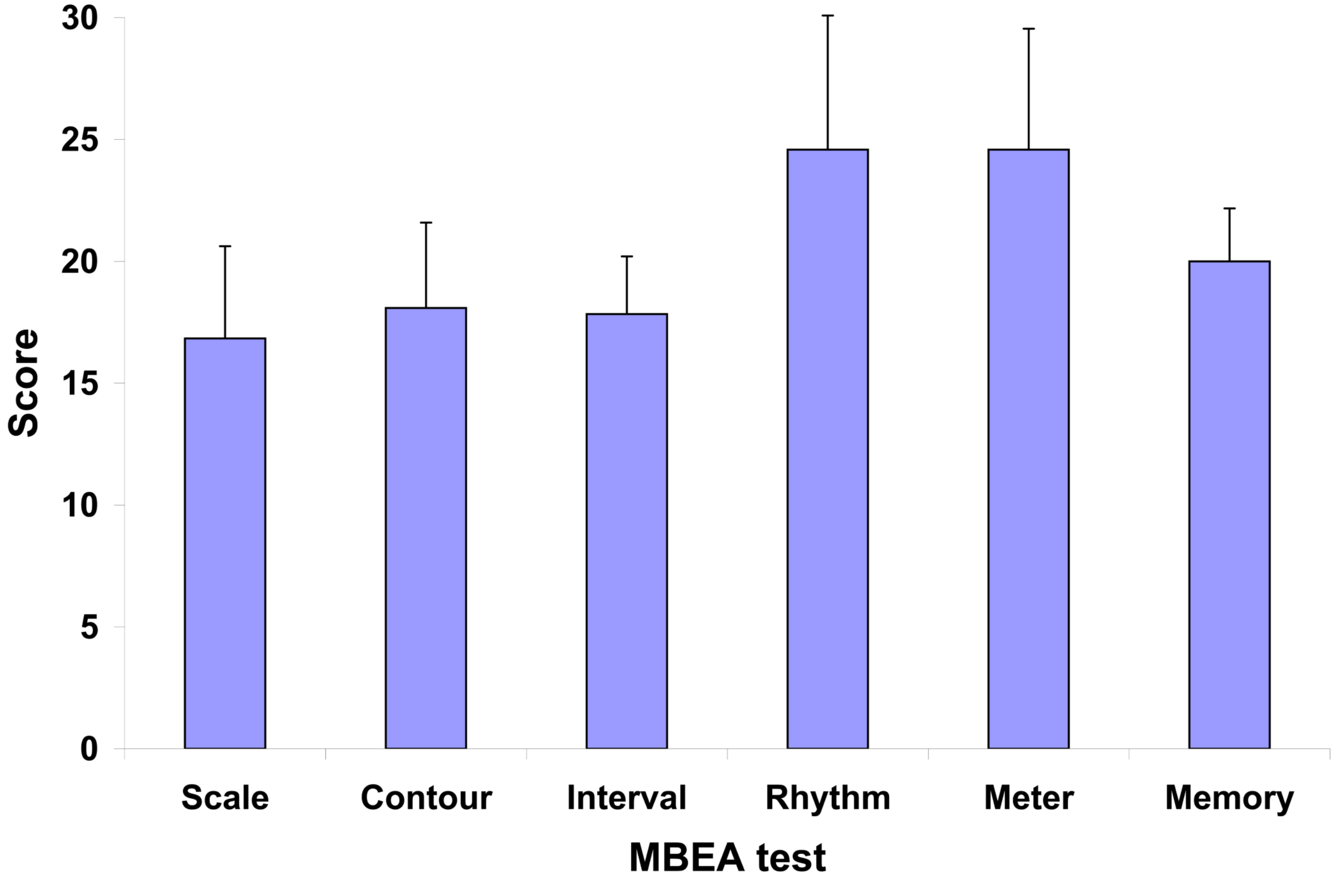

Figure 1.
Mean scores of 12 cochlear implant users on tests from the Montreal Battery for Evaluation of Amusia. Chance score is approximately 15. Error bars represent standard deviations.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

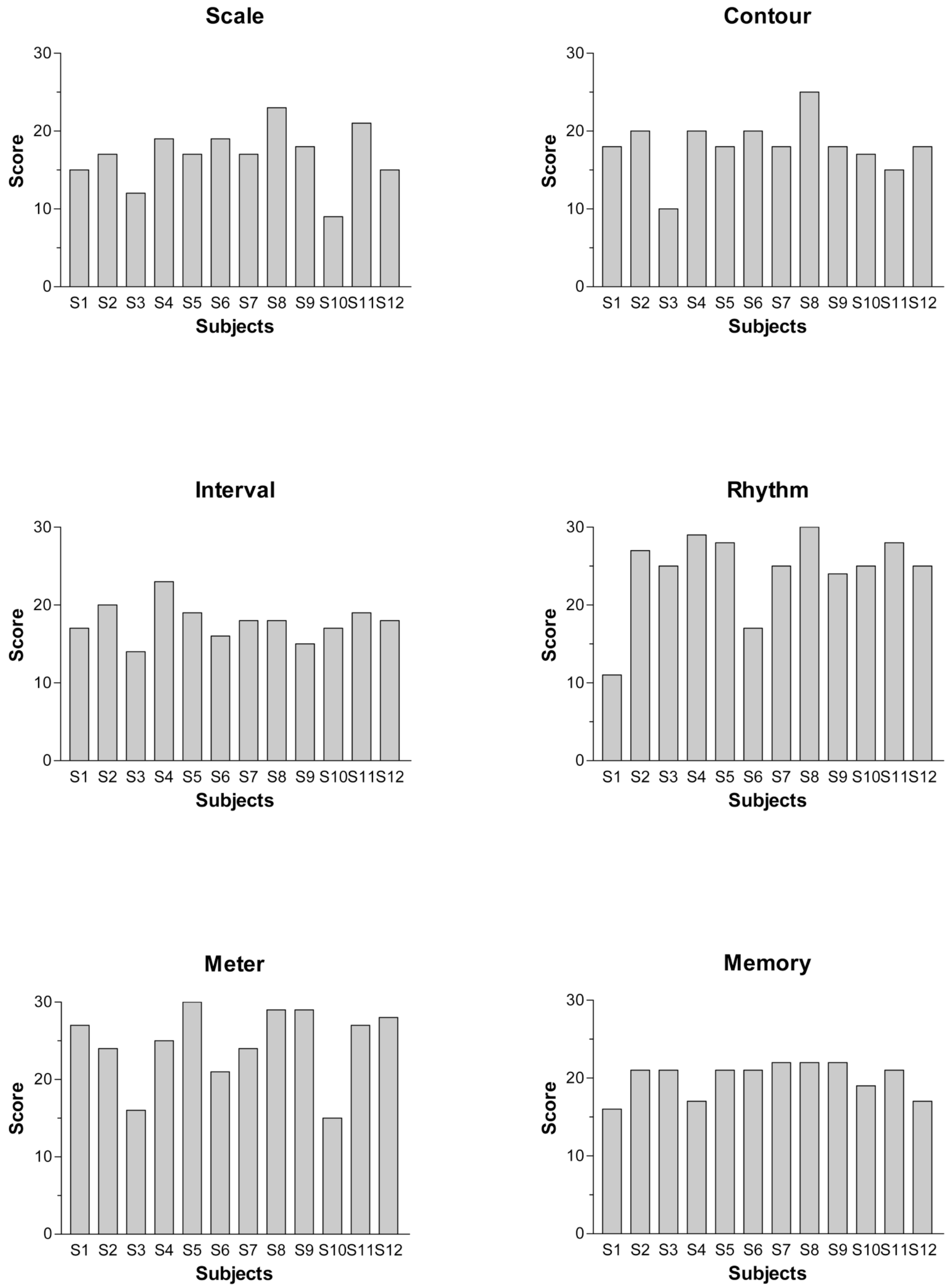

Figure 2.
Individual scores of CI users on the six musical tests.

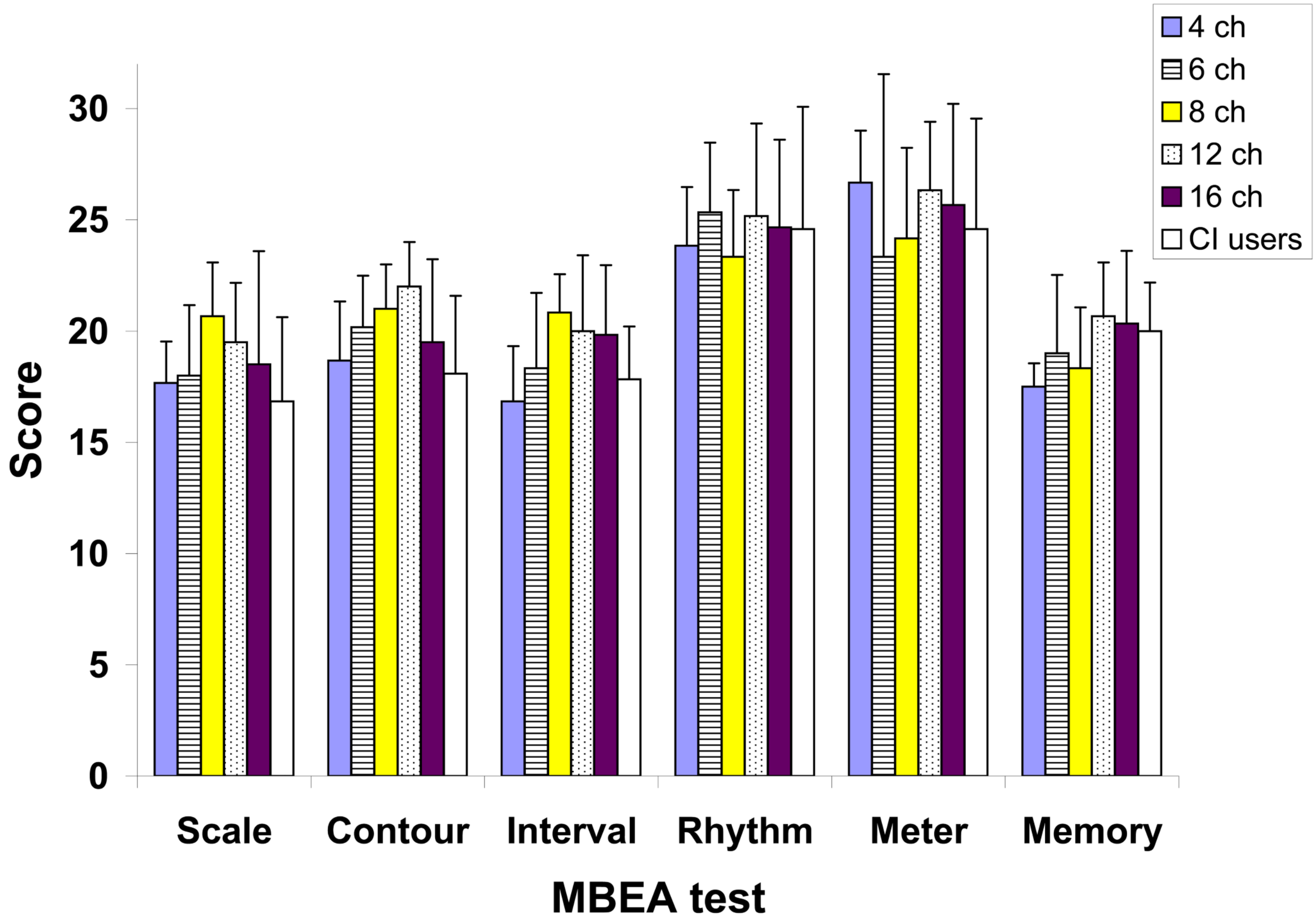

Figure 3.
Mean normal-hearing listener scores on tests from the Montreal Battery for Evaluation of Amusia. The CI users' scores are superimposed for comparison. Chance score is approximately 15. Error bars represent standard deviations.

Table 1

Biographical data for the CI users tested.

Subject	Sex	Age	Number of Years Wearing Device	Etiology of Deafness	Dur. Of Deafness (years)	Device	Musical Training (Years)	CNC (%)	HINT (%)
S1	M	45	3	Unknown	5	Nucleus 22	6	92.5	81.8
S2	F	49	3	Unknown	5	Clarion CII (HiRes)	0	56.0	93.3
S3	F	61	10	Unknown	5	Nucleus 22	0	70.7	90.5
S4	F	38	4	Hereditary	19	Clarion S (8 Ch)	5	95.3	97.1
S5	F	35	3	Unknown	5	Nucleus 22	15	64.0	94.5
S6	M	43	9	Unknown	10	Clarion S (8 ch)	5	82.0	100
S7	M	68	4	Unknown	4	Clarion CII (HiRes)	0	72.0	92.5
S8	F	51	4	Otosclerosis	13	Clarion CII (HiRes)	0	87.3	100
S9	F	51	3	Unknown	9	Clarion CII (HiRes)	0	96.0	99
S10	F	36	5	Unknown	23	Clarion CII (HiRes)	2.5	86.0	100
S11	F	46	4	Hereditary	15	Clarion CII (HiRes)	0	80.67	94
S12	M	71	4	Menieres	25	Clarion CII (HiRes)	0	89.3	100