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Music Perception of Adolescents Using Electroacoustic Hearing

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Introduction

The Cochlear[®] Nucleus[™] Hybrid L24 cochlear implant (L24) system was designed for patients with residual low-frequency hearing. It provides electric stimulation in the mid- to high-frequency region of the cochlea and acoustic amplification to the low-frequency regions via a power speaker and dome or earmold [1, 2]. The 16 mm, 22-electrode device is currently approved by the FDA for patients 18 years of age and older who have severe to profound high-frequency sensorineural hearing loss, but who have residual low-frequency hearing and obtain limited benefit from appropriately fit hearing aids (HA). Preoperative hearing thresholds ranged from normal to moderate hearing loss in the low frequencies. Individuals with access to preserved low-frequency information have been found to demonstrate superior performance over those using electric hearing (traditional long-electrode (LE) cochlear implants) in speech and music recognition [3, 4].

Pediatric LE recipients' perceptual accuracy of music

Children whose auditory development has progressed primarily through CI input cannot compare the signal conveyed through the CI with percepts associated with normal hearing as can postlingually deaf adults. Because the implant does not replicate normal hearing, pediatric CI users often have music perception that is significantly poorer than their peers

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with normal hearing (NH) or aided hearing [5, 6]. For example, Stordahl [7] found that children with CIs were significantly less accurate than NH children on a song recognition task that included both melodic and rhythmic components of commonly heard children's songs (e.g., "Twinkle, Twinkle", "Row, Row, Row Your Boat"). In two studies, Olszewski et al [5, 8] found that children with CIs were less accurate than both NH peers and adults with CIs on several melody recognition tasks, though the types of cues available had a significant impact on recognition accuracy. Olszewski et al, [8] also found that children with CIs were significantly less accurate than NH children when only pitch cues (i.e., isochronous presentation of melodic contours) were available, and were also less accurate than adult CI users when rhythmic cues were provided. However, the pediatric CI users performed similarly to both NH peers and adult CI users when lyrics and speech reading cues were available.

Vongpaisal, Trehub, and Schellenberg [9] evaluated the ability of children with CIs to identify recorded musical excerpts of theme songs from children's television programs both in the original (e.g., as heard during the TV program) and modified versions (e.g., melody only). The authors compared the outcomes of children with CIs to children with NH. They found the children with CIs were able to accurately identify the original recordings; however, the modified items that contained only partial cues (e.g., instrumental or melody only) resulted in chance level responses. Children with NH had no issues with either modified version.

Adult electroacoustichearing with music

Unlike children who have prelingual deafness and no memory for music with acoustic hearing, adults with electroacoustic devices have memory of music via acoustic input. Adults also have greater access to low frequency information, which can aid in pitch and melody perception. Gantz and colleagues [3] reported on the ability of individuals with electroacoustic devices to recognize familiar melodies (melody only). When compared to adults with LEs and adults with NH, NH participants scored highest on song recognition (87.1%), recipients of the electroacoustic device scored similarly at 80.1% while individuals with LEs performed at 30.7% [3]. In a follow up study examining recognition of more complex (blends of melodies, harmonies, multiple timbres) real-world songs, with and without lyrics, Gfeller et al [4] found individuals with the electroacoustic device were significantly more accurate than LE users on real-world song recognition with and without lyrics.

Pediatric CI recipients with residual hearing

Performance of acoustic and electric hearing has been evaluated in the pediatric population in bimodal condition, in which the listener utilizes a CI and contralateral hearing aid [10]. While much research has been conducted regarding speech perception, speech prosody and localization, fewer studies have addressed bimodal music perception in the pediatric population. Looi and Radford [11] compared children with NH to children with bilateral HAs, CI only and bimodal listeners. They postulated the recipients with the bimodal listening condition would show superior performance on pitch ranking when compared to children with CI only. Interestingly, their findings showed no difference between CI only

and bimodal condition on performance, while those with normal hearing performed significantly better than both groups.

Electroacoustic hearing in pediatric population

Skarzynski, et al [10, 12] evaluated the preservation of residual hearing in pediatric patients using Med-El Combi+ 40 or PULSAR. For nearly all recipients, measureable residual hearing was maintained. The authors, however, could not find a difference in speech perception (quiet or noise) in the group listening in electroacoustic condition versus those who utilized bimodal hearing with LE.

Music perception for pediatrics with ipsilateral residual hearing, utilizing electroacoustic hearing condition has not yet been evaluated. It is important to differentiate between the child and adolescent populations. Many studies referring to children often use large age ranges that reach 18 years of age as fits the term pediatric. The majority of studies examining music and pediatric recipients have focused on children 5 to 12 years of age [13].

The value of music is indescribable for this age group. It is challenging to conceive of a social experience in adolescence that does not in some way involve music. Zillmann and Gan [14] write that adolescents report music is the most important recreational activity in which they engage. North and Hargreaves [15] reported the average adolescent listens to approximately 10,500 hours of music between grades 7 and 12. Hodges and Sebald [16] state music plays a large part in the socializing force that influences how adolescents talk, dress, and act; how they feel; what they think; and with whom they most closely identify. Adolescents with varying hearing capabilities still may desire to experience and relate through music like their peers with NH. The ipsilateral residual hearing, utilizing electroacoustic hearing setup may help achieve a more realistic representation of music for these adolescents.

Adolescents are sometimes identified by their recklessness and lack of impulse control. Vaidya et al. [17] suggest adolescents exhibit these behaviors because they have a greater sensitivity to the reinforcing properties of pleasurable stimuli. Neuroimaging studies such as Koelsch, Fritz, Müller, & Friederici [18], have revealed that listening to music stimulates dopaminergic regions of the cortex. Given the combination of these findings, it is likely adolescents may seek a neurologic high from listening to music, regardless of hearing configuration. Sturman and Moghaddam [19] describe adolescent structural neurodevelopment, particularly identifying the increase in white matter in cortical and subcortical fiber tracts, resulting from increased myelination, axon caliber, or both. These authors also state changes in the patterns of connectivity also occur; changes which may have a profound effect on how this study's cohort processes music through the device and through residual hearing and how it is very likely their processing of the music stimuli will continue to change as they mature. The plasticity of the auditory system presents an additional point of interest in the specific evaluation of adolescents. Skoe et al [20] found that components of the auditory brainstem (where the signal from the inner ear is transferred to and processed by a series of nuclei before being sent to the thalamus) responses mature at different rates, with responses to low frequencies maturing first, around the age of 9. High frequency responses are last to mature around ages 14-17. This study supports further

investigation to the use of hybrid implants in adolescents, given these differences in maturation rates and how those may be affected by the electroacoustic hearing combination.

This age group is developmentally different from a younger cohort and has demonstrated a stable hearing profile. While adolescents who have grown up using CIs have been evaluated on music perception and involvement, adolescents with ipsilateral residual hearing are a novel population. The purpose of this study was to evaluate a preliminary group of adolescent recipients of the Hybrid L24 on three measures of music perception in CI only and hybrid listening conditions. We examined the following research questions: 1) How do adolescents who are using a L24 cochlear implant perform on measures of pitch, melodic error detection, and melody recognition? 2) How do their results compare to the performance of children and adolescents with the LE on these same measures? 3) How do they compare to children with NH?

Method

Participants

L24 Adolescents—Five adolescents were implanted with the L24 following hearing aid verification and trial as part of an FDA, Investigational Device Exemption (IDE) at 11-16 years ($M = 12.6$ years); four were female, one was male. Specific audiometric thresholds and selection criteria can be found in Gantz, et al (this issue) [21]. Briefly, participants were required to have a sensorineural hearing loss with pure-tone average (PTA) between 70-90 dB HL from 125-1500 Hz and profound loss at higher frequencies. Specifically, these subjects possessed hearing thresholds > 90 dB HL at 1500 Hz. Subjects were tested preoperatively and at 4, 8, 12, 18 and 24 months post connection on three measures of music perception. At their most recent visit, the adolescent L24 recipients were 14-18 years of age ($M=15$ years) with 13-36 months of implant use ($M=22.6$ months, $SD=8.73$). Demographic information can be found in Table 1. Cut-off frequencies in Table 1 represent the lowest frequency programmed on the array below which residual, acoustic hearing provides input. Thus, the higher the number, the more residual hearing the user possessed. All subjects had stable cut-off frequencies from 4 months to 24 months.

Comparison groups—We compared the outcomes of our L24 group at 24 months to children and adolescents with LEs and also children with NH. Seventy-three children and adolescents with LEs implanted between 1-14 years of age ($M=4.9$) were tested on music perception measures as part of their annual audiology clinic visits. Age at time of testing ranges from 6-25 years ($M=12.1$). Children ($n=58$) were determined to be those aged 14 and below (LEC), while adolescent participants ($n=15$) were those above age 14 who were implanted as children and had been followed by the pediatric team (LEA). Eighty-seven children, 6-15 years of age ($M=10.47$), with NH were recruited through advertisements at a midwestern university. All participants were typically-developing and spoke English as their primary language. NH status was established as a pure-tone average < 20 dBHL across 250, 500, 1000, 2000, 4000 Hz. All participants received compensation for their time, and the studies were approved by the institution's Human Subjects Review Board. Because testing

took place over time, a subset of LEC, LEA, and NH participants was used for each test. Specific breakdown of subjects for each test are included in Table 2.

Comparisons with the LEC, LEA, and NH children permitted testing as a function of chronological age. Some of the LECs shared similarities in length of implant use; whereas, the adolescents in the NH and LEA groups were more similar in other developmental characteristics (i.e., physical maturation).

Measures

Three music measures were used, which represented “more isolated” to “more musical” listening tasks.

Complex Pitch Ranking Test (PR-C)—Developed by Gfeller, et al [22], the test consists of a two alternative-forced choice (2AFC) paradigm, used to determine the ability of CI recipients to rank pairs of complex pitch stimuli. The listener indicated which of two pitches was higher in frequency. The test is adaptive, beginning with large interval differences, and increasing or decreasing the interval size between the pitches as the participant responds correctly or incorrectly. Maximum (poorest) score is 24 semitones (or 2 octaves); minimum score on this test is 1 semitone (the smallest interval of the diatonic scale in Western music).

Melodic Error Detection (MED)—The MED is an adapted version of The Modified Melodies test by Swanson et al [23] and was used to determine the ability of listeners to indicate, within the context of a familiar melody (“Old MacDonald” or “Twinkle, Twinkle Little Star”), which of two iterations was correct. In one, the melody was presented incorrectly, with one note “nudged” by 2 semitones (augmented for Old MacDonald and diminished for Twinkle, Twinkle). Each melody was presented four times in three base frequencies 131, 252, 523 Hz; each base frequency range included three potential starting notes. Frequency presentation was randomized for each subject.

Melody Recognition by Information Cue (MRIC) [8]—The MRIC measures the accuracy of listeners to identify four familiar melodies prepared using MIDI technology (acoustic piano setting) and a solo female vocalist. The melodies were presented with four types of cues: isochronous melody (no rhythmic cues); melody with rhythmic cues; melody plus rhythm plus lyrics sung by a female vocalist; and the melody, rhythm, and lyrics accompanied by a video of the vocalist's face (providing the visual cues of speech reading). In the isochronous condition, the melody was broken down into pulse trains to remove the rhythmic cues, leaving only pitch information. Each item was presented in a 4AFC paradigm and the listener identified the melody they believed they heard. The presentation formats were randomized within the test to avoid a learning effect of moving from easier to more difficult levels.

Test Protocol

Testing took place for the L24 group preoperatively and at 4, 8, 12, 18 and 24 months post activation. PDT and MED were administered to the L24 group in CI only and hybrid

conditions for within and across-subject comparisons. This design allowed evaluation of the benefit of the ipsilateral residual hearing on performance compared to electric stimulation alone. For the LE comparison groups, testing took place during annual clinic visits using their typical listening configuration; the most recent test data was used in the analyses. NH subjects were recruited for specific tests as they were developed. All subjects were tested in a sound treated room via a desktop computer. Presentation level was set to 70 dBC SPL with subjects seated 3 feet from the speakers at 0° azimuth.

Results

Statistical Analyses

Descriptive statistics were used to compare the CI only and hybrid listening conditions due to small sample size. An analysis of variance (ANOVA) was used to compare the outcome scores for MED, PRT, and MRIC between the groups (L24, LEC, LEA, NH adolescents), and follow up t-tests were used to elucidate where, if any, differences exist. For each of the measures, LEC and LEA were compared using two-sample t-tests; groups only significantly differed on PR-C ($p=0.0467$). LEC and LEA were combined into a single group (CI LE) in the analysis for MED and MRIC.

Complex Pitch Ranking (PDT)

Both the L24 and LE groups show a great deal of variation in outcomes on all three music tests. Scores at each time point can be seen in Figure 1. A lower score indicates better perception; a higher score indicates poorer perception. At baseline, perceptual accuracy ranged from 1 to 13 semitones; 13 semitones is the mean score of the combined LEC and LEA. At most recent testing of the L24 group, scores ranged from 1 semitone (best possible score) to 6 semitones in the hybrid condition. The L24 adolescent who scored poorest at 18 months (P04), showed dramatically improved perception at 24 months. The other 4 participants scored poorest around 8-12 months before improvement began.

Comparing within L24 subjects' scores (hybrid vs. CI only) for PR-C, (see Figure 1b for 24 month testing), three of five subjects show improved performance when the ipsilateral acoustic component was utilized; the remaining two showed optimal scores in both conditions. From a clinical standpoint, the maintained, residual hearing appears to provide fundamental frequency information to allow for better pitch perception than implant alone for those three recipients. It is believed a larger sample may support this assertion.

A comparison of the participant groups (L24, LEC, LEA, and NH adolescents) using ANOVA showed evidence of a difference between at least two of the groups (see Figure 2). The follow up t-tests reveal a significant difference between LEA and LEC ($p=.0467$). The L24 performed significantly better than LEA ($p=.0002$) and LEC ($p=.0076$). NH also performed significantly better than LEA and LEC ($p<.0001$ for both). However, there was no significant difference between L24 and NH ($p=.9124$).

Melodic Error Detection (MED)

The L24 adolescents were compared to LE and NH using ANOVA for their most recent visit. Recall that because there was no significant difference between LEC and LEA, they were combined into one (CI LE). For the average scores on MED (Figure 3), there is a significant difference between at least two of the groups ($p < .0001$). The follow up tests indicate NH is significantly better than both CI LE and L24; L24 were significantly better than CI LE ($p < .0001$). There was no difference between NH and L24 ($p = .1364$).

The three bass frequencies (131, 262 and 523 Hz) were then analyzed. The ANOVA for each of these measures showed that there is evidence of a difference between at least two of the groups ($p < .0001$ for each). The follow up tests show the differences are between CI LE and NH for each of the bass frequencies ($p < .0001$ for all). There is no significant difference between L24 and CI LE for any frequency ($p = .2826$, $p = .1805$, $p = .2830$, respectively), nor is there a difference between NH and L24 for any frequency ($p = .1013$, $p = .0987$, $p = .2830$, respectively).

Melody Recognition by Information Cues (MRIC)

Average scores on melody recognition for the different groups are presented in Figure 4, with outcomes broken out on the left for the Isochronous and Melody conditions. Again, since the LEA and LEC groups were not significantly different on any of the MRIC measures, they were combined to form the group CI LE. For the average melody recognition scores, there is a significant difference between at least two of the groups ($p < .0001$). The follow up tests show that there is a difference between CI LE and both L24 and NH ($p = .0018$ and $p < .0001$, respectively), however there is not a significant difference between L24 and NH ($p = .4769$).

For MRIC with visual cues, there was not a significant difference between groups (ceiling = .3026); note that all groups performed near ceiling. Similarly, for recognition with lyrics, there was again no significant difference between the groups ($p = .2630$). However, when lyrics were removed (melody), there is a significant difference between the groups ($p < .0001$). The follow up tests indicate a significance difference between CI LE and both the L24 and NH ($p = .0009$ and $p < .0001$, respectively), however there is no significant difference between L24 and NH ($p = .9189$). Finally, when only pitch information is provided (isochronous), there was a significant difference between the groups ($p < .0001$). The follow up tests show differences between CI LE and both L24 and NH ($p = .0066$ and $p < .0001$, respectively). Again, there is not a significant difference between L24 and NH ($p = .0983$).

Discussion

Our results are consistent with prior studies indicating residual, low-frequency information, preserved for many electroacoustic patients, is advantageous for pitch perception, especially for melody recognition and error detection. Considerable variability with regard to pitch ranking is still present in this novel population. It also appears that continued improvement in pitch perception with an L24 can occur over 24 months. However, the L24 scores at 24 months are greatly similar to the NH group. We believe it may be due to their maintained,

low-frequency residual hearing. This maintenance of hearing contributes to greater accuracy in difficult listening situations in which low-frequency information not typically conveyed by a CI (e.g. <250 Hz) provides valuable input for perceptual processing. From a developmental standpoint, access to residual hearing also contributes to the development of a closer-to-normal mental representation of music than children who have grown up with the LE, and who tend to have poor frequency resolution [4].

While only 5 children have received this device, our current data shows promising trends in their performance. A larger sample would provide further clarification. The fact they outperform children who have had their devices for significantly longer periods of time is positive. Additionally, they are showing exceptional performance on tests that are often difficult for adults with conventional LE implants. However, despite identical devices and listening conditions, we have found the adolescent L24 recipients do not perform as well as their adult counterparts with hybrid devices [24]. This may be due to maturation, which impacts test-taking strategies. Additionally, one adolescent L24 recipient [P02] had not worn her device consistently and now attends a School for the Deaf. Her lack of consistent use may have contributed to large variance. It is known from adult CI music research that variability can be expected. The variability for P04 may be attributed to emotional maturity observed during patient testing. She often appears less socially mature than her cohorts. Despite attending to the tasks, as observed by the testing administrator, her performance may reflect that lack of maturity and focus that is observed in others. The remarkable performance of P05 may be attributed to her astute problem-solving skills. This participant utilizes all available cues to determine her response. Further study is needed with a larger sample to determine the effect of anelectroacoustic device in a pediatric population for music. Thus far the results are promising.

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Figure 1.

a. Scores on pitch ranking of complex stimuli for each adolescent L24 recipient up to 24 months. LE mean indicates the mean score from the most recent clinical visits of children and adolescents using the LE. A lower score indicates better performance.

b. Scores on pitch ranking of complex stimuli for each adolescent L24 recipient in CI only and Hybrid condition at most recent visit.

Figure 2. Scores on pitch ranking of complex stimuli for groups at most recent visit in semitones. Lower scores indicate better performance.

Figure 3. Scores on Melodic error identification for each bass frequency for CI LE (child and adolescent combined) and L24.

Figure 4. Percent correct on Melody Recognition by information level for CI LE, L24, and NH. A higher score indicates greater accuracy.

Table 1

Demographic data on L24 recipients

ID	Gender	Age at Implant	Age at Most Recent Test	Ear Implanted	Cut-off Frequency	Months of use for Data
P01	M	11	13	Left	313	24
P02	F	12	14	Left	438	24
P03	F	12	14	Right	313	24
P04	F	13	15	Left	938	24
P05	F	15	18	Left	813	18

Table 2

Number of subjects for each test, broken out by group membership.

Test	Group										NH	
	L24					Adolescent LE			Child LE			Age
	#	Age	Months of use	#	Age	Months of use	#	Age	Months of use	#	Age	
PDT	5	<i>M</i> =14.8 (SD=1.72)	<i>M</i> =22.8 (SD =2.4)	11	<i>M</i> =19.9 (SD=3.37)	<i>M</i> =164.64 (SD=71.96)	22	<i>M</i> =11.4 (SD=2.08)	<i>M</i> =100.55 (SD=31.91)	49	<i>M</i> =10.15 (SD=2.03)	
MRIC	5	<i>M</i> =14.8 (SD=1.72)	<i>M</i> =22.8 (SD =2.4)	15	<i>M</i> =18.53 (SD=2.83)	<i>M</i> =146.36 (SD=57.22)	58	<i>M</i> =10.42 (SD=2.50)	<i>M</i> =78.63 (SD=33.60)	27	<i>M</i> =10.93 (SD=2.51)	
MED	4	<i>M</i> =14.75 (SD=1.48)	<i>M</i> =21 (SD=4.64)	12	<i>M</i> =19.9 (SD=3.37)	<i>M</i> =157 (SD=77.46)	25	<i>M</i> =11.4 (SD=2.08)	<i>M</i> =104.36 (SD=32.45)	14	<i>M</i> =10.36 (SD=2.72)	