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The Effects of Musical and Linguistic Components in Recognition of Real-World Musical Excerpts by Cochlear Implant Recipients and Normal-Hearing Adults

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Abstract

Background—Cochlear implants (CI) are effective in transmitting salient features of speech, especially in quiet, but current CI technology is not well suited in transmission of key musical structures (e.g., melody, timbre). It is possible, however, that sung lyrics, which are commonly heard in real-world music may provide acoustical cues that support better music perception.

Objective—The purpose of this study was to examine how accurately adults who use CIs ($n=87$) and those with normal hearing (NH) ($n=17$) are able to recognize real-world music excerpts based upon musical and linguistic (lyrics) cues.

Results—CI recipients were significantly less accurate than NH listeners on recognition of real-world music with or, in particular, without lyrics; however, CI recipients whose devices transmitted acoustic plus electric stimulation were more accurate than CI recipients reliant upon electric stimulation alone (particularly items without linguistic cues). Recognition by CI recipients improved as a function of linguistic cues.

Methods—Participants were tested on melody recognition of complex melodies (pop, country, classical styles). Results were analyzed as a function of: hearing status and history, device type

(electric only or acoustic plus electric stimulation), musical style, linguistic and musical cues, speech perception scores, cognitive processing, music background, age, and in relation to self-report on listening acuity and enjoyment. Age at time of testing was negatively correlated with recognition performance.

Conclusions—These results have practical implications regarding successful participation of CI users in music-based activities that include recognition and accurate perception of real-world songs (e.g., reminiscence, lyric analysis, listening for enjoyment).

Keywords

cochlear implants; music

Introduction

Hearing loss is the third most common chronic condition to affect Americans after hypertension and arthritis. Approximately one-third of people older than 60, and half of those older than 85, have hearing loss. In recent decades, approximately 188,000 people worldwide, who receive limited if any benefit from conventional hearing aids, have chosen to use a bionic ear called a cochlear implant (CI). In the United States, there are roughly 41,500 adult and 25,500 pediatric CI recipients (National Institutes of Health, 2009).

Cochlear implants are very effective at transmitting spoken communication in quiet listening environments. With current-day technology, the majority of postlingually-deaf implant recipients score above 80% on high-context sentences in quiet listening conditions without visual cues. Speech recognition declines, however, in complex listening conditions (e.g., background noise) (Gantz, Turner & Gfeller, 2006; Wilson, 2000). In addition, the electric stimulation transmitted by the CI is poorly suited for conveying several key features of music (e.g., pitch, harmony, timbre) (e.g., Gfeller et al., 2008; Looi, 2008; McDermott, 2004). This can have a negative impact on perception and enjoyment of music, including meaningful participation in social activities that include music, music making, and also music therapy sessions.

As the population of CI users expands, music therapists and music educators are increasingly likely to work with individuals who use various types of cochlear implants. Consequently, it is of professional relevance to determine which elements in music are most readily accessible to CI recipients. This study expands on prior research of real-world music recognition (Gfeller et al., 2005), examining systematically (a) the roles of linguistic (song lyrics) and non-linguistic (instrumental- only music) information, (b) recent trends in CI technology (different forms of auditory stimulation) and (c) changes in criteria for CI candidacy (characteristics of hearing loss) as these factors influence perception of several commonly-heard styles of music.

In-depth description of cochlear implants (CI) can be found in other sources (Looi, 2008; McDermott, 2004; Wilson & Dorman, 2009, etc.). Just as technology such as cell phones and personal computers vary in features and capabilities depending upon the manufacturer and model, CIs can vary somewhat with regard to the technical specifications of the hardware (e.g., shape, length of internal electrode array, etc.) and processing strategy (software controlling the parameters of the auditory signal transmitted to the internal array). However, most CIs have similar basic components and principles of auditory stimulation. In brief, unlike conventional hearing aids that amplify sound via the auditory canal, a CI system has both an externally-worn sound processing unit (sound processor) and surgically-implanted internal parts. The external portions of the CI include a microphone, which picks up the acoustic signal, and a sound processor (a mini computer), which extracts and

processes the features of the sound wave most salient to speech perception. The electrical signal produced by the sound processor is then transmitted to the internal electrode array in the cochlea, which provides direct electrical stimulation to the nerve fibers (spiral ganglion cells) in the cochlea (Looi, 2008; Wilson, 2000). Specific frequencies are distributed to the electrodes on the internal array. For example, one electrode may be stimulated in response to acoustical sounds in the environment ranging from approximately 1300 to 1600 Hz, while the neighboring electrode may cover frequencies of approximately 1600 to 2100 Hz (Tyler et al., 2010). This results in limited spectral selectivity, which has a negative impact on perception of pitch and timbre (e.g., Gfeller et al., 2007; Kong et al., 2004).

Advances in the design of the internal electrode and processing strategies (e.g., different pulse rates, more fine structure, etc.) have enhanced speech perception for some individuals (Firszt et al., 2009; Wilson & Dorman, 2009). It has been hypothesized that technical advances that facilitate transmission of more fine spectral information may enhance perception of complex sounds, such as speech in noise and music (Firszt et al., 2009; Gfeller et al., 2007). However, numerous studies reporting group data indicate that adult CI recipients (regardless of device brand or processing strategy) whose hearing is based essentially on electric stimulation are significantly less accurate than NH adults in pitch discrimination, direction of pitch change, and pitch pattern discrimination (Dorman et al., 1990; Fujita and Ito, 1999; Galvin et al., 2007; Gfeller, Turner et al., 2002; Gfeller et al., 2007; Kong et al., 2004; Looi, McDermott, McKay, & Hickson, 2004; McDermott, 2004; Pijl, 1997; Pijl & Schwartz, 1995; Pressnitzer, Bestel & Fraysse, 2005; Schultz & Kerber, 1994). Because melodies are made up of sequences of pitches, recognition of melodies (no lyrics) with or without harmony is also problematic (Fujita & Ito, 1999; Galvin et al., 2007; Gfeller, Turner et al., 2002; Looi, 2008; McDermott, 2004).

The electrical stimulation presented to the CI's electrode array is also less effective in transmitting the natural and distinctive timbre associated with different musical instruments or instrumental blends. Although CIs provide enough spectral information to enable discrimination (e.g., determining that a flute and piano are different instruments), the level of spectral information conveyed makes timbre recognition problematic (Fujita and Ito, 1999; Gfeller et al., 1997, 1998, 2002a, 2002b; Looi, 2008; McDermott, 2004; Schulz and Kerber, 1994; Stainsby, 2001).

On a more positive note, CIs are effective in transmitting durational elements of music (rhythm, tempo); CI recipients compare favorably with NH listeners in perception of tempo and rhythm patterns (Donnelly, Guo & Limb, 2009; Gfeller, 2000; Gfeller and Lansing, 1991, 1992; Gfeller et al., 2000; Kong et al., 2005; Leal et al., 2003; Looi, 2008; Schulz and Kerber, 1994; Vongpaisal, 2006). Perception of the melodic rhythm (sequence of long and short notes in a melodic pattern) can help CI recipients recognize melodies that have distinct rhythmic patterns (Gfeller et al., 2002a, 2007; Hsiao, 2008; Masia et al., 2002; Olszewski et al., 2005, 2006).

Real-world music, such as songs heard over the radio, are generally composed of complex blends of melodic, harmonic, and rhythmic patterns presented with varying timbral qualities. NH listeners with no formal music training can readily recognize commonly-heard real-world songs. In contrast, prior research demonstrates the difficulty of this same task for adult CI recipients who rely on electrical stimulation (Gfeller et al., 2005). In a test of recognition (Musical Excerpt Recognition Test- MERT) for well-known musical excerpts from country, classical, and pop styles, CI recipients were significantly less accurate than NH non-musicians on all three musical styles. However, CI recipients were significantly more accurate in recognizing country and pop items compared with classical items. Because CIs have been developed to transmit speech sounds, it is possible that song lyrics may assist

in melody recognition more than pitches or melodic patterns. However, the contribution of song lyrics per se was not systematically investigated in the Gfeller et al., 2005 study.

Some preliminary data (Fujita and Ito, 1999; Gfeller, Buzzell, et al., 2009) and anecdotal evidence from interviews suggests that some, though not all CI recipients are able to extract lyrics from music; however, the ease of recognizing lyrics can vary depending in part upon the characteristics of the singer's voice (e.g., clarity of articulation, use of singer's formant) and background music (e.g., frequency range and masking properties, intensity, etc., Gfeller, et al., 1997, 1998, 2009).

Recent trends in implant technology and CI candidacy

In the first few decades of CI development, CIs have been targeted to persons with bilateral severe to profound hearing loss. Advances in CI technology have often involved small modifications to the 22 mm internal array (e.g., curved vs. straight electrode) or parameters of the processing strategies (e.g., rate of stimulation, digital vs. analogue stimulation, etc.) (Looi, 2008). A recent advance in CI technology, named the Hybrid device, has been developed with a slightly different population in mind: individuals who have a significant hearing loss in the high frequencies, but who retain considerable residual (acoustic) hearing in low frequencies (Gantz and Turner, 2003). The Hybrid device has a 10 mm internal electrode, which is considerably shorter than the array found in most conventional CI devices. The name, "Hybrid" refers to the fact that this device allows for the transmission of both acoustic and electric stimulation (A+E): acoustic stimulation (amplified by a hearing aid) of residual hearing in the lower frequencies, and electric stimulation of high frequencies (transmitted by a CI) that do not respond well to conventional amplification. Recipients using a Hybrid device typically use a hearing aid (HA) along with the CI in/on the same ear. Some Hybrid users also use a hearing aid in the contralateral ear if they retain enough residual hearing in that ear to benefit from conventional amplification.

The shorter Hybrid electrode array, because it is inserted less deeply into the cochlea, can help preserve useable acoustic hearing in the apical end of the cochlea, which is responsible for encoding lower frequency sounds. As a result of this technology, selection criteria for implant candidacy has changed somewhat to include individuals with more residual hearing, not only persons with severe and profound loss.

The presence of low-frequency acoustic hearing, seen as having a synergistic relation to electrical stimulation, has been documented as beneficial in perception of speech against background noise and pitch perception (Dorman et al., 2008; Gantz and Turner, 2003; Gantz, Turner & Gfeller, 2006; Gfeller et al., 2007; Kong et al., 2004, 2005). Some preliminary studies indicate that Hybrid CI users have greater simple melody and timbre recognition than CI recipients receiving electric stimulation only (Dorman et al., 2008; Gantz, Turner and Gfeller, 2006; Gfeller et al., 2007).

In summary, the extent to which CI recipients will be able to recognize real-world music is likely to be affected by several factors. These factors include (a) the structural properties of the music itself (e.g., melody, rhythm, lyrics), (b) the form of auditory stimulation presented by the CI (e.g., type of processing strategy; acoustic or electric stimulation), and (c) the hearing profiles of the CI recipient. Systematic study is required to determine how accurately adult CI recipients using various types of stimulation are able to perceive linguistic and musical elements in recognizing real-world musical excerpts. Because CI recipients are likely to be exposed to complex musical selections with and without lyrics on a regular basis in real life, including therapeutic (e.g., lyric analysis, reminiscence through songs) and educational (making music, music appreciation, etc.) aspects of music, the extent

to which CIs transmit real-world musical sounds effectively is of pragmatic interest to clinicians and educators.

The primary focus of this study was to examine recognition of three types of real-world music by adult CI recipients, in comparison with NH adults, and the extent to which such recognition is influenced by musical cues only (instrumental music), and song lyrics paired with instrumental accompaniment. In addition, we examined whether recipients of particular CI technology (e.g., different processing strategies, electrical stimulation vs. acoustic plus electric stimulation) are more accurate in recognizing real-world musical excerpts. Finally, because past studies regarding music perception have demonstrated large variability among implant recipients, we wished to examine the relations between melody recognition and potentially influential individual differences, such as speech perception, indices of cognitive abilities, and demographic factors.

Method

Participants

Participants included 87 postlingually-deafened adults (50 female, 37 males) with at least one year of CI experience, and 17 adults with normal or near-normal hearing (14 female, 3 male), who served as a comparison group to ascertain difficulty of the response task for persons with normal acoustic input. Both CI and NH groups were native English-speaking adults culturally affiliated with the United States, an important factor given that recognition of particular musical selections is influenced by exposure to particular styles of music. The study was approved by the Institutional Review Board and all participants were provided with, and gave, informed consent to participate.

CI recipients—The implant recipients were assigned to two primary groups as a function of the implant electrode and device configuration they were using: a group whose CI signal presented electrical stimulation only (ES; $n = 79$), and a Hybrid device group who received a combination of acoustic plus electric stimulation (A+E; $n = 8$).

Electrical Stimulation Group (ES)—CI recipients in the ES group used an internal electrode array of 22 mm in length, with 22 separate electrodes that stimulate the auditory nerve; all had bilateral severe or profound deafness prior to implantation. On average, the pure tone averages for the ES are 105+dBHL across their audiograms. The ES group ranged in age from 21 to 84 ($M = 61.56$ yrs, $SD = 14.60$); mean length of CI use was 82.47 months ($SD = 60.65$). The ES group used a variety of standard internal electrodes¹ and processing strategies.² ES recipients also varied on whether they used one (monaural) ($n = 62$) or two (binaural) ($n = 17$) implants (which we will refer to in this study as mode of implantation). Of the recipients with monaural devices, 21 participants used a hearing aid in the opposite ear in conjunction with their implant.

More contemporary internal devices and processing strategies have been associated with improved speech perception (Firszt, et al., 2009; Wilson, 2000) and theoretically have been hypothesized as capable of providing more salient cues for pitch or timbre. However,

¹Types of internal electrodes arrays used by LE recipients in this study included: Freedom, CIHF1/2, Clarion, 90K, CI24M, CI22, Contour. Extensive descriptions of these devices are available in books and articles focusing on CI design (e.g., Looi, 2008; McDermott, 2004). Because none of the LE devices were significantly different in relation to melody recognition, no further detail regarding specific devices is covered in this paper.

²Types of external signal processing strategies used by LE recipients in this study included: HiRes-S/P, ACE, CIS, SPEAK, Mod CIS, HRPS, HiRes 120. Extensive descriptions of these signal processing strategies are available in books and articles focusing on CI design (e.g., Looi, 2008; McDermott, 2004). Because none of the strategies were significantly different in relation to melody recognition, no further detail regarding specific devices is covered in this paper.

preliminary analyses of our test data indicated that none of the devices or strategies within the ES group was superior with regard to melody recognition. Consequently, our test data were combined into one CI group (ES) for subsequent analyses. While there were no significant differences as a function of type of internal device or processing strategy, preliminary analyses indicated significant differences as a function of mode (monaural or binaural CI) for recognition of items that included sung lyrics; therefore, two ES subgroups (monaural and binaural) were distinguished for analyses involving the contribution of lyrics to melody recognition.

Acoustic +Electric Stimulation Group (A+E)—The CI recipients in the A+E group were implanted with a 10 mm internal electrode array (note: the technical features of this device as well as complete selection criteria are described in detail in Gantz & Turner, 2003). The short electrode has six electrodes placed in the basal end of the cochlea that electrically transmit high-frequency information; low-frequency information is perceived via the patient's residual hearing. Briefly, candidates for the Hybrid device (A+E) must have good residual acoustic hearing for low frequencies but extremely poor hearing for high frequencies. Figure 1 shows the mean pure tone averages for the A+E group. Selection criteria include severe to profound hearing loss for frequencies >1500 Hz, Consonant Nucleus Consonant (CNC) word recognition scores (Nilsson, Soli, & Sullivan, 1994) between 10% and 60% in the ear to be implanted, and CNC word recognition score in the contralateral ear equal to or better than the ear to be implanted (though not more than 80%). These criteria are consistent with better neural preservation, less degraded central auditory function, and usually less duration of deafness than typically found in the ES group. In short, the A+E group differs from the ES group both with regard to the internal electrode array (shorter) as well as greater residual hearing associated with a healthier auditory system. The A+E group ranged in age from 50 to 72 ($M = 61.375$ yrs, $SD = 8.53$); the mean length of CI use was 32.875 months ($SD = 22.1$). Participants in both CI groups were enrolled in concurrent studies that included assessment of speech perception, cognitive processing, and access to demographic information including hearing history. These measures were utilized in the correlational analyses for this study.

Normal hearing adults (NH)—The comparison group of adults with normal hearing was recruited through advertisements. The NH group included 3 males and 14 females who ranged in age from 25 to 58 years of age ($M = 45.9$, $SD = 9.6$). Because none of the participants in the implanted group were professional musicians, persons who are or have been music majors and professional musicians were excluded from the NH group. The following criteria were applied to assure a NH sample with at least near-normal hearing adequate for the response task, which is defined as follows: (a) the pure tone average (calculated from thresholds obtained at 250, 500, 1000 calculated from thresholds obtained at 250, 500, 2000, and 4000 Hz) on either ear no greater than 25 dB and no single frequency above 30dB for one ear and (b) no prior or current hearing aid use. Volunteers who did not meet these criteria were excluded from participation. The NH group served as a comparison to confirm the ease with which normally hearing persons are able to complete the experimental task.

Measures

Complex Melody Recognition Test (CMR)—For purposes of this study, real-world music refers to music that can be heard through popular media sources (e.g., radio, CDs, etc.) in everyday life within American culture. In prior research of real-world melody recognition, (Gfeller et al., 2005), listeners were tested on excerpts characterized as multi-dimensional combinations of melodies and harmonies, timbres, rhythmic patterns, and sometimes sung lyrics in a test named the Musical Excerpt Recognition Test (MERT). The

MERT included items confirmed by experts as representative of three commonly-heard musical styles: pop, country, and classical. Item selection and the test protocol for the MERT are described in detail in Gfeller et al. (2005); the stability of test outcomes over time are reported in Gfeller et al., (2010). Through item difficulty analyses of the MERT, the presence or absence of lyrics emerged as an important factor in complex melody recognition; however, presence or absence of lyrics was not directly controlled in that study (Gfeller et al., 2005). Consequently, we developed a new melody recognition test, the Complex Melody Recognition Test (CMR), to systematically examine the impact of linguistic and non-linguistic (instrumental music) elements on complex melody recognition.

A subset of items from the 36 items in the MERT was chosen for use in the CMR, based upon the following three criteria: (a) representative of a variety of composers and performers within the three musical styles of country, pop, and classical;³ (b) confirmation of high levels of previous familiarity for most CI recipients in our center (which is an important factor in a recognition task); (c) items that would collectively present a continuum of item difficulty as an important psychometric property.

The CMR comprised two primary item categories: Part A: musical excerpts without linguistic cues (instrumental only), and Part B: the same song titles as used in Part A, but with sung lyrics and background instrumental accompaniment. Part A consisted of pop and country (pop and country instrumental only, PC-I), and classical (CL) items chosen from the MERT based upon the selection criteria noted above. Part B included only pop and country items.

In the original recordings of the country and pop items in the MERT, items included sung lyrics with background instrumental accompaniment (e.g., small combo of guitar, bass and drums); the classical items were all instrumental only. In order to compare melody recognition for all three musical styles based upon instrumental cues alone, we created instrumental-only versions of the pop and country items. A professional music arranger created instrumental-only versions using the same melodic, harmonic, and rhythmic elements present in the recorded version with lyrics. The instrumental arrangements were recorded by a small ensemble of professional musicians in a professional recording studio. Each recorded excerpt was encoded by AIFF with compression using *SoundEdit 16* software (44 kHz sampling rate and 16 bits sampling size). In order to confirm that the instrumental-only arrangements remained recognizable as the original song title, the instrumental excerpts were presented in open set to NH adults (non-musicians). All the instrumental versions were easily identifiable.

³For purposes of this study, we have categorized items within the pop and country categories as defined and described in several relevant sources (Lamb & Hamm, 1986; Pembroke, 1990; Rothenbuhler, personal communication, 1996; Tudor, 1983). “Pop” music typically has prominent melodic lines sung by a vocal soloist or small ensemble and generally a simple harmonic accompaniment. According to the *New Grove Dictionary of Music & Musicians*, country music (sometimes referred to as country western or country and western) often focuses upon stories of everyday life (Whitburn, 1994), with lyrics often being a key aspect of this musical genre. The term, ‘classical’ music refers to a particular period of western European music as well as (in common parlance) any serious art music that can be categorized into broad styles with distinct structural features (e.g., Baroque music, classical music, romantic music), which was the use of this term for this study.

While vocal artists singing lyrics comprise a large proportion of well-known repertoire within pop and country styles, many very famous classical selections, such as Beethoven’s 5th Symphony, or Vivaldi’s Four Seasons, have no lyrics. The use of only instrumental items for the classical genre followed a review of those classical items that were deemed most familiar through industry lists. The greater majority of items were instrumental only, and many that did have lyrics were sung in foreign languages (e.g., “Un Bel Di” from *Madame Butterfly*, Ave Maria), which is problematic with regard to using words as a cue for recognition). Some that are in English included text that had a strong religious component (e.g., “Halleluia Chorus” from the Messiah), which we chose to avoid, due to the diverse religious background of patients in our center, or had phonemes that were significantly altered as a result of singer formant associated with art songs and operatic style

Part B of the CMR included items with lyrics (the original popular recordings with lyrics). In our prior selection of highly familiar classical items for the MERT, we determined that recognition of classical items with lyrics can be problematic for a number of reasons.³ This indicated an inherent difference in highly familiar classical items and pop or country items with regard to linguistic content. Therefore, Part B contained only pop and country items (Pop and country with lyrics, PC-L).

Prior analyses confirmed that the categories of pop and country shared similar characteristics with regard to structural complexity and common use of sung lyrics, and that the CI recipients showed similar accuracy on these two genres in the prior study (Gfeller et al., 2005). However, CI recipients showed significantly different accuracy for the classical category than either the pop or country styles. Therefore, for this study, the pop and country were combined as one category in the CMR; classical style acted as a separate category.

The CMR excerpts were 12–17 seconds in length and were presented in random order at 70 dBA in free field. Response was open set; no feedback was given on accuracy.

Alphabetized List of Melodies (ALM)—Because musical training and experience are unevenly distributed among the general population, an individual may have no prior exposure to (and thus familiarity with) a specific item in the CMR, despite the fact that the excerpts selected were confirmed as well-known to the general public. Therefore, to eliminate unfamiliarity as a factor in item recognition, an Alphabetized List of Melodies (ALM) was used to identify the songs known by the participants. The ALM is an alphabetized list of 106 well-known musical selections, including the CMR test items.^{4, 5} Participants were asked to place a check mark next to each title that they recalled as familiar from the time prior to deafness (or prior to testing time, in the case of normal-hearing adults). The scores based on any song item not identified as familiar prior to testing was eliminated from recognition scores.

Speech, Cognitive, and Demographic Measures

A number of speech perception, cognitive, and demographic measures (described below) were obtained for CI recipients that have been identified in prior research as predictive of implant benefit for speech (e.g., Roditi et al., 2009; Turner et al., 2004; Tyler & Summerfield, 1996) or music perception (e.g., Gfeller et al., 2007, 2008). Speech perception performance is known to improve over time as a result of implant experience (Tyler and Summerfield, 1996); consequently, the speech perception measures selected for analysis were based on those tests administered in closest temporal proximity (e.g., during the most recent annual visit to our clinic, typically within 1 to 2 years) to the music perception testing for the current study.

Speech perception measures—The following standardized measures of speech recognition were correlated with melody recognition accuracy: the *Hearing in Noise Test (HINT)*, and the CNC word and phoneme tests (Nilsson, Soli, Sullivan, 1994). An additional speech perception measure, a speech in noise task, is described below. Multiple regression studies indicate that these measures have been predictive of CI benefit for speech (Roditi et al., 2009), as well as selected music perception tasks, in particular, those containing lyrics (Gfeller et al., 2008, 2010).

⁴Additional song titles beyond those tested were included in order to reduce ability to utilize the list as a cue in song recognition in the case that repeated testing with the CMR would be a part of future experiments.

⁵Because this test, which requires open-set response, is still being used in research studies, no information will be provided on accuracy for titles of particular items, which if read, could influence response by future participants.

SNR- Speech in Noise Tasks—The two speech reception in noise tasks are described in detail in Turner et al. (2004). Briefly, the speech reception tasks required the participant to identify a spondee word spoken by a female talker in the presence of a background sound (multi-talker babble or steady-state white noise). Following each item, the listeners responded on a touch screen with the spondee (from a closed set of 12 spondees) that they thought had been presented. Listeners were required to respond on each trial and were instructed to guess if they were not sure of the correct answer. The level of the background was increased 2 dB following a correct response and decreased by 2 dB following an incorrect response, thus converging on the 50%-correct level of performance. The adaptive procedure continued until 14 reversals occurred, and then the average signal-to-noise ratio of the final 10 reversals was taken as the Speech Reception Threshold (SRT) value in either steady-state white noise or multi-talker babble (a lower SRT means that the listener could understand speech in more adverse conditions). Prior research indicates that the SNR is significantly correlated with tests of pitch perception (Gfeller et al., 2007).

Cognitive tests measuring sequential processing—Experimental tests of cognitive ability were administered prior to implantation. Because the population tested has serious hearing deficits, the tests were presented visually only. *The Visual Monitoring Task (VMT)* (Knutson et al., 1991; Knutson 2006) is a test of attention, reaction time, continuous performance, and working memory, in which participants observe a computer monitor as numbers are displayed at either a one per second rate (*VMT1*) or a one per two second rate (*VMT2*). When the displayed number and the two preceding numbers reflect an even-odd-even pattern, the subject is required to strike a key on the computer keyboard. Thus, the subject must maintain recently displayed characters in “working memory,” and respond quickly to the currently displayed character. The score from the *VMT* is a standardized signal detection score that incorporates accurate responding (true positive and true negatives) and inaccurate responding (false positives and false negatives). The average of the two scores (*VMT1* and 2) was used for correlational analyses. The *VMT* has been a strong predictor of implant recipient success in both speech recognition and music perception and appraisal tasks regardless of the implant design used (Knutson et al., 1991; Gfeller et al., 1998; Gfeller et al., 2008, 2010).

Demographic variables—Prior research indicates that a number of individual differences among CI recipients can contribute to variable outcomes in speech and music perception (Gfeller et al., 2008, 2010; Roditi, et al., 2009). Therefore, CMR results for the CI groups were examined in relation to age at the time of testing, length of profound deafness prior to implantation, months of implant use, and whether or not the ES CI recipient also used a hearing aid. Musical background of implant recipients was quantified using the Iowa Musical Background Questionnaire (IMBQ), which is described in considerable detail in Gfeller et al. (2000). Multiple regression studies indicate that more advanced age is associated with poorer performance on music perception, while hearing aid use and music training prior to CI user have been predictive of better pitch perception. Length of profound deafness and months of implant use have not been predictive of music perception (Gfeller et al., 2008); however, these same measures have been associated with improved speech perception (Tyler & Summerfield, 1996).

In general, the IMBQ assesses musical training and listening habits before deafness and after implantation, and measures perceived quality and clarity of musical sounds through the CI. Self-report of sound quality was assessed using visual analog scales with the following bipolar adjective pairs: unpleasant-pleasant, unnatural-natural, clear-fuzzy, does not sound like music-sounds like music, easy to follow-difficult to follow, and like very much-dislike very much. Participants made a hash mark on a scale of 0 to 100 to indicate how music sounds to

them on each of these descriptors. These self-report measures were correlated with perceptual accuracy of melody recognition.

Test Administration and Scoring

The implant recipients were tested as part of their annual visit to the clinical research center; NH adults were recruited explicitly for this project. The CMR was administered in a sound-treated room via a Dell OptiPlex computer (model 755) with factory model speakers and a Sound Blaster Live!® soundcard. For CI users, the test stimuli were transmitted through the microphone of the speech processor, which reflects to a considerable extent everyday listening experiences in quiet. The initial sound level was averaged at 70 dBC SPL; however, implant recipients were permitted to adjust their processor for maximum comfort and normal-hearing adults could adjust the volume on the speakers.

Melody-recognition—Test administration began with standardized instructions on the computer screen and the two practice items. Each test item was presented in a standard format, with items presented in random order. The participant viewed a prompt on the computer screen to “listen” while the item was played. After the excerpt ended, another screen prompted the participant to indicate whether or not the item sounded familiar (“Yes” or “No”). If the participant stated “No,” the next item was presented. If the participant stated “Yes” then the test administrator first asked the subject, “What is the title of the song?” The test administrator entered the participant’s response into the computer indicating it as the given title of the item. A correct response on the title of the song was subsequently scored as “Accurate Recognition.”

Recognition of a previously familiar melody can be compromised by what is known as “tip of the tongue” phenomenon. That is, a person may actually recognize an item or object as familiar, yet be unable to retrieve from long-term recall the title/label of the item. In order to reduce the impact of this phenomenon, and to retain the focus on auditory acuity, a protocol of structured prompts⁶ was used to ascertain recognition when the subject indicated familiarity but could not name the source of the excerpt. If, after the structured prompts, the participant could not provide any distinguishing information of an item that they believe sounded familiar, the test administrator recorded “No Response,” which was considered an incorrect response. The test administrator recorded exact verbatim participant responses on the computer for later score verification.

Following the administration of the CMR, the ALM was administered. Because the song titles listed in the ALM could have provided cues regarding the items in the test (which required open-set response), the ALM was administered following the CMR.

Each participant’s verbatim responses printed from the computer record were scored for accurate recognition by research assistants with at least four years of formal collegiate music training. Scorers were familiar with the test excerpts and had access to the correct title, composer or artist, lyrics, and a full recording of the excerpt to which the participant had indicated familiarity in the CMR. In addition, the research assistants had criteria for alternate

⁶If the respondent could not name the title of the item because of either recall problems or poor auditory acuity, the test administrator used the following systematic sequence of prompts to reduce non-response to items based upon recall problems as opposed to poor auditory acuity: (a) “Can you name the composer or musical artist responsible for composing or performing the excerpt?” An example of a correct response would be naming Rossini as the composer of “The William Tell Overture” or Elvis Presley as the artist for “Blue Suede Shoes.”; (b) “Can you recite some of the lyrics from the song?” [NOTE: Merely repeating lyrics heard in the excerpt indicated only the ability to extract the lyrics heard, but being able to extrapolate other lyrics of the song from those heard indicated prior familiarity with the song, and thus accurate recognition.]; (c) “Can you tell me any event or circumstance the song is associated with?” If a participant accurately described such an event (e.g., “Auld Lang Syne” as the song played on New Year’s Eve.) the response was classified as Accurate Recognition.

answers considered to be accurate recognition (e.g., “The Lone Ranger Theme Song” as an alternative to “The William Tell Overture”). In cases of unique responses, the response would be discussed with additional research assistants to determine a final assessment of recognition accuracy for that item.

In this study, both success and failure in open-set recognition are of interest. Successful recognition reflects both the ability to identify the excerpt and the recall of the title of the selection from which the excerpt is taken. The failure to name a previously familiar musical selection can be the result of either poor auditory acuity, difficulties in retrieval of the title from memory, or both. Auditory acuity is the overwhelming factor for the CI users in this study, but retrieval (recall) is a potential problem for both CI and NH participants. The inclusion of the NH sample provides an indication as to the memory challenge presented by the open set task.

Because participants cannot be expected to recognize material that was unfamiliar, responses to ALM items categorized as familiar were used to eliminate CMR excerpts from data analysis that participants indicated were unknown. Thus, for each participant, the percentage of items scored as Accurate Recognition was based on the number of excerpts reported known by that participant.

It is possible that a participant could fail to identify a title of a song on the ALM as previously familiar, but provide an Accurate Recognition or Attribute Recognition in response to the sound of the excerpt. This was, however, a rare occurrence. Individual participant scores were adjusted to include for these occasional correct responses to the CMR after denying familiarity on the ALM.

Results

Statistical Analyses

The analyses in this paper are group comparisons. Since the normality assumption is rarely satisfied for these data, we report the nonparametric tests, namely the Wilcoxon rank sum test for comparing 2 independent groups and the Kruskal-Wallis test for three or more independent groups. For paired comparisons, the Wilcoxon signed rank test is used. Correlations are presented as the nonparametric Spearman correlation.

Prior Familiarity and Accurate Recognition

The analyses included data from only those participants (CI or NH) who were familiar with at least 25% of the test items in the CMR, as determined through the ALM. Recognition of those selections known prior to taking the test (and in the case of implant recipients, prior to deafness), was the dependent variable, rather than the raw score (number of items correct).

Accuracy as a result of device, strategy, or mode

As noted previously, there were no significant differences among the ES recipients as a result of coding strategy or implant type. Consequently, the data from users of all types of internal devices and coding strategies transmitting electrical stimulation only were combined. A Wilcoxon rank sum test was used to determine whether performance of ES recipients differed significantly as a result of mode (monaural vs. bilateral implant use). The bilaterally-implanted users in the ES group were significantly more accurate than monaurally-implanted users of CI recipients on the dependent variable, recognition of pop and country items with lyrics (PC-L) (Z -score = 2.5417, $p < .01$) and the combined correct scores of all items (Z -score = 2.4387, $p < .01$) (CCS). There was no significant difference between the bilateral and monaural ES users for the two melody recognition categories

without lyrics (classical, CL; pop and country without lyrics, PC-I). The bilateral vs. monaural ES participants were analyzed as a separate group for analyses of the pop and country items with lyrics (PC-L), and the combined correct score for all items (CCS). The summary statistics (means, standard deviations, median, range) for each group by type of musical stimuli appear in Table 1. This table reveals the considerable variability demonstrated by each group.

Recognition of instrumental-only items

After accounting for devices, strategy and mode among ES recipients, subsequent analyses included a comparison of melody recognition for instrumental only items. This included both pop-country without lyrics (PC-I) and classical items (CL). These items proved difficult for most CI participants as 69 users did not recognize any of the pop-country excerpts without lyrics and 59 users did not recognize any of the classical items. Means and standard deviations (error bars) for the ES, A+E, and NH group are summarized in Figure 2. Using a Wilcoxon signed rank test, ES users demonstrated significantly better song recognition ($p < .001$) on classical items than on pop and country items (instrumental only). There was no significant difference, however, for either A+E recipients or NH listeners for recognition of instrumental only classical vs. pop and country items.

A Kruskal-Wallis Test was used to compare melody recognition of pop and country instrumental-only items (PC-I) and revealed a significant difference (Chi-Square = 62.5985, $DF=2$, $p < .0001$) as a function of group. Pairwise comparisons indicate significant differences between the ES and NH groups (Z-score = 7.9059, $p < .0001$), the A+E and NH groups (Z-score = -2.3203, $p < .02$), and the ES and A+E groups (Z-score = 4.6184, $p < .0001$). A Kruskal-Wallis Test comparing melody recognition of classical instrumental-only items also revealed a significant difference (Chi-Square = 40.0951, $DF=2$, $p < .0001$) as a function of group, with follow-up pairwise comparisons showing significant differences between the ES and NH groups (Z-score = 6.0462, $p < .0001$), and between the ES and A+E group (Z-score = 3.0411, $p < .002$). There was no significant difference between the A+E and NH groups.

Recognition of items with lyrics

In this analysis, we examined recognition for pop and country items with lyrics (PC-L) as a function of CI group membership. Means and standard deviations (error bars) are summarized in the right-hand panel of Figure 3. As noted earlier, significant differences were revealed between binaural and monaural ES listeners. Therefore, the ES group was subdivided by mode for this analysis. A Kruskal-Wallis Test revealed a significant difference among the four groups (Monaural ES, Binaural ES, A+E, NH) (Chi-Square = 21.9334, $p < .0001$). Pairwise comparisons from a Wilcoxon rank sum test indicates that the monaural ES were significantly less accurate than the NH (Z-score = 4.2659, $p < .0001$) and binaural ES groups (Z-score = 2.5417, $p < .01$).

Recognition of items with and without lyrics

In addition to summarizing melody recognition of items for PC-L, Figure 3 also summarizes the means and standard deviations for PC-I as a function of group membership. In order to compare items with and without lyrics as a function of group, contrasts were conducted by means of a Wilcoxon signed rank test. The ES and A+E groups were tested separately. As noted earlier, binaural users were significantly more accurate than monaural users (mode) on pop and country items with lyrics (PC-L). Therefore, for the PC-L category of stimuli, the ES group was divided into binaural and monaural users.

The tests revealed that both monaural and binaural ES users were significantly more accurate on country and pop items with lyrics than without (monaural, Signed Rank Statistic $S = 398.5$, $p < .0001$) (binaural $S = 60$, $p < .0001$). Signed rank tests revealed that A+E users had no significant differences in recognition of pop and country items with and without lyrics.

Combined instrumental and lyrics score for recognition

Figure 4 summarizes combined correct score for melody recognition (lyrics and instrumental only, classical and pop and country) as a function of group. The Kruskal-Wallis test detected that four subgroups (Monaural ES, Binaural ES, A+E and NH) have significantly different outcomes on the combined scores (F -value = 24.47, $p < 0.0001$). As expected, pair-wise comparisons using a Wilcoxon rank sum test revealed that the NH group was significantly more accurate than both the monaural and binaural ES groups (Z -score = 5.9780, $p < .001$), that the A+E group was more accurate than the monaural ES group (Z -score = 2.8205, $p < .005$), and that the binaural ES group was significantly more accurate than the monaural ES group (Z -score = 2.4387, $p < .01$). The differences between the A+E and NH group and the binaural ES and A+E groups were not significantly different at the 5% level of significance.

Correlations between CMR scores, demographics, measures of speech and cognition, music background, and pitch ranking

In order to better understand those factors that contribute to the considerable variability among the CI participants, Spearman coefficients of correlation were calculated for CI population and two sets of variables described in Table 2 and Table 3. Table 2 presents variables for speech, cognitive processing, or age that were significantly correlated with CMR scores. The sample size is noted for each variable in the correlational analyses because speech, cognitive and demographic data were not available for all of the CI recipients who were tested for recognition of musical excerpts. Note that the sample size in the A+E group was 8 so the power to detect a significant correlation was extremely low. Table 2 reveals a number of significant correlations between all four melody categories and speech perception scores for the ES group. The correlations between melody recognition and the cognitive measures (VMT) were significant on two of the melodic categories for ES and two categories for A+E.

With regard to demographic and hearing history variables, the recognition scores were correlated with age at time of testing, length of profound deafness, length of implant use, pre- and post-implant listening habits, and musical training. Notably strong correlations (negative) appear across all melody categories for the factor of age at time of testing. That is, the older the participant, the poorer the recognition scores. Correlations involving length of profound deafness and months of implant use were not statistically significant.

Table 3 shows data from the Iowa Music Background Questionnaire (formal musical training, music listening habits, and self-report regarding quality and clarity of music) that are significantly correlated (Spearman correlations) with the 4 recognition scores of the CMR. The IMBQ items included in correlational analyses were early childhood music training (T1), post childhood (high school, college, and beyond) music training (T2), how enjoyable music listening was before the implant (BLIS), how enjoyable music listening was after the implant (ALIS), number of hours spent listening to music before the implant (BHOURL), and number of hours spent listening to music after the implant (AHOURL). The correlations for the combined ES and A+E groups are presented in Table 3. All of the correlations were positive indicating that the more musical training and the more the CI recipient listens to and enjoys music, the higher their recognition scores will be. With regard to ratings of sound quality, the only two bipolar adjectives that were significantly correlated

with perceptual accuracy on the CMR were ‘easy to follow-difficult to follow’ and ‘like very much-dislike very much.’

Discussion

Consistent with prior studies, CI recipients in this study were significantly less accurate than NH listeners in the recognition of familiar melodies. The CI, while quite beneficial for speech perception is less technically suited for transmitting salient features of music, notably pitch and timbre. Thus, it is not surprising that CI recipients, and particularly those reliant on electrical stimulation alone, find melody recognition particularly difficult when linguistic cues are unavailable. However, the results of this study also provide more nuanced information with regard to the various structural components that contribute to melody recognition. Identification of those aspects of complex real-world music that are most and least accessible to CI recipients can assist in counseling of CI recipients with regard to realistic expectations and the exploitation of those aspects of music listening that can enhance perceptual accuracy and possibly enjoyment in music listening.

Because current-day implants are designed primarily to transmit salient features of speech, and because controlled experiments indicate that some implant recipients are able to extract the linguistic information in song lyrics (Gfeller et al., 2009), we hypothesized that implant recipients would show superior recognition on those real-world musical items that included song lyrics compared with items consisting of instrumental music only. Figure 3 reveals that linguistic cues (lyrics) do assist in the recognition of real-world melodies from pop and country music, musical styles often heard in everyday life. Therefore from a practical standpoint, musical materials that have lyrics may be more easily perceived and thus accessible to adult CI recipients in activities (e.g., reminiscences, musical games such as Name that Tune, lyric analyses) in which recognition of formerly familiar songs is important to successful participation. Keeping in mind that the testing condition in this study was open set, the benefit of linguistic cues could be enhanced further through multi-sensory input or contextual cues, such as providing song titles, a copy of song lyrics, or names of musical artists or composers, strategies that have been reported as beneficial in questionnaire data (Gfeller et al., 2000).

A second important finding of this study is the advantage of preserved residual hearing in the perception of pitch, melodies, and timbre. The Hybrid CI has been designed to preserve low-frequency residual hearing, while providing electronic stimulation to higher frequencies that are not adequately supported through conventional hearing aid amplification. This combination, which has been shown in prior studies to benefit simple melody recognition (Gfeller, Turner, et al., 2007), can also assist in recognition of more complex combinations as heard in real-world music, with or without lyrics. Thus, clinicians or educators should be aware of different hearing profiles (e.g., more residual hearing) and the technical characteristics of the CIs used by any clients/students when considering realistic listening tasks and those musical sounds most accessible for therapy, instruction, and listening enjoyment.

Although CI recipients, as a group, performed significantly poorer than normal-hearing adults on the recognition of complex melodies, it is important to note the considerable variability demonstrated by all groups, as revealed in Table 1. While median scores of CI recipients were generally significantly poorer than median scores for NH listeners, some implant users performed quite well on this challenging task. For example, the range for the ES group on the classical items was 0 to 100%. Their median score was 0% correct. In comparison, the scores for the NH ranged from 25 to 100%, with median scores of 100% on this same subtest. Interestingly, some CI recipients performed as well as or even better than

some NH listeners on particular items. This variability on recognition accuracy points up the importance of individual assessment and individualized goals and objectives with regard to listening tasks and accommodations.

The correlations between melody recognition and other factors (speech perception, cognitive processing, hearing history, and age) may help in predicting influential factors in individual abilities. For example, more advanced age was predictive of poorer performance on the CMR. This may be a reflection of slower central processing associated with advanced age, which can compromise the ability to extract useful information efficiently or compensate for a degraded signal through contextual cues (Gordon-Salant & Fitzgibbons, 1995). Thus, when counseling or planning music activities with many older adults, it could be beneficial to present information at a slightly slower pace, along with more contextual cues, such as pictures of the artist or song topic, large-print song lyrics, or background information about the music related to the lives of the listener (e.g., selecting songs that are associated with important social, political, events from the past) that could assist in recognition.

It is important to keep in mind that the participants in this study all had postlingual hearing losses occurring well into adult life, thus these findings are most relevant to adult CI recipients who had already developed normal mental representation of pitch and timbre during auditory development. CI recipients with pre or perilingual losses (whose auditory development has not included exposure to normal representation of pitch and timbre) may demonstrate somewhat different results, and may utilize different cues for melody recognition. Thus, similar research initiatives with prelingually-deaf CI recipients would assist in determining suitable musical materials and accommodations for music therapy and education with pediatric CI recipients.

More musical training and time devoted to music listening is associated with greater perceptual accuracy for real-world music. It is possible that individuals with more extensive musical experiences can draw upon past listening experiences as part of top-down (contextualized) processing in order to make sense of a degraded signal. Another explanation may be that extended music training assists listeners in detecting subtle acoustic elements, even within a degraded or highly complex signal (Chandrasekaran & Kraus, 2010). It is interesting to note, however, that only two of the bipolar adjectives describing sound quality were strongly correlated with perceptual accuracy. Thus, ease of recognition is not an overwhelming factor with regard to self-perceived quality of musical sound.

Correlations indicate that those ES recipients who have good speech perception, especially in background noise, are more likely to do well on melody recognition. In part, this may be a result of ability to extract the target lyrics of the song from the background accompaniment. In addition, some CI recipients may identify songs as a result of unique timbral blends (Vongpaisal et al., 2004).

In order to aid CI recipients whose speech recognition is more compromised by background noise, it may be helpful to adjust the bass and treble on sound equipment in order to make the proportional loudness of the song lyrics more accessible. Better yet, music therapists or music educators could sing songs (rather than using recordings), using a very light accompaniment. The provision of live music permits the CI recipients to use visual cues such as speech reading the singer, and ongoing adjustment of the loudness level of the accompaniment in order to reduce the masking properties of the accompaniment.

Consistent with prior studies using isolated structural features of music (e.g., pitch discrimination, melody recognition); none of the ES devices or strategies used by participants in this study was superior to the others (though acoustic stimulation available through the A+E was significantly more effective). This is not surprising, given that these

ES devices and strategies are all limited with regard to pitch resolution and transmission of fine timing features. The difference in recognition despite the use of similar CI technology emphasizes the importance of listener characteristics with regard to listening to real-world music. Variability among CI recipients is likely due in part to individual differences in the auditory and neural systems of individual implant recipients (including the typically better neural preservation and less degraded central auditory function of Hybrid recipients), which may be differentially capable of handling the information transmitted by the implant. At this point in technological design, improved music listening for CI users is reliant to a considerable extent upon a suitable listening environment, helpful contextual cues, and the choice of music with more accessible structural features (e.g., songs with clear lyrics) than from particular signal processing strategies used with conventional CIs that transmit electric stimulation only (Gfeller et al., 2000, 2008).

Consistent with other music studies, the length of implant use was weakly correlated with recognition of melodies without lyrics (e.g., Gfeller et al., 2008, 2010; Looi, 2008). Thus, casual exposure to music in every-day use with the implant does not appear to contribute to accurate recognition of instrumental music to a significant extent. Several extant studies, however, suggest that focused training can help listeners in perception of timbre (Driscoll et al., 2009; Gfeller et al., 2002), melodic patterns (Galvin et al., 2007), and complex melodies (Gfeller et al., 2002). Thus, some focused listening exercises may be beneficial to adult CI recipients who are interesting in developing improved song recognition.

In closing, these data indicate that the more conventional internal electrode arrays that transmit only electrical stimulation and the specific signal processors examined in this study are far from ideal in transmitting key structural features of real-world instrumental music. Major changes in signal processing will be required before most implant recipients, reliant upon electrical stimulation alone, can more nearly resemble NH persons in recognition of familiar musical selections of the sort heard in everyday life.

These outcomes also indicate the benefit of preserved acoustic hearing in conjunction with electric hearing for perceiving musical as well as linguistic (lyrics) cues in music. Thus, the device and auditory status of individual CI users should be considered in selection of realistic listening tasks and clinical interventions.

Furthermore, the extent to which adult implant recipients can identify a previously familiar musical selection depends on structural features of the music as well as availability of contextual cues and individual recipient differences. For example, recognition may be facilitated if song lyrics are sung against a quiet musical accompaniment (e.g., a quiet piano or guitar background) that makes extraction of the lyrics possible. The findings of this study with regard to structural features of music have practical implications for the choice of musical selections, contextual and multisensory cues, and appropriate expectations in music therapy interventions such as musical reminiscence, lyric analysis, and social or performance music activities that involve song recognition.

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Figure 1.

Mean pure tone averages for recipients of A+E devices without implant or hearing aids. The circles (right ear) and squares (left ear) denote the amount of amplitude required to perceive sound at each frequency; the lower the dB HL the better. All participants show a mild hearing loss at 125Hz, increasing to moderate 250–500Hz and showing severe-profound in the subsequent frequencies.

Complex Melody Recognition: Instrumental-Only Items

Figure 2.

The mean percentage of previously familiar musical excerpts correctly recognized by the Normal-Hearing (NH) Group and the Cochlear Implant Recipient Groups (ES, A+E) within each musical style. Previous musical familiarity was established prior to testing through participant responses to the Alphabetical List of Song Titles. Error bars indicate within-condition standard error values.

Figure 3.

The mean percentage for melody recognition of pop and country items with lyrics vs. those without lyrics as a function of group membership. Error bars indicate within-condition standard error values

Figure 4.

The mean percentage for combined melody recognition scores (lyrics and instrumental only, classical and pop and country) as a function of group. Error bars indicate within-condition standard error values.

Table 1

Melody recognition as a function of type of music and group membership: Summary statistics.

	Mean (SD)	Median	Range
CCS			
Monaural	15.23 (15.59)	10.82	0–75
Binaural	27.52 (19.88)	20.71	0–60
A+E	46.54 (30.02)	51.98	0–90
NH	71.19 (22.56)	75	26.32–100
CL			
ES	14.53 (24.60)	0	0–100
A+E	48.96 (34.63)	50	0–75
NH	75 (29.17)	100	25–100
PC-L			
Monaural-ES	29.95 (30.87)	11.11	0–75
Binaural-ES	53.08 (34.83)	20.71	0–60
A+E	54.15 (33.44)	25	0–100
NH	69.80 (24.92)	71.14	25–100
PC-I			
ES	2.94 (8.38)	0	0–5
A+E	39.64 (33.37)	41.43	0–57.14
NH	71.09 (23.87)	75	25–100

CCS=Combined correct score (all items with and without lyrics)

CL=category of classical items (no lyrics)

PC-L=category of pop and country items with lyrics

PC-I=category of pop and country items without lyrics

Table 2

significantly correlated with CMR scores for two populations (p-value)

	ES (n)	Correlations, p values	A+E (n)	Correlations, p values
CCS	HintNoise (66) HintQuiet (79) CNCword (80) CNCphon (80) VMT (76) Age (80)	0.391 (.001) 0.283 (.011) 0.376 (.001) 0.388 (.000) 0.294 (.010) -0.613 (.000)	VMT (8) Age (8)	0.714 (.047) -0.847 (.008)
CL	SNR-Noise (49) SNR-Babble (45) HintNoise (64) HintQuiet (76) CNCword (76) CNCphon (76) Age (76)	-0.311 (.030) -0.308 (.039) 0.413 (.001) 0.375 (.001) 0.358 (.002) 0.347 (.002) -0.289 (.011)		
PC-L	HintNoise, (66) CNCword, (80) CNCphon, (80) VMT (76) Age (80)	0.300 (.014) 0.323 (.004) 0.345 (.002) 0.275 (.016) -0.604 (.000)	Age (8)	-0.920 (.001)
PC-I	HintQuiet (79) Age (80)	0.245 (.029) -0.359 (.001)	VMT (8) Age (8)	0.771 (.025) -0.845 (.008)

CCS=Combined correct score (all items with and without lyrics)

CL=category of classical items (no lyrics)

PC-L=category of pop and country items with lyrics

PC-I=category of pop and country items without lyrics

VMT=Test of sequential cognitive processing

SNR-Noise=Threshold for Speech Reception in Steady-State Noise

SNR-Babble= Threshold for Speech Reception in Multi-Talker Babble

HintNoise=Hint in Noise Test

HintQuiet=Hint in Quiet Test

CNCword=CNC Word Test

CNCphon=CNC Phoneme Test

Age=age at time of testing

Table 3

significantly correlated with CMR scores for the IMBQ (p-value)

	CI Groups Combined	Correlations, p values
CCS	T1	0.33 (.010)
	T2	0.48 (.000)
	BLIS	0.27 (.040)
	ALIS	0.26 (.047)
	BHOUR	0.36 (.004)
	AHOUR	0.37 (.004)
	ED	0.31 (.017)
CL	T2	0.39 (.002)
PC-L	T1	0.39 (.002)
	T2	0.47 (.000)
	BLIS	0.32 (.012)
	ALIS	0.25 (.052)
	BHOUR	0.43 (.001)
	AHOUR	0.37 (.004)
	ED	0.26 (.046)
PC-I	T2	0.29 (.024)
	ALIS	0.26 (.047)
	AHOUR	0.36 (.005)
	ED	0.29 (.026)
	LD	0.25 (.056)

CCS=Combined correct score (all items with and without lyrics)

CL=category of classical items (no lyrics)

PC-L=category of pop and country items with lyrics

PC-I=category of pop and country items without lyrics

T1= early childhood music training

T2= post childhood (high school, college, and beyond) music training

BLIS= how enjoyable music listening was before the implant

ALIS= how enjoyable music listening was after the implant

BHOUR= hours spent listening to music before the implant

AHOUR= hours spent listening to music after the implant

ED= Is Easy to Follow to Is Difficult to Follow

LD= Like Very Much to Dislike Very Much