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Temporal Modulation Detection in Children and Adults With Cochlear Implants: Initial Results

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Objectives: The auditory experience of early deafened pediatric cochlear implant (CI) users is different from that of postlingually deafened adult CI users due to disparities in the developing auditory system. It is therefore expected that the auditory psychophysical capabilities between these two groups would differ. In this study, temporal resolving ability was investigated using a temporal modulation detection task to compare the performance outcomes between these two groups.

Design: The minimum detectable modulation depth of amplitude modulated broadband noise at 100 Hz was measured for 11 early deafened children with a CI and 16 postlingually deafened adult CI users.

Results: Amplitude modulation detection thresholds were significantly lower (i.e., better) for the pediatric CI users than for the adult CI users. Within each group, modulation detection thresholds were not significantly associated with chronologic age, age at implantation, or years of CI experience.

Conclusions: Early implanted children whose auditory systems develop in response to electric stimulation demonstrate better temporal resolving abilities than postlingually deafened adult CI users. This finding provides evidence to suggest that early implanted children might benefit from sound coding strategies emphasizing temporal information.

Key Words: Cochlear implant—Prelingual implantation—Temporal processing.

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INTRODUCTION

Children who are born deaf and receive a cochlear implant (CI) in early childhood are fit with the same coding strategies as postlingually deafened adult CI users. However, it is likely that the optimal sound coding strategy for these two populations would be different due to developmental dissimilarities in their auditory systems. The auditory system of postlingually deafened adults typically develops in response to the rich acoustic input of normal hearing. At some point after auditory maturation, their auditory system must adapt to a period of hearing deprivation from their hearing loss. At a later point in time, these adults receive a CI and need to learn to interpret the information provided by the implant. By contrast, children who are deaf at birth or at a young age do not have this same advantage. However, if implanted young enough, these children have the benefit of learning to interpret the signal from a CI within the early sensitive time window for auditory development (1). Because the developmental histories for adult and child populations are different, it is likely that contrasts in basic perceptual abilities and limitations will emerge when compared empirically. A better understanding of the differences in perceptual abilities for these two populations is expected to guide the optimization of new sound coding strategies.

Landsberger et al. (2) measured spectral resolution using the spectral-temporally modulated ripple test (SMRT) (3) in early implanted children and postlingually deafened adults. It was found that early implanted CI users performed significantly poorer on this task than postlingually deafened CI adults. That is, despite receiving similar input from their CIs, adult users with auditory systems that developed in response to normal acoustic hearing performed better on the spectral resolution task than pediatric users whose auditory systems developed in response to electric stimulation. Furthermore, no significant correlation was found between age and the performance for early implanted children on the SMRT. This

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finding is in contrast to the significant correlations found between age and SMRT score for children with normal hearing (2,4) or children with moderate hearing loss who use hearing aids (4). This discrepancy in findings between studies suggests that almost complete absence of the sensory mechanism of hearing (i.e., hair cells) early in life may compromise the child's ability to develop adequate spectral resolution capabilities, even with a CI.

It has been shown in a number of studies with adult CI users that the performance on speech perception measures correlates with spectral resolving abilities (5–9). However, Jung et al. (10) and Gifford et al. (5) both reported that, unlike adults, there is no correlation between spectral resolution and speech perception abilities for children with CIs. It is therefore notable that many early implanted children are able to acquire open-set speech recognition (11) and develop spoken language skills with their CI processors (12). Taken together, these findings support the hypothesis that speech understanding skills develop without the benefit of spectral resolution for implanted children. Thus, it is likely that early implanted children depend on other auditory cues, such as temporal information, to support their auditory skill development with the CI.

In the present experiment, we compare the performance between pediatric CI users and postlingually deafened adult CI users on a temporal modulation detection task to assess temporal resolution. This specific task was selected because modulation detection has been shown to correlate with CNC word scores for postlingually deafened adult CI users (13). The specific modulation detection task implemented in the present experiment was based on the task used by Won et al. (13), which was in turn adapted from a task used by Bacon and Viemeister (14).

METHODS

Subjects

Eleven children aged 9 to 17 years of age (mean 13.73 years, SD 2.53) participated in the study. Children were implanted between 8 months and 5 years of age (mean 2.15 years, SD 1.60). Seven of the children were implanted with Cochlear devices and the remaining four were implanted with Advanced Bionics devices. Sixteen postlingually deafened CI adults (7 Cochlear users, 6 Advanced Bionics users, and 3 MED-EL users) aged 29–81 years (mean 55.75 years, SD 15.97) also participated. Unilaterally implanted subjects were tested with their one CI activated and bilaterally implanted subjects were tested with both devices activated. All subjects were tested with their implants set to daily use settings. Participants with residual hearing were tested without a hearing aid and with an earplug in the corresponding ear.

Stimuli

Based on the methods described in Won et al. (13), the stimuli consisted of 1000 ms of broadband white noise sampled at 44100 Hz with 50 ms onset and offset ramps. Reference stimuli were unmodulated. Target stimuli were sinusoidally amplitude modulated at 100 Hz. The modulation depth of the target stimuli varied across trials. To maintain equal loudness with unmodulated stimuli, the waveform of the modulated stimuli was divided by $1+(m^2/2)$ where m is the modulation depth (13–15).

Procedure

Modulation detection thresholds (MDTs) were measured with an adaptive 3-interval forced choice task. Each of the stimuli had a 1000 ms duration with a 300 ms interstimulus interval. Two of the stimuli consisted of unmodulated references and one stimulus consisted of a modulated target. In the first trial, the target stimulus was modulated using a 100% modulation depth. The modulation depth was adjusted by 1 dB steps (re: 100% modulation) based on a 1-up, 1-down procedure. The procedure was repeated until 12 reversals were measured. The modulation depth threshold was estimated as the average of the last 6 reversals. The stimuli were presented using a software package called EasyTMT (developed by the first author), which is designed to measure modulation detection of broadband noise at a single modulation frequency or at many modulation frequencies to generate a full modulation transfer function. The EasyTMT interface is derived from the interface of the SMRT software (3) and will eventually be distributed for free to allow an easy, clinically implementable, and standardized temporal modulation detection task.

Depending on available time for each subject, between 3 and 6 estimates of the modulation detection threshold were measured. The average modulation detection threshold was calculated for each subject. Before measuring the MDT, practice runs consisting of the first 4 trials were conducted. All stimuli were delivered at 60 dB SPL in the sound field from a loudspeaker at 0^o azimuth. The subjects were tested in a sound-treated, double-wall booth.

RESULTS

The average pediatric modulation detection threshold was -13.874 dB $\pm$ 3.752 standard deviation for 100 Hz modulations. The pediatric MDTs are plotted as a function of age at testing (left panel of Fig. 1), age at implantation (center panel of Fig. 1), and experience with a CI (right panel of Fig. 1). Correlations were not statistically significant between MDTs and age ($r = 0.07$, $n = 11$, $p = 0.840$), age at implantation ($r = 0.12$, $n = 11$, $p = 0.717$), or experience with a CI ($r = -0.15$, $n = 11$, $p = 0.667$) for the pediatric subjects.

The average MDT for the adult subjects as a group was -10.24 dB $\pm$ 4.60 standard deviation. Correlations were not statically significant between MDTs and age ($r = 0.04$, $n = 16$, $p = 0.885$), age at implantation ($r = 0.09$, $n = 16$, $p = 0.745$), or experience with a CI ($r = -0.191$, $n = 16$, $p = 0.480$) for the adult subjects. A t-test detected a statistically significant difference between the MDTs of the pediatric and postlingually deafened adult CI users ($t(25) = 2.170$, $p = 0.0397$), with the children demonstrating better MDTs than the adults. These are represented using boxplots in Figure 2. The average MDT difference between the pediatric and postlingually deafened adults was 3.636 dB with a 95% confidence interval ranging between 0.184 and 7.087 dB. No statistically significant correlation was detected between the standard deviation of responses and the number of

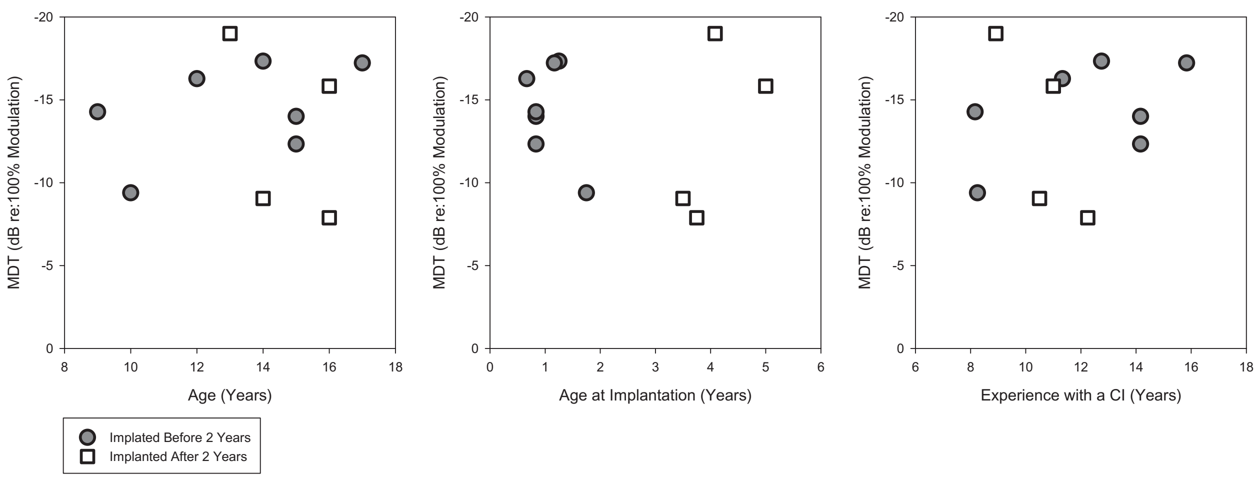

FIG. 1. Modulation detection thresholds plotted as a function of age (left panel), age at implantation (center panel), and experience with a CI (right panel) for the pediatric subjects. Circles indicate children who received their first implant before 2 years of age and squares indicate children who received their first implant after 2 years of age.

estimates of modulation detection measured ($r = 0.163$, $n = 27$, $p = 0.416$).

A post-hoc power calculation suggests that for this relatively small number of participants, the power to detect a significant difference was 0.550. Despite the small sample size of the primary analysis, a secondary analysis was conducted to determine if there was a difference in modulation detection between unilateral and bilateral implantation (CI configuration) and age group. A two-way ANOVA failed to find a main effect of CI configuration ($F(1,26) = 1.789$, $p = 0.194$) or an interaction between CI configuration and age group ($F(1,26) = 1.589$, $p = 0.220$). However, the power for detecting the main effect of CI configuration (unilateral vs bilateral) was only 0.128 and the power for detecting the interaction with age group was only 0.107.

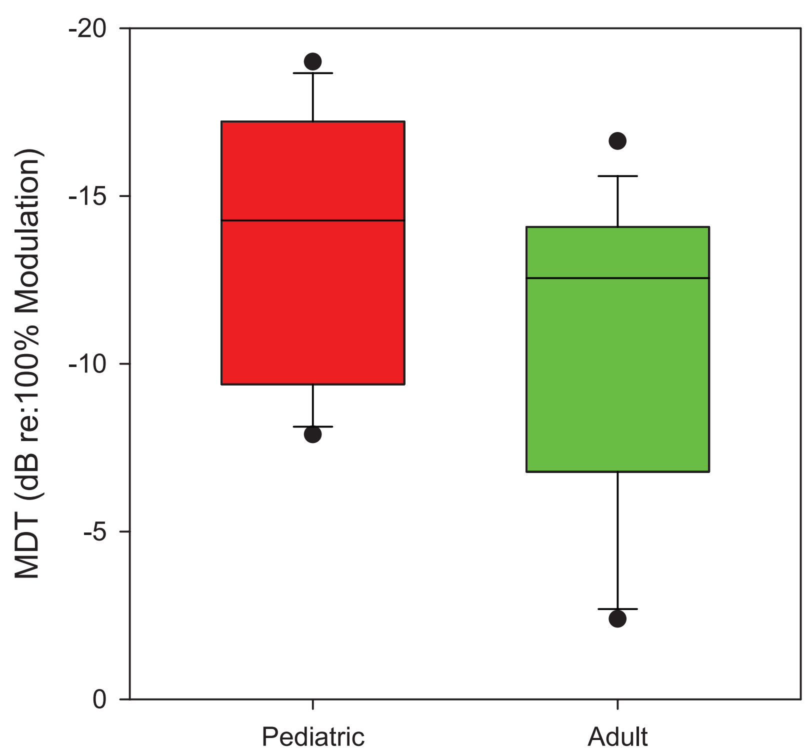

FIG. 2. Box plots representing the distribution of modulation detection thresholds for the pediatric and postlingually deafened adult populations.

DISCUSSION

The results from this experiment suggest that children who receive a CI at a young age perform better on a temporal modulation detection task than postlingually deafened adult CI users. This outcome suggests that normal auditory acoustic development does not provide an advantage relative to auditory development in response to electric stimulation for a temporal task through a CI. In fact, there may indeed be a benefit of pediatric implantation for psychoacoustic temporal tasks. The clinical relevance of the 3.636 dB improved MDT for the implanted children when compared to that of the adults is unknown. However, Figure 7 of Won et al. (13) suggests that a difference in modulation detection of 3.636 dB for postlingually deafened CI users corresponds approximately to an improvement of approximately 15 percentage points in CNC words or -2.7 dB SRT for speech presented in steady-state noise.

A similar experiment by Park et al. (16) measured MDTs of postlingually deafened adult CI users and early implanted children. At 100 Hz, no differences between the two groups were detected, although there was a trend toward poorer MDTs for the early implanted children. It is unknown why the results from the present manuscript differ from the results by Park et al (16). One potential explanation is that the task in the present experiment used a 3-interval forced-choice task in which the subject had to identify which of the sounds were different. In contrast, Park et al. (16) used a 2-interval forced-choice task in which the subject was instructed to identify the interval with modulations. This required the subject not only to discriminate between a modulated and unmodulated stimulus but also to label the modulated stimulus as being ''modulated.'' It is plausible that for more difficult trials, the early implanted children in the Park et al. (16) study were able to discriminate correctly between modulated and unmodulated stimuli but not identify the modulated stimulus.

The results from the present study are in sharp contrast to those of Landsberger et al. (2) which found that postlingually deafened adult CI users performed better on a spectral resolution task than early implanted children. The results from this experiment and Landsberger et al. (2) add to the growing evidence that the auditory systems of children implanted at a young age respond differently to electrical stimulation than postlingually deafened adults. Furthermore, it may be the case that these populations use available cues differently. The performance on speech tests has shown significant correlations with both spectral (6–9) and temporal (13,17) abilities for postlingually deafened adult CI users. However, no such correlation has been found between spectral resolution and speech perception performance for pediatric CI users (5,10). It seems reasonable to conjecture that early implanted CI users depend on temporal cues as much (if not more) than postlingually deafened CI users. Collectively, these data reinforce the idea that early implanted children may benefit substantially from sound coding strategies that seek to optimize temporal processing in contrast to the commercial sound coding strategies in use today that emphasize spectral processing.

No significant effect of CI configuration (unilateral vs bilateral) was detected. However, as the statistical power of the analysis was very small, a larger study would be required to draw appropriate conclusions. It is plausible that bilateral implantation may allow for better modulation detection for the simple reason that the MDT will be based on the CI that provides the best performance. Conversely, it is possible that for some subjects, the two implants will provide competing information and reduce the performance.

Although amplitude modulation detection is generally considered a temporal task, it is possible that the performance is also dependent on sensitivities to loudness differences or changes. Loudness growth in response to electrical stimulation has been described as an expansive function in postlingually deafened CI users (18,19). This expansive function may compensate for the loss of compression that is typically generated by normal cochlear mechanics (20–22). However, the auditory systems of pediatric CI users never developed in response to a normal acoustic input, and therefore may not have developed the same loudness growth functions as postlingually deafened CI users. For a fixed stimulus, a change in loudness growth functions will yield a change in the perceived contrasts produced by variations in amplitude. It is therefore possible that differences in modulation detection could be attributed to differences in loudness growth functions and not temporal abilities.

To conclude, the evidence from this study suggests that pediatric CI recipients perform better on a 100 Hz MDT task than postlingually deafened CI users. Further research is needed to better understand the differences in temporal processing between these two very different populations of CI recipients. Comparing the two groups on a temporal task that is less dependent on intensity discrimination (such as gap detection) would minimize the impact of differences in loudness growth functions. Furthermore, in the present experiment, the children participants were mostly older than 10 years of age, which is the approximate age at which modulation detection performance becomes equal to adult performance in hearing listeners (23). Extending to younger pediatric participants would provide insight into the developmental trajectory of temporal resolution in children with CIs.

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