Evaluation of a Test Battery to Assess Perception of Music in Children With Cochlear Implants

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**IMPORTANCE** A number of studies have investigated music perception in adult cochlear implant (CI) users. However, little is known about how pediatric CI users perceive and process music, in part because suitable methods for assessing music perception in this population are lacking. Therefore, we developed the Music in Children With Cochlear Implants (MCCI) battery to assess music perception in pediatric CI users younger than 9 years.

**OBJECTIVE** To pilot test the MCCI on a group of pediatric CI users to determine its feasibility for measuring music perception and to compare performance of CI users with that of normal-hearing (NH) control participants.

**DESIGN, SETTING, AND PARTICIPANTS** The pilot test was conducted in an academic tertiary care center. The MCCI evaluated rhythm, pitch, melody, harmony, and timbre perception. For each section, 10 pediatric CI users and 10 NH controls were presented with a pair of stimuli that possibly varied along a single musical element (eg, rhythm). Participants were required to indicate whether the stimuli in the pair were the same or different.

**INTERVENTIONS** Administration of the MCCI.

**MAIN OUTCOMES AND MEASURES** Percentage correct on each section of the MCCI and the aggregate score of all sections by group.

**RESULTS** The MCCI provided a basic characterization of musical perceptual abilities. In the aggregate, NH controls significantly outperformed CI users in music perception (mean [SD] accuracy for CI users vs NH controls: rhythm, 73% [20%] vs 78% [20%]; pitch, 84% [12%] vs 91% [13%]; melody, 65% [16%] vs 75% [18%]; harmony, 74% [13%] vs 75% [14%]; and timbre, 80% [17%] vs 90% [12%]; repeated-measures analysis of variance, $F_{1,17} = 9.3; P < .01$). Despite obtaining lower accuracies than NH controls, however, the CI users achieved above-chance accuracy in all sections of the MCCI (1-sample t test, $P < .01$), including pitch-based sections that are traditionally difficult for CI users. These results suggest that CI users can make use of temporal and spectral cues to discriminate between musical stimuli, although not to the extent of their NH peers.

**CONCLUSIONS AND RELEVANCE** The MCCI provided an efficient and user-friendly assessment of music perception in pediatric CI users. This test battery may serve as a valuable tool to evaluate music perceptual abilities of pediatric CI users and measure the effects of interventions.
The number of children with cochlear implants (CIs) has increased steadily during the past few decades. This technology has resulted in impressive improvements with respect to language perception and speech production for children who receive CIs at a young age. However, high levels of music perception remain out of reach for most CI recipients, mainly owing to the degraded representation of pitch and timbre cues by the CI device. Although a substantial body of evidence has been collected regarding the limitations of the CI device when applied to musical stimuli, most of these investigations have been performed with adult CI users with post-lingual hearing loss. As a result, relatively little is still known about how pediatric CI users with prelingual and perilingual hearing loss process music.

The few existing pediatric studies of music perception have focused mainly on pitch discrimination and melody (song) recognition. Although these studies suggest that pediatric CI users perform below their normal-hearing (NH) peers, much more work is warranted to understand these limitations fully. Outside pitch and melodic studies, little emphasis has been placed on assessing other features of music such as harmony, rhythm, and timbre perception, which also play an important role in music listening. Furthermore, few test batteries and methods have been designed specifically to assess music perception in pediatric CI users. Without evaluations suitable for children with CIs, quantification of current music perceptual abilities and assessment of possible improvements with interventions, such as rehabilitation and technological advancements, are difficult within this population.

To address this gap, we referred to Gordon's Primary Measures of Music Audiation (PMMA), the most widely used, standardized music aptitude test for children younger than 9 years that has also been applied to assess music perception in adult CI users. The PMMA includes tonal and rhythm sections in which participants must indicate whether stimuli in a pair (that possibly differ only along the music element under test) are the same or different. Although this test allows for a basic assessment of whether the participant can discriminate differences in musical stimuli, it is limited in providing more fine-grained quantification of perceptual abilities. For example, the PMMA assesses whether a participant can distinguish the differences between 2 synthetic pitches but provides little information about whether the attributes of the sound itself (eg, frequency, quality) were perceived correctly. Despite these limitations, the PMMA is easy to implement in a pediatric population and provides a basic understanding of perceptual abilities in a timely assessment. The PMMA demonstrates high diagnostic and predicative validity and test reliability, and its content and test administration are practical and developmentally appropriate for this age group.

For these reasons, we used the basic approach of the PMMA (same/different discrimination of individual musical elements) in the development of a new test battery of music perception in pediatric CI users, which we named Music in Children With Cochlear Implants (MCCI). The MCCI preserves the basic framework of the PMMA by using a same/different task paradigm, age-appropriate auditory directions and answer recording procedures, and a goal-oriented game to increase participant focus. This approach has been used successfully in the children's version of the Montreal Battery of Evaluation of Amusia, which lends further support to the use of a similar paradigm for the purposes of evaluation in children with CIs. Outside the basic testing framework, however, the actual contents of the MCCI differ from those of the PMMA in several critical ways. First, the MCCI assesses other pitch-based aspects of music that are difficult to discern with CI devices (melody, harmony, and timbre) to understand more fully the musical deficits in pediatric CI users. Second, the novel stimuli used in the MCCI approximate real-world listening (as opposed to synthetic pitches used in the PMMA) to assess music perception better in everyday situations. Last, a new goal-oriented game, child-friendly characters, and computer program were created specifically for the MCCI, and no test material from the PMMA was included in the MCCI.

We used the MCCI to assess music perceptual accuracy of pediatric CI users and then compared their performance with that of a group of NH control individuals within the same age range. Owing to the degraded frequency representation of the CI device, we hypothesized that pediatric CI users would perform at lower levels than their NH peers, especially in sections assessing the spectral and spectral-temporal elements of music. In addition, we anticipated that the MCCI would provide an objective and user-friendly measure of music perception in children with CIs.

### Methods

#### Participants

Ten NH children (3 boys and 7 girls; mean [SD] age, 6.5 [1.3] years) were recruited from local elementary schools in the greater Baltimore area through dissemination of study information provided to teachers; any child diagnosed as having a hearing disorder was excluded from this group. Ten children with CIs (5 boys and 5 girls; mean [SD] age, 7.2 [0.8] years) were recruited from the Listening Center at The Johns Hopkins University. To recruit pediatric CI users, e-mails were sent to the parents of children with CIs who were currently being seen by an audiologist at the Listening Center. The selection criteria for the CI group included ages 5 to 9 years and at least 1 year of CI experience with no device malfunctions. We included users of bilateral and unilateral CIs. The CI group included 7 children with bilateral CIs (4 boys and 3 girls; mean [SD] age, 7.2 [0.4] years) and 3 with unilateral CIs (1 boy and 2 girls; 8.1 [0.3] years). The mean (SD) duration of implant use was 5.9 (0.8) years, and a variety of CI devices and processing strategies were used by participants (Table). No significant difference in age between the CI and NH groups was found ($t_{18} = 1.76; P = .10$). The experimental protocol was formally approved by the institutional review board at The Johns Hopkins University School of Medicine. Written informed consent was obtained from the parents or the guardians of all participants.

| Table |
The MCCI test protocol consisted of 5 sections in the order of rhythm, pitch, melody, harmony, and timbre. Each section required approximately 8 minutes to administer and was composed of 10 novel trials. In each trial, participants were presented with a pair of stimuli and required to indicate whether the pair was the same or different (Figure 1). Each stimulus within a pair was delimited by the spoken words “first” or “second,” with a 500-millisecond silence between stimuli. Pictorial representations were used to elaborate the meaning of same and different. For same stimuli, 2 identical rabbits were shown to represent the meaning of the same, and a rabbit and a pig were shown to represent the meaning of different. Participants recorded answers by clicking “same” or “different” using a mouse and computer screen. An animal character guided and encouraged the children through each section to help maintain interest in the task, but no feedback was given during the actual evaluation.

Within a section, 5 different pairs were presented in increasing order of difficulty, such that pairs with the least differences appeared later in the trial. Five same pairs were randomly dispersed among the different-pairs trials. This method of ordering presentation was favored over randomized presentation because pilot testing revealed that young participants frequently became discouraged and frustrated when the beginning trials were too challenging.

Preceding each section, prerecorded verbal instructions and written instructions were presented. Participants then completed 2 training trials in which one same and one different sample question were presented. These questions were created for the training section only and would not later be encountered in the evaluation. After each sample question, participants indicated their answers and received feedback. If participants answered both sample questions correctly, the responses confirmed that they had an understanding of the task and were allowed to proceed to the evaluation. If participants answered one or both sample questions incorrectly, the experimenter again explained the task, and more practice was provided until a clear understanding of the task was achieved.

### Table. Demographic Characteristics of CI Users

<table>
<thead>
<tr>
<th>CI User No./Sex/ Age at Assessment, y</th>
<th>CI Features</th>
<th>Right</th>
<th>Internal Device</th>
<th>Processor</th>
<th>Strategy</th>
<th>Left</th>
<th>Internal Device</th>
<th>Processor</th>
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<td>Second</td>
<td>Strategy</td>
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<tr>
<td>1/M/6.3</td>
<td></td>
<td>14 (R)</td>
<td>73 (L)</td>
<td>Nucleus 512&lt;sup&gt;a&lt;/sup&gt;</td>
<td>NS</td>
<td>ACE</td>
<td>Nucleus 24&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Freedom</td>
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<td>10 (L)</td>
<td>63 (R)</td>
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<td>Freedom</td>
<td>ACE</td>
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<td></td>
<td>23 (R)</td>
<td>92 (L)</td>
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<td>Harmony</td>
<td>Fidelity 120 P</td>
<td>HiRes 90K&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Fidelity 120 P</td>
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<td>50 (L)</td>
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<td>Harmony &amp; PSP</td>
<td>Fidelity 120 P</td>
<td>HiRes 90K&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Harmony</td>
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<td>43 (L)</td>
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<td>56 (L)</td>
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<td>Fidelity 120 P</td>
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<td>HiRes 90K&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Harmony</td>
<td>Fidelity 120 P</td>
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Abbreviations: ACE, Advanced Combination Encoder; CI, cochlear implant; L, left; NA, not applicable; R, right.

<sup>a</sup> Manufactured by Cochlear.

<sup>b</sup> Manufactured by Advanced Bionics.

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Figure 1. Representative Same and Different Pairs for Each Section of the Music in Children With Cochlear Implants (MCCI) Battery

The MCCI included rhythm, pitch, melody, harmony, and timbre sections. A different animal character guided participants through each section to help maintain attention.
Sections of the MCCI

Rhythm

The rhythm section measured the perception of temporal aspects of music. Stimuli were a single bar in duration, performed in a 4/4 time signature (4 beats per bar with a quarter note equaling 1 beat) at a standard tempo of 120 beats per minute (bpm). Stimuli were created as Musical Instrument Digital Interface (MIDI) data and presented using a sample (pre-recorded) snare drum hit (an 8-millisecond peak with a 95-millisecond decay trial). Ten rhythmic patterns were created by permutation of 5, 6, or 7 eighth-note beats and 3, 2, or 1 eighth-note rests, respectively, into 8 positions to create a single measure of eighth-note beats and rests. Five of the 10 rhythmic patterns were chosen randomly to serve as the first rhythm within the different pairs. To create the second stimulus within the different pairs, an even number of beats (range, 2-4) was selected randomly and changed from a played note to a rest (unplayed note) or vice versa. This process kept the total number of notes constant within a pair, requiring the participant to detect rhythmic changes through the temporal relationship of beats and rests only. A different pair was considered to have increasing difficulty when fewer notes were altered between stimuli within the pair.

Pitch

The pitch section measured the ability of participants to distinguish differences between 2 piano notes. Tones were created as MIDI data and presented using a sample (pre-recorded) grand piano instrument patch in a digital audio workstation and music sequencer program (GarageBand 09, version 5.1; Apple). The MIDI data were exported as a .wav file, and tones within a pair were balanced to equal loudness using recording software (Audition, version 3.0; Adobe Systems, Inc.). Each note was 2.4 seconds in duration. For this study, we specifically chose tones created from piano samples to better represent real-world acoustic notes that contain the fundamental frequency and all overtone cues. Some studies of pitch in CI users have used highly synthesized complex tones or pure tones only, which afford the benefit of greater experimental control but make it difficult to extrapolate the findings to real-world music listening. Our method of tone creation produces a highly realistic grand piano timbre that replicates the type of tones participants must discriminate in everyday musical settings. In addition to this high ecological validity, the MIDI data presented as sample instrument patches still allow experimenters to control the length (duration), loudness, and velocity of each piano tone to minimize differences between stimuli that are unrelated to pitch.

The fundamental frequency (F0) of the stimuli in this task ranged from 131 Hz (1 octave below middle C) to 523 Hz (1 octave above middle C). Western music encompasses a much larger frequency range, but the notes around middle C are the most common in Western music and nursery songs. For that reason, we limited our frequency range to 1 octave above and 1 below middle C. For the different pairs, pitch differences included 1 semitone (approximately 6% F0 difference), major third (4 semitones), perfect fifth (7 semitones), major seventh (11 semitones), and 1 octave (12 semitones; 100% increase in F0); these specific pitch intervals were chosen because of their important roles in Western music. Smaller frequency differences between stimuli in different pairs were considered more challenging. Although a wider frequency range and smaller intervals between notes might have allowed a more exact approximation of pitch discrimination limens, the frequency range and intervals chosen kept the test short and practical while providing an assessment of pitch perception as it relates more specifically to intervals encountered in real-world music.

Melody

The melody section measured the ability of participants to detect pitch differences between pairs of melodies with identical rhythms. All melodies were novel and composed for the purpose of this study. Melodies were collected as MIDI data, and each note was presented using a grand piano sample instrument patch, similarly to the notes presented in the pitch section. All melodies were a single bar in duration, performed in the 4/4 time signature and presented at 90 bpm. Melodies contained eighth, quarter, and/or half notes to create a unique rhythm for each pair. Unique rhythmic patterns were chosen instead of isochronous melody presentation to better represent real-world melodies that commonly contain a mixture of various note lengths. However, because rhythms were kept constant within a pair and rhythmic cues could not be used, participants could rely solely on pitch differences to make a distinction between different pairs.

Melodies were composed of musical intervals typical of Western tonality, and the frequency ranged from C4 (262 Hz) to C5 (523 Hz), a range commonly used in Western music. For different pairs, the rhythmic patterns were kept constant but the contour of the melody was altered by changing the pitch of various notes. The mean pitch change for a different pair was 4 (range, 1-7) semitones, and the mean number of notes changed was 2 (range, 1-4). To provide a range of difficulty, larger semitone transpositions were placed in different pairs that contained a greater number of notes changed. Difficulty for the different pair was calculated by taking the mean of the semitone transposition of each note.

Harmony

The harmony section measured the ability of participants to detect differences between 2 chord progressions. Stimuli were composed as MIDI data and presented using the grand piano sample instrument patch. Each chord progression contained 3 chords sequentially presented with the first 2 beats composed of quarter notes and the third beat as a half note. Each stimulus was 1 measure long and performed in a 4/4 time signature at 100 bpm. Chord progressions were selected (instead of comparisons between 2 single chords in isolation) so that harmonic relationships could be studied to provide a more accurate measure of harmony perception as it occurs during real-world music listening. All chord progressions were composed of 3 note chords (triads), unless 4 note chords (tetrads) were required to reduce ambiguity of key. However, we anticipated that the inclusion of tetrads would have little effect on the results because CI users have difficulty extracting the
number of pitches in polyphonic stimuli, such that the presence of tetrads would provide few additional cues.21

For all stimuli, the first chord was a C major chord (I) in its root position as C₄ (262 Hz), E₄ (330 Hz), and G₄ (392 Hz) played simultaneously. The second and third chords included 2 of the following chords in the key of C major: I, V₇, IV, V₇/IV, i₆, ii₆, i₄, and i₇. All chord progressions followed the rules of Western music. The notes within the chords ranged from C₄ (262 Hz) to F₅ (698 Hz). For different pairs, the second or third chord in the progression was varied from the first stimulus. Difficulty in different pairs was increased by minimizing the change in harmonic relationship between stimuli within a pair. For example, the chord progressions I, iii (E₄, G₄, B₃), I and I, iii, i₆ (E₄, G₄, C₄) would be considered very difficult because only the last note of the chord in the progression was inverted 1 octave higher (from C₄ to C₅). On the other hand, the chord progressions I, I, I and V₇, I would be considered much easier because the varied second note has a relatively small frequency overlap with the original note.

**Timbre**

The timbre section measured the ability of participants to detect differences between 2 musical instruments playing identical melodies. Earlier studies22-24 suggest that the temporal envelope is the most salient cue for timbre perception for CI users22-23 and that CI users tend to confuse instruments that have similar temporal envelopes (ie, percussive or nonpercussive (sustained)).24 For these reasons, we chose 5 popular Western musical instruments, 2 of which contained sustained envelopes (trumpet and flute) and 3 of which contained percussive envelopes (guitar, violin, and piano) while also maintaining a range of instrument families (brass, woodwind, and string). Melodies were collected as MIDI data and presented using a prerecorded sample instrument patch (trumpet, flute, guitar, violin, or piano). All samples were balanced for equal loudness. Sample instrument patches (as opposed to digitally synthesized timbres) were used for similar reasons stated in the pitch section, that is, mainly to maintain high ecological validity that allows results to be extrapolated to real-world listening situations while still allowing the experimenter to control key variables.

To promote the attention of the children (whose attention tended to wander during repetitive tasks), 2 melodies ("Twinkle Twinkle Little Star" or "Ode to Joy") were alternated between trials. Within a trial, length, onset/offset, and velocity of each note in the melody were kept identical (same MIDI data), but each stimulus could be presented using a different sample instrument patch. As a result, the only potential difference between stimuli within a pair was the timbre of the instrument. A different pair was considered more difficult if both instruments had the same envelope (percussive or nonpercussive) and if both were from the same instrument family (ie, string). For example, trumpet (sustained envelope and brass family) and a guitar (percussive envelope and string family) would be considered an easy pair to differentiate because the instruments have different temporal envelopes and different families. On the other hand, a violin and guitar would be considered a difficult pair because both instruments have a percussive envelope and are from the string family. All melodies were 4 measures in duration (approximately 10 seconds).

**Test Administration**

All sounds were created as MIDI data using the same digital audio workstation and music sequencer program (Garage Band ’09, version 5.1) and presented using standard sample instrument patches from the software. Stimuli were exported and then presented as .wav files. All stimuli were normalized by root-mean-square power with equal contour adjustments to loudness using the recording software to minimize the effect of loudness variation on the same/different tasks. The music test was presented on a customized, computerized interface developed in system design software (LabVIEW; National Instruments).

Two external speakers (Studiophile AV 40; M-Audio) positioned approximately 2 feet from the listener at ±10° azimuth presented the stimuli in sound field. Volume was set to a comfortable listening level for each participant. All CI users listened to the stimuli using their everyday sound-processing strategy set to a comfortable listening level. Bilateral CI users were allowed to use both implants for the study to maintain ecological validity. No hearing aids were permitted.

**Statistical Analysis**

Statistical analysis was performed using a commercially available software package (SPSS, version 21; IBM). Values are reported as mean (SD). To address the possible confounding by the number of implants, we conducted a repeated-measures analysis of variance (ANOVA) with the number of implants (bilateral or unilateral) as a between-subjects factor to determine group differences between unilateral and bilateral CI users. We found an insignificant between-subjects effect (F₁₈ = 0.8; P = .40), suggesting that the number of implants did not significantly affect performance in this music test. Owing to the insignificant effect of implant number, we combined CI users into a single group for the purposes of the remaining analyses. To assess differences between NH controls and CI users, we performed a repeated-measures ANOVA with a Greenhouse-Geisser correction25; the music subtest (pitch, melody, harmony, timbre, and rhythm) served as a within-subjects factor and group (CI users and NH controls) served as a between-subjects factor, with age as a covariate. Post hoc analyses of simple effects examined differences between NH controls and CI users at each level of the subtest. For all statistical tests, the α level was set to .05.

**Results**

To address the first objective, we assessed the feasibility and relevance of the MCCI for CI users. For administration of the entire test, the mean duration was less than 45 minutes, well within the attention span of our participants. Task instructions were within the cognitive limits of the participants, and most of the CI users correctly completed the training session without additional help from the test administrator. Skewness and kurtosis levels for CI users for each section were insignificant (P > .15), indicating that musical stimuli were of an
appropriate difficulty level for this group and demonstrating the utility of this test to capture a wide range of performances for pediatric CI users.

To assess the second objective, we compared performance across each subtest and between pediatric CI users and NH controls. Figure 2 shows performance in each music subtest by group (CI or NH). The CI users achieved a mean accuracy of 73% (20%) for the rhythm section, 84% (12%) for the pitch section, 65% (16%) for the melody section, 74% (13%) for the harmony section, and 80% (17%) for the timbre section. In comparison, NH controls achieved a mean accuracy of 78% (20%) for the rhythm section, 91% (13%) for the pitch section, 75% (18%) for the melody section, 75% (14%) for the harmony section, and 90% (12%) for the timbre section. A repeated-measures ANOVA revealed a significant between-subject factor ($F_{1,17} = 9.3; P < .01$) such that the aggregate score for all sections was significantly higher for NH controls than CI users. Further analysis revealed that NH controls performed significantly better in the timbre section ($P = .02$) and differences approached significance for the pitch section ($P = .07$). Although NH controls achieved a greater accuracy than CI users in all sections, CI users still scored a mean of 25.5 percentage points greater than the chance level (50% accuracy) across all sections, and this difference compared with chance was significant (1-sample $t$ test, $P < .01$). An insignificant within-subjects factor for music subtest suggests that scores were not significantly different for any single section of the MCCI ($F_{2,7,45.4} = 1.2; P = .22$). An insignificant interaction between group and subtest ($F_{2,7,45.4} = 0.3; P = .80$) was found.

Discussion

This study investigates several key aspects of music perception in pediatric CI users. The pediatric CI users in this study achieved a lower percentage correct than NH controls in all sections and a significantly lower aggregate score ($P < .05$). Despite their poorer performance, however, the CI users still performed significantly better than the chance level in all sections ($P < .01$). These finding suggest that although CI users cannot readily perceive the musical elements tested as well as their NH peers, they still can make use of various musical cues (eg, pitch, timbre) to detect differences in musical stimuli. This test provided an objective measure of music perception in pediatric CI users. This test battery is the first, to our knowledge, that measures rhythm, pitch, melody, harmony, and timbre perception within a single user-friendly evaluation designed particularly for the pediatric CI population.

Strengths of the MCCI

The primary aim of this study was to develop a child-friendly music perception test that provides a basic and efficient characterization of music perceptual ability of pediatric CI users younger than 9 years. Earlier music evaluations for NH children have demonstrated the same/different tasks and answering procedures that we used to be well suited for this age group from a developmental and cognitive perspective (ie, ability to understand the task, length of attention, and motivation).14

Because the MCCI uses a same/different task paradigm that is within the cognitive abilities of our participants, it helps to ensure that negative results are not due to a lack of understanding of the task. Equally important, this same/different paradigm could be applied to all sections of the assessment. This application minimizes the need to explain a new set of directions before the start of each section and reduces the cognitive burden of the participant because newly learned directions can apply to subsequent sections. Furthermore, same/different tasks also offer improvements over melody and/or timbre recognition assessments that are commonly used within the adult CI user population.26 Unlike recognition tasks, same/different paradigms require no previous knowledge of the stimuli to excel—an important criteria for a naive listening population of children—and issues of memory recall that may affect recognition accuracy (independent of perceptual abilities) are largely removed. Last, the MCCI requires no prior music training (outside the instructions) before test administration. Minimal required training allows for a same-day test administration, keeps the total testing time within the attention span of our pediatric target group, and makes it feasible to administer in a clinical setting.

Limitations of the MCCI

The major limitation of the same/different task is that the test is only sensitive enough to detect whether participants can discriminate differences between 2 stimuli and not whether the stimulus itself was perceived accurately. For example, if CI users can differentiate between a flute and violin (playing identical melodies), these results shed little light as to whether participants accurately perceive whether the instruments were in fact a flute and violin (ie, correct identification). Furthermore, a distinction between stimuli only indicates that CI users are using some acoustical cue (eg, temporal or spectral envelope) to make this distinction, but which specific cue is not
clear from this paradigm alone. The difference cue that CI users perceive also may not be equivalent to what NH listeners perceive. As a result, the same/different task provides less precise results than may be obtained by a more fine-grained assessment of any single given element.

Tasks that elucidate discrimination abilities provide less detailed information precisely because discrimination is low on the hierarchy of hearing. This hierarchy follows a stepwise approach that begins with detection and proceeds to discrimination, identification, and comprehension of sound.24 Our test specifically used a same/different approach to assess discrimination because it (with detection) forms the foundation of this hierarchy of hearing and thus our understanding of basic music perceptual abilities in pediatric CI users. We believe that starting at the bottom of this hierarchy (even if tasks that assess higher hierarchical levels provide more fine-grained information) was important because discrimination, identification, and comprehension are not well understood in this population as they relate to music. The MCCI quantifies more basic levels of musical perceptual deficits in pediatric CI users that can inform further efforts. Future studies should be directed toward more specific characterization of each individual element at higher levels. More robust test batteries are warranted to better understand specific pitch, melody, timbre, and harmony deficits in pediatric CI users.

The sequence in which stimuli are presented during the MCCI also warrants discussion. During each section, the MCCI presents stimuli in order of increasing difficulty. This design is intended to allow children (who frequently may become discouraged) to develop familiarity and confidence with the task while working to more challenging stimuli. Sections that are traditionally easier for CI users (ie, rhythm) preceded sections that are considered more difficult (ie, timbre) for the same reasoning.24 With this order of stimuli presentation, a small learning effect might have occurred for the later stimuli within a trial and for later sections. However, existing studies suggest that extended training is needed to improve at a music perceptual task, and guided feedback is important for progress.26,29 Therefore, any learning effects occurring during a 45-minute test (without feedback) are likely to be very small and mainly associated with proficiency in same/different tasks in general, not overall improvements in the perception of a musical feature. We believe that this possible limitation is largely offset by the significant increase in positive engagement by the participants, which in turn allows a more accurate quantification of perceptual abilities. Owing to the lack of randomization, however, the fatigue of testers may bias results, especially for later sections. Although strong performance by both groups in the last section (timbre) suggests that fatigue had little effect on performance, future studies should address this aspect of the MCCI. Randomized presentation may prove more valid for future testing and therefore warrants additional investigation.

Future studies should investigate further refinements of the MCCI. Test presentation (ie, randomization vs increasing level of difficulty) needs to be addressed. In addition, the musical stimuli need to be validated using a larger group of NH controls and pediatric CI users. Test reliability and diagnostic validity should be assessed as well. Although additional testing of the MCCI is still needed, this assessment provides a useful foundation for characterizing music perception in pediatric CI users in an efficient and developmentally appropriate manner.

Comparisons Between CI Users and NH Controls

Studies with adults CI users24 suggest that pitch, melody, and timbre perception are severely impaired in this population. The relatively small numbers of pediatric studies also provide some evidence that children with CIs typically perform worse than their NH peers on pitch-based tasks, although they generally attain an accuracy well above that of chance in identifying pitches, melodies, and timbres.5–11 This study closely agrees with previously reported studies. The aggregate score of all sections was significantly greater for NH controls than CI users. More specifically, NH controls outperformed CI users in all sections, although only the differences in the timbre section reached significance.

Despite the lack of statistical significance in all pitch-based sections between groups, pediatric CI users are unlikely to perceive spectral elements of music as accurately as their NH peers. Instead, the insignificant difference observed herein may reflect the imprecision of the paradigm. As noted previously, same/different tasks are inherently easier and provide less detailed measurements than other possible assessment methods (eg, identification tasks), which may mask differences between groups; in other words, successful performance on this task says little about pitch accuracy, musical sound quality, or fine-grained pitch discrimination. Furthermore, the small sample sizes and large variability of this study decreased the power to detect a significant difference. Therefore, we believe that this lack of statistical difference between groups, especially in pitch-based sections, may inflate the performance of CI users artificially and should be interpreted within the constraints of this study.

The performance of CI users most closely resembled that of NH controls in the harmony sections; in mean scores, CI users scored only 1 percentage point below NH controls. These results in the harmony section support an earlier study that reported pediatric CI users are able to perceive some aspects of harmony within chord progressions similarly to NH children.12 Considering the extremely poor pitch perception in CI devices, however, CI users are unlikely to perceive harmony normally. These findings more likely reflect issues of cognitive development. Children younger than 9 years have significant difficulties following harmony, possibly attributable to their limited attention behaviors that impair their ability to attend to more abstract cues, such as harmony and key, in a musical stimulus.30 As a result, both groups may have struggled equally with this task owing to limited harmonic development rather than perceptual acuity.

Conclusions

We believe the strength of the MCCI test lies in its ability to provide a user-friendly and relatively quick assessment of
The MCCI was designed intentionally to assess music perception within a population of CI users younger than 9 years. Although the limitations in precision (due to the use of a same/per different paradigm), we believe that this drawback is counterbalanced by the gain in other factors, namely allowing the use of a test that was developmentally appropriate for our tested age group and could be implemented without any significant prior training. The MCCI also permitted the testing of several elements of music perception in a short period (well within the attention span of our participants) to provide a more inclusive measure of music perception than could be obtained by the test of any single musical element. Although much more work is needed to develop and validate this musical test battery, the MCCI offers the potential to quantify a wide range of perceptual abilities in pediatric CI users within a single evaluation and may serve as a useful diagnostic tool in the future.

**REFERENCES**

17. Gelfer K, Lansing C. Musical perception of cochlear implant users as measured by the primary