Amplitude Modulation Detection and Speech Recognition in Late-implanted Prelingually and Postlingually Deafened CI Users

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ABSTRACT

Objectives: Many late-implanted prelingually deafened cochlear implant (CI) patients struggle to obtain open-set speech understanding. Since it is known that low-frequency temporal-envelope information contains important cues for speech understanding, the goal of this study was to compare the temporal-envelope processing abilities of late-implanted prelingually, and postlingually deafened CI users. Furthermore, the possible relation between temporal processing abilities and speech recognition performances was investigated.
Design: Amplitude modulation detection thresholds (AMDTs) were obtained in 8 prelingually and 18 postlingually deafened CI users, by means of a sinusoidally modulated broadband noise carrier, presented through a loudspeaker to the CI user's clinical device. Thresholds were determined with a 2-down-1-up 3-interval oddity adaptive procedure, at 7 modulation frequencies. Phoneme recognition (Consonant-Nucleus-Consonant) scores (% correct at 65 dB SPL) were gathered for all CI users. For the prelingually deafened group, scores on 2 additional speech tests were obtained: (1) a closed-set monosyllable-trochee-spondee (MTS) test (% correct scores at 65 dB SPL on word recognition and categorization of the suprasegmental word patterns), and (2) a speech tracking test (number of correctly repeated words per minute) with texts specifically designed for this population.
Results: The prelingually deafened CI users had a significantly lower sensitivity to amplitude modulations than the postlingually deafened CI users, and the attenuation rate of their TMTF was greater. None of the prelingually deafened CI users were able to detect modulations at 150 and 200 Hz. High and significant correlations were found between the results on the amplitude modulation detection test and CNC phoneme scores, for the entire group of CI users. In the prelingually deafened group CNC phoneme scores, word scores on the MTS test, and speech tracking scores correlated significantly with the mean AMDT of the modulation frequencies between 5 and 100 Hz and with almost all separate amplitude modulation thresholds. High correlations with these speech measures were also found for the attenuation rate of and the surface area below the TMTF. In postlingually deafened CI users, CNC phoneme scores only correlated significantly with the 100- and 150-Hz amplitude modulation thresholds, as well as with the attenuation rate of and surface area below the TMTF.
Conclusions: Prelingually deafened CI users were less sensitive to temporal modulations than postlingually deafened CI users, and the attenuation rate of their TMTF was steeper. For all CI users, subjects with better amplitude modulation detection skills tended to score better on measures of speech understanding. Significant correlations with low modulation frequencies were found only for the prelingually deafened CI users and not for the postlingually deafened CI users.

INTRODUCTION

While many cochlear implant (CI) users have excellent speech recognition in quiet (Dorman 2006), part of this population still struggles (Teoh et al. 2004a; Santarelli et al. 2008; Lazard, Giraud et al. 2012). Most of them are late-implanted prelingually deafened patients, i.e. with an onset of deafness before the end of the language acquisition period. Important information for speech recognition is present in temporal cues up to about 50 Hz: normal-hearing subjects can achieve nearly perfect speech recognition using slow temporal cues (<20 Hz), combined with limited spectral information (Friesen et al. 1995; Shannon et al. 1995). Since temporal cues seem to be important, and long-term auditory deprivation induces changes along the entire auditory pathway (Teoh et al. 2004b), the present study was conducted to compare the temporal processing abilities of prelingually and postlingually deafened CI users, and to assess whether these abilities are related to speech recognition performance.

A powerful approach to determine the temporal processing abilities of CI users is to measure the sensitivity to sinusoidal amplitude modulations. The amplitude modulation detection threshold (AMDT), expressed as the smallest modulation depth that can be detected, measured at several modulation frequencies, results in a temporal modulation transfer function (TMTF). In normal-hearing subjects and postlingually deafened CI users the TMTF has a low-pass filter characteristic, i.e. high sensitivity at low modulation frequencies and decreasing sensitivity with increasing modulation frequency (Viemeister 1979; Bacon et al. 1985; Shannon 1992; Dau et al. 1997).

A range of studies on amplitude modulation detection in CI users reported the effects of stimulation rate (Galvin et al. 2005, 2009; Pfingst et al. 2007; McKay et al. 2010; Arora et al. 2011), stimulation site (Pfingst et al. 2007; Garadat et al. 2012), stimulation mode (Galvin & Fu 2005; Pfingst 2011), stimulus duration (Luo et al. 2010), stimulus level (Galvin & Fu 2005, 2009; Pfingst et al. 2007), and loudness growth (McKay & Henshall 2010) on AMDTs. In most of these studies the electrical stimulus was presented directly to one or more electrodes using computer-controlled stimulation, bypassing the clinical sound processor. Recently however, Won et al. (2011) and Gnansia et al. (2014) conducted studies in which stimuli were presented in sound-field to the sound processor of postlingually deafened CI users. This approach assesses the sensitivity to amplitude modulations in a clinical setting, including both the processors' signal processing and the subjects' individual maps. Won et al. (2011) showed that the TMTFs of CI users measured in free-field, have the same low-pass filter shape as the TMTFs of CI users measured with electric stimulation directly at one electrode. When they compared the sound-field TMTFs of the postlingually deafened CI users to the sound-field TMTFs of normal hearing and hearing-impaired subjects as obtained by Bacon and Viemeister (1985), Won et al. (2011) found a lower general sensitivity to amplitude modulation and a steeper slope for the CI users compared to the 2 other groups.

Almost all studies regarding temporal processing mentioned so far, investigated the amplitude modulation detection abilities of postlingually deafened CI users. However, for prelingually deafened CI users the shape of the TMTF is not well characterized. One study, by Busby et al. (1993), obtained electric TMTFs of 3 prelingually deafened CI users. All 3 subjects showed a lower sensitivity to amplitude modulation, and for one of these subjects the shape of the TMTF differed from the low-pass filter characteristic; this TMTF had a characteristic of 2 band-pass filters.

Temporal information in speech, e.g. syllabicity, rhythm, manner of articulation, voicing, stress, and intonation, is present in the envelope and periodicity of an acoustic waveform (Rosen 1992). It is therefore not surprising that several studies have found a correlation between amplitude modulation detection abilities and speech recognition performance for postlingually deafened CI users. Cazals et al. (1994) found that the rejection rate, which they defined as the difference between the AMDT at the 400- and at the 71-Hz modulation frequency, measured at the most apical electrode, correlated with average performance for vowel and consonant recognition administered at 70dBA. Fu (2002) found highly significant correlations between mean electric AMDTs (for a 100 Hz modulation, averaged over several stimulation levels) and both vowel and consonant recognition scores. In a study by Luo et al. (2008), mean electric AMDTs (averaged for 20-Hz amplitude modulation across 5 stimulation levels) were significantly correlated with Chinese tone, consonant, and sentence recognition scores. Arora et al. (2011) found that mean AMDTs (obtained with vowel-like stimuli presented via direct audio input to a research processor), predicted sentence in noise outcomes at 65 dB SPL. These mean AMDTs were determined by averaging across the 50- and 100-Hz modulation frequencies and various stimulation rates, presented at an acoustic level that when processed through the processor, produced electrical stimulation levels close to the subjects' electrical most comfortable level (MCL). Won et al. (2011) found significant correlations between the mean AMDTs, averaged over 7 modulation frequencies ranging from 10 to 300 Hz, and both consonant-nucleus-consonant (CNC) monosyllabic phoneme scores and speech reception thresholds (SRTs) in noise. When looking at the individual modulation frequencies, significant correlations were found only for the higher modulation frequencies (from 75 Hz onwards for the CNC scores and from 150 Hz onwards for the SRTs in noise). In addition, Won et al. (2011) found that the attenuation rate, i.e. the slope, of the sound-field TMTF, which is defined as the b-component of the exponential function, $AMDT(f_{\mathrm{mod}}) = -ae^{bf_{\mathrm{mod}}}$ fitted through the AMDTs from 10 to 200 Hz, correlated with both CNC scores in quiet and speech reception thresholds (SRTs) in noise. Given that the attenuation rate is mainly determined by the AMDTs at higher modulation frequencies, the results of Won et al. (2011) suggest that CI users with better thresholds for high modulation frequencies obtain better speech understanding scores. In a recent study of Gnansia et al. (2014), sound-field AMDTs measured at a low modulation frequency of 8 Hz also correlated significantly with vowel and consonant identification scores in quiet. In noise, no significant correlations were found (Gnansia et al. 2014). Since in all these studies only postlingually deafened CI users were tested, it is unknown whether a correlation exists between amplitude modulation detection measures and speech performance scores for prelingually deafened CI users.

The first goal of the present study is to compare the sound-field AMDTs of prelingually deafened CI users with the sound-field AMDTs of postlingually deafened CI users. It is hypothesized that prelingually deafened CI users perform more poorly than postlingually deafened CI users on the temporal modulation detection tests.

The second goal of this study is to assess the possible relation between temporal processing abilities, measured with AMDTs, and speech recognition scores for the entire group of CI users, and for the prelingually and postlingually deafened CI users separately.

MATERIALS AND METHODS

Subjects

Both prelingually (n=8) and postlingually (n=18) deafened CI users participated in this study. All subjects were Dutch native speakers with oral communication as their primary mode of communication. Some of the prelingually deafened CI users were also familiar with Dutch sign language. All CI users were unilaterally implanted after the age of 18 years and had minimally one year experience with the CI. The age at onset of deafness for the prelingually deafened subjects can be found in Table 1. Note that 3 of the prelingually deafened subjects had an onset at 2 or 3 years of age, and might therefore be considered perilingually rather than prelingually deafened. For convenience of comparison however, it was preferred to use the term “prelingual” for all subjects with an onset of deafness before the end of the language acquisition period. The duration of the moderate to profound hearing loss of both the pre- and postlingually deafened CI users is also listed in Table 1, together with information about the age at implantation, etiology and implant type. The duration of hearing loss was referred to as the time up to the implantation date, from when the PTA of the best ear was at least 60 dB HL or, if this information was not available, the time from when the subject had started to wear hearing aids bilaterally. The use of human subjects was approved by the local Medical Ethical Committee.

Setup

The acoustic stimuli were presented in a sound-treated booth through a speaker (Klein + Hummel O 110 D) positioned 1 m in front of the subjects. The APEX 3 program (developed at ExpORL-K.U.Leuven (Francart et al. 2008)), run on a laptop, was used to present the stimuli in an adaptive procedure. All subjects listened to the stimuli presented in the sound-field with their own sound processor and with the clinical map of their own preference.

Stimuli

Stimuli were generated digitally in MATLAB (The Mathworks, Inc.) with a sampling frequency of 44.100 Hz. A broadband noise carrier was created, which was limited by a fourth-order band-pass filter with cut-off frequencies of 80 and 8500 Hz.
Sound pressure level verification was performed at the position of the head to assure linearity of the setup system. The average sound pressure level of the unmodulated stimulus was 65 dB SPL.

The broadband noise carrier was sinusoidally amplitude modulated by the following equation: $y(t) = f(t)\left[1 + m_i \sin(2\pi f_m t)\right]$, where $y(t)$ is the stimulus, $f(t)$ is the broadband noise carrier, m_i is the modulation depth and f_m the modulation frequency. Seven modulation frequencies were used: 5, 10, 50, 75, 100, 150, and 200 Hz. To compensate for acoustic intensity increment due to the amplitude modulation, the modulated signal was divided by the long-term average power of the sinusoidally modulated waveform, $1+(m_i^2/2)$, to equalize the RMS values of the stimuli. Both the modulated and unmodulated stimuli were gated on and off with 30-ms linear ramps. Stimulus duration was 500 ms and 1000 ms for an additional test condition administered to a limited number of subjects.

Procedure

AMDTs were obtained using a 2-down-1-up, 3-interval oddity, adaptive forced-choice procedure, tracking the 70.7% point of the psychometric function (Levitt 1971). The stimulus duration as well as the interstimulus duration was 500 ms. Subjects were instructed to choose the stimulus which they perceived as being different from the other two.

The initial modulation depth was -2 dB re 100% amplitude modulation and the initial step size was 4 dB. After 2 reversals the step size was reduced to 2 dB. In a single run 8 reversals were obtained, and the average of the last 6 reversals was used to determine the modulation detection threshold. After completing the runs for all 7 modulation frequencies in a randomized order, the entire session of 7 runs was repeated in order to check for reproducibility. The average of these 2 sessions was taken as the final measure of the modulation detection threshold per modulation frequency. A pause was planned at least once between each session of 7 runs, in order to reduce the possible influence of diminished concentration and fatigue.

Speech Tests

For both the pre- and the postlingually deafened CI users, phoneme scores on an open-set Dutch monosyllabic (CNC) word test (Bosman et al. 1995) were gathered at 65 dB SPL. In this test, the phoneme recognition score is measured as a percentage correct. The scores were obtained from the last yearly clinical evaluation of the subject.

Since prelingually deafened CI users generally score poorly on standard open-set word tests, 2 more simple speech tests were also administered to this group. The monosyllable-trochee-spondee (MTS) test, adapted from Erber et al. (1976), is a Dutch 12-item closed-set word identification test, where each word is presented twice. Word scores (entire word should be correct) and suprasegmental scores (number of correct syllables per presented word and the stress pattern of the word should be correct) were gathered as a percentage correct for administration at 65 dB SPL. The speech tracking test, with texts designed specifically for prelingually deafened CI users (Boons et al. 2011), is an open-set sentence identification test where a number of additional cues (e.g. repeating parts of the sentence, allowing lip reading) is given to the subject in a predetermined order. The amount of time the subject needs to repeat the entire text is used to calculate the score, expressed as the number of words per minute. Speech tests were administered during one of the 2 visits.

Data Analysis

Normality of AMDTs was checked with the Shapiro-Wilk test. Non-parametric tests were applied in cases of non-normality, which occurred at higher modulation frequency data because of floor effects, and for the attenuation rate data because of outliers. Floor values occurred when modulations were undetected by the participant; in these cases a value of zero was assigned.

To check reproducibility, Spearman correlation coefficients between the first and second measurements of all AMDTs were obtained. A mixed-model was estimated to compare the AMDTs of prelingually and postlingually deafened CI users over the 7 modulation frequencies. Additional analyses included independent *t* tests and Mann-Whitney *U* tests, depending on normality, to compare the different modulation frequencies pairwise.

Both groups were further compared with respect to the attenuation rate and the surface area below the TMTF. The attenuation rate relates to the shape of the entire TMTF and the surface area below the TMTF relates to the gain (overall sensitivity to amplitude modulation) and shape of the TMTF, whereas the AMDTs only describe the sensitivity to temporal modulations at individual frequencies. The attenuation rate of the TMTF is, as in Won (2011), defined as the b-component of an exponential function fitted through the data: $AMDT(f_{\mathrm{mod}}) = -ae^{bf_{\mathrm{mod}}}$, with $AMDT$ the absolute amplitude modulation detection threshold in dB re 100% modulation. Here, a is the intercept, b the attenuation rate, and f_{mod} the modulation frequency in Hz. The mean fit through the data of both the prelingually and postlingually deafened CI users is plotted in Figure 1. The surface area below the TMTF is calculated as the integral of the exponential function $AMDT(f_{\mathrm{mod}}) = -ae^{bf_{\mathrm{mod}}}$. An independent *t* test or Mann-Whitney *U* test was used to compare the attenuation rate and the surface area below the TMTF between both groups, depending on normality. Bonferroni adjustments occurred separately for the 7 modulation frequencies and the 3 overall AMDT outcome parameters.

One-sample *t* tests were performed to investigate the difference between the AMDTs obtained in this study for the postlingually deafened CI users and the mean AMDT values reported by Won et al. (2011).

Since floor effects occurred for higher modulation frequencies, Spearman's rank correlation coefficient was used to describe relations between speech performance scores and individual AMDTs, mean AMDTs, the attenuation rate of the TMTF, and the surface area below the TMTF. This was done for the total group of CI users and for the pre- and postlingually deafened CI users separately. A Bonferroni adjustment for multiple comparisons was added per group for the 7 modulation frequencies and also for the 3 overall AMDT outcome parameters.

Finally, additional measurements were done with 1000-ms stimuli in all prelingually and 8 of the postlingually deafened CI users. To compare the results obtained with both stimulus lengths, a paired sample *t* test or Wilcoxon Signed Rank test was used, depending on normality.

RESULTS

Spearman correlation coefficients of the 2 AMDT measurements for each of the 7 modulation frequencies ranged from 0.86 to 0.99, providing evidence of reproducibility. In Figure 1, the mean sound-field AMDTs of the prelingually and postlingually deafened CI users are plotted against the modulation frequency, resulting in sound-field TMTFs. The mean exponential fits of both groups are shown as thin lines in the figure. For comparison, mean sound-field TMTFs of 24 postlingually deafened CI users (Won et al. 2011) and of 4 normal-hearing listeners (Viemeister 1979) are displayed. The low-pass filter shape of the TMTFs of those other studies can also be observed in the mean TMTFs of the prelingually and postlingually deafened subjects tested in this study: sensitivity to amplitude modulation decreased with increasing modulation frequency.

A significant difference was found between the mean sound-field AMDT of the prelingually and postlingually deafened CI users ($F = 8.69$, df = 1, 24, $p = 0.007$), indicating that prelingually deafened CI users are less sensitive to amplitude modulations than postlingually deafened CI users. Analysis of the different modulation frequencies showed a significant difference ($p < 0.05$) between both groups for the modulation frequencies 5 to 150 Hz, but not for the 200-Hz modulation frequency, as can be seen in Table 2. After Bonferroni correction for multiple comparisons, however, only the difference for the 100-Hz modulation frequency remained significant. When comparing the numbers relating to the shape of the TMTF, a significant difference was found between pre- and postlingually deafened CI users with respect to the attenuation rate ($p = 0.021$), and the surface area below the TMTF ($p = 0.003$); the latter remained significant after Bonferroni correction (see also Table 2).

The individual sound-field TMTFs of the prelingually deafened CI users are shown in Figure 2. Two prelingually deafened CI users (PRE01 and PRE04) scored in the range of the postlingually deafened CI users, while one of the subjects (PRE02) was unable to distinguish modulated from unmodulated stimuli at any of the 7 modulation frequencies. In addition, none of the prelingually deafened CI users were able to detect amplitude modulations at modulation frequencies of 150 and 200 Hz. Three of the 8 subjects (38%) were able to detect amplitude modulations at 75 Hz and 2 of the 8 (25%) at 100 Hz, as shown in Figure 3. When a subject was unable to detect amplitude modulations at a certain modulation frequency, the threshold was reported as 0 dB re 100% modulation. Of the 18 postlingually deafened CI users in this study, the percentage of subjects that was able to distinguish modulated from unmodulated stimuli decreased with increasing modulation frequency: 89% of subjects could detect modulations at 100 Hz, 61% at 150 Hz and 44% at 200 Hz (see Figure 3).

The mean sound-field TMTF of the postlingually deafened CI users in this study indicated a lower overall sensitivity to amplitude modulation when compared to the mean sound-field TMTF of the 24 CI users tested by Won et al. (2011), as can be seen in Figure 1. Significant differences between both groups were found for the modulation frequencies 10 to 100 Hz ($p < 0.05$). AMDTs at 5 Hz could not be compared since this modulation frequency was not tested by Won et al. (2011). No significant differences were found between the AMDTs at the modulation frequencies 150 and 200 Hz.

Table 3 presents correlations (Spearman's Rho) between the temporal modulation detection abilities and various speech scores (CNC phoneme scores, MTS words scores, MTS suprasegmental scores, and speech tracking), for the prelingually and postlingually deafened group, as well as for the total group of subjects. The means and standard deviations of the speech tests are also given for each group. Note that for the MTS-test and the speech tracking test, scores are only available for the prelingually deafened CI users.

When looking at all the CI users tested in this study, the correlations between the CNC phoneme scores and the thresholds for the individual modulation frequencies, the mean AMDT, the attenuation rate of and the surface area below the TMTF, were significant ($p < 0.05$), as can be seen in the last column of Table 3. After Bonferroni correction for multiple comparisons, only the correlations with the 5-, 10-, and 200-Hz modulation frequencies were no longer significant.

For the prelingually deafened CI users separately, significant correlations ($p < 0.05$) were found between the individual modulation frequencies 5, 10, 50, 75, and 100 Hz and CNC phoneme scores, MTS word scores, and speech tracking scores. Correlations with MTS suprasegmental scores were not significant, except for the 100-Hz modulation frequency. The mean AMDT of this group was significantly correlated with all speech measures (see Table 3). Finally, the attenuation rate of the TMTF and the surface area below the TMTF were significantly correlated with all speech measures, except for the correlation between the attenuation rate and the MTS suprasegmental score. Only a limited number of correlations remained significant after the correction for multiple comparisons was applied (see Table 3).

When looking at the postlingually deafened CI users, significant correlations were found between CNC phoneme scores and the 100- and 150-Hz modulation frequencies, as well as the attenuation rate of the TMTF. These correlations remained significant after Bonferroni correction (see Table 3).

In Figure 4, the graphs represent the mean TMTFs for the 8 prelingually and 6 of the 18 postlingually deafened subjects, in 2 test conditions: a short (500 ms) versus a long (1000 ms) stimulus duration. The prelingually deafened CI users demonstrated a higher sensitivity to 5-Hz ($p = 0.005$, significant after Bonferroni correction) and 10-Hz ($p = 0.011$, significant with $p < 0.05$) amplitude modulations obtained with the 1000-ms stimuli in comparison to the 500-ms stimuli. For the 6 postlingually deafened CI users, there was no significant difference for the pairwise comparisons between AMDTs obtained with 500- or 1000-ms stimuli at any modulation frequency.

DISCUSSION

The TMTF of Prelingually and Postlingually Deafened CI Users

The first goal of the study was to compare the sound-field AMDTs of prelingually and postlingually deafened CI users. The absolute sensitivity of prelingually deafened CI users to amplitude modulation was significantly lower than that of the postlingually deafened CI users. The modulation frequency where the difference remained significant, even after correction for multiple comparisons, was 100 Hz. This might be interpreted as such that below 100 Hz, the prelingually deafened CI users are still reasonably capable of detecting amplitude modulations, as can also be found in Figure 3. At 100 Hz, their performances start to decline very quickly, whereas most of the postlingually deafened CI users still perform adequately. Above 100 Hz, however, CI users in both groups start to have great difficulties, resulting in smaller group differences again. In addition, both the attenuation rate of the TMTF and the surface area below the TMTF differed significantly between both groups. Although not meeting the stricter criterion for multiple comparisons, it does point to a trend that the slope of the TMTF of the prelingually deafened CI users is steeper, thus that performances in this group declined more rapidly towards the higher modulation frequencies.

These findings are in agreement with Busby et al. (1993), who found lower sensitivity to electrical amplitude modulation in 3 prelingually deafened CI users than in 4 postlingually deafened CI users. A likely explanation is that the changes along the entire auditory pathway, due to the early onset and long-term auditory deprivation (Teoh et al. 2004b), contributed to a reduced sensitivity to amplitude modulation in prelingually deafened CI users.

The individual TMTFs of 2 prelingually deafened CI users (PRE01 and PRE04), as can be seen in Figure 2, lay within the 95% - confidence interval of the postlingually deafened CI users, while one subject (PRE2) was unable to distinguish any of the modulated stimuli from the unmodulated stimuli. In Table 1 it can be seen that there are no striking differences between the etiologies of these subjects. A possible explanation for these interindividual differences could be that better performing prelingually deafened CI users had a larger amount of residual hearing (mostly at low frequencies) preoperatively, or had this during a longer period in their lives. Residual hearing, especially at 500 Hz, and age at onset of severe to profound hearing loss are both good predictors for CI outcome (Blamey et al. 2013; Lazard, Vincent, et al. 2012). To evaluate this theory, the mean preoperative hearing thresholds of the 8 prelingually deafened CI users in this study at 250 and 500 Hz, were compared to their mean AMDT, but no significant correlation was found. Also, no correlation between the mean AMDT and the age at onset of deafness was found for the prelingually deafened CI users.

The individual sound-field TMTFs of the prelingually deafened CI users in this study all had a low-pass filter characteristic. The band-pass filter shape of the TMTF, as found in one prelingually deafened CI user by Busby et al. (1993), was not found in this study. However, for some subjects the AMDT at the 5-Hz modulation frequency was lower than at the 10-Hz modulation frequency. A similar observation was done by Viemeister (1979), who found lower modulation sensitivity for short stimulus durations (250 and 500 ms) in combination with slow modulation frequencies (< 8 Hz) in normal-hearing listeners, for a gated broadband noise carrier. When they applied continuous stimuli with the same durations and modulation frequencies, the sensitivity was comparable with the threshold at the 10-Hz modulation frequency again. The authors hypothesize that the effect might be due to interferences from the gating, which consequently “mask” some of the modulations. More recently, there are no studies where a gated broadband noise stimulus was used in combination with modulation frequencies below 10 Hz (except for Gnansia (2014), but no TMTF was determined there).

The sound-field AMDTs of the 18 postlingually deafened CI users were compared to those of the 24 CI users evaluated by Won et al. (2011), as shown in Figure 1. At the 10- to

100-Hz modulation frequencies, the measured AMDTs in this study were significantly worse than those of Won et al. (2011). Since it is known that preoperative factors, such as duration of severe to profound hearing loss, duration of moderate hearing loss (up to the onset of severe to profound hearing loss), and the PTA of the better ear have a significant influence on speech performance with CI (Lazard, Vincent, et al. 2012; Blamey et al. 2013), it was investigated whether such differences between the subjects in this study and the subjects in the study of Won et al. (2011) could account for the lower sensitivity to modulations found in this study. Although no information about the preoperative residual hearing of the subjects of Won et al. (2011) is available, there is no reason to assume that preoperative PTAs would be different between both groups. The CNC scores of both groups could not be compared, since phoneme scores were measured in this study and word scores by Won et al. (2011). The duration of the moderate to severe hearing loss before implantation could be compared, although no details are given by Won et al. (2011) as to how the "duration of hearing loss" is defined. It was found that the "duration of hearing loss" of the subjects in the study of Won et al. (2011), was significantly shorter ($p = 0.033$) than of the subjects in this study. This shorter duration of hearing loss could contribute to the better AMDTs found by Won et al. (2011).

Another difference between both studies lies in the adaptive procedure: in this study a 3AFC procedure was used, versus a 2AFC procedure in Won et al. (2011). It is known that with a 2AFC procedure, threshold estimates show a larger variability due to smaller values of the sensitivity index d' (Hacker et al. 1979; Leek et al. 1992). Although this might have contributed to the significant differences that were found, it cannot explain them.

Finally, whereas in this study stimuli of 500 ms were used, Won et al. (2011) used stimuli of 1000 ms. The reason why the shorter duration might have an influence pertains to the effect of short, gated carriers on low-frequency ~~slow-rate~~ modulation (Viemeister et al. 1979), as mentioned above. For the prelingually deafened CI users, the improvement of the sensitivity to 5- and 10-Hz modulations for 1000-ms stimuli compared to 500-ms stimuli, might be an illustration of this phenomenon. The additional measurements that were done with 1000-ms stimuli in 6 of the postlingually deafened CI users, however, showed that the longer stimulus duration had no effect. It is not clear why this effect was found only for the prelingually deafened CI users, but it must be concluded that stimulus duration did most likely not contribute to the differences with the results of Won et al. (2011).

The Relation between Sensitivity to Amplitude Modulation and Speech Performance

The second goal of the present study was to determine the possible relation between the ability to detect amplitude modulations and speech recognition scores, for the entire group as well as for prelingually and postlingually deafened CI groups separately.

When looking at all CI users from both groups together, all correlations with CNC phoneme scores and AMDT parameters were significant. For the individual modulation frequencies 5, 10 and 200 Hz, the correlations were no longer significant after multiple comparisons correction, which is consistent with the weak correlations that are found for these modulation frequencies in the postlingually deafened group.

In the group of prelingually deafened CI users, the MTS word scores, the speech tracking scores, and the CNC phoneme scores had high and significant correlations with the separate modulation frequencies (5, 10, 50, 75, and 100 Hz), the mean threshold across modulation frequencies and the measures relating to the shape of the TMTF. Even though not all separate correlations met the strict multiple comparisons criterion, the high correlation coefficients suggest a relation between the variables. This may indicate that this group was able to utilize modulations in the speech envelope up to 100 Hz for the identification of segmental information (CNC phoneme scores and MTS word scores), and running speech (speech tracking). Correlations with the MTS suprasegmental scores were less high and mostly not significant, which may be partly due to ceiling effects, since suprasegmental scores were generally high (up to 100%) and the standard deviation was smaller than that of the other speech scores.

For the postlingually deafened CI users, significant correlations were found between the CNC phoneme scores and AMDTs at the higher modulation frequencies of 100 Hz, 150 Hz, and with the attenuation rate and the surface area below the TMTF, but not with individual AMDTs at 5, 10, 50, 75, or 200 Hz, or the mean AMDT. This was unexpected, given that it is known from literature with normal hearing subjects that especially low-frequency temporal cues contain important information for speech recognition when spectral cues are limited. Moreover, additional temporal information above approximately 20 Hz does not even seem to be used as long as minimal spectral cues are available (Friesen et al. 1995; Shannon et al. 1995). Also in contrast with this finding is the fact that mainly the slowly-varying envelope, with frequency components up to about 250 Hz, is encoded in current commercial cochlear implant sound processing strategies (McDermott et al. 1992; Vandali et al. 2000).

The presence of a ceiling effect for the low modulation frequencies in this subject group, which could give rise to the absence of correlations, is not very likely since the standard deviations for these results were not particularly smaller for the postlingually deafened CI users (see Table 2).

Looking at the literature, however, these findings in the postlingually deafened group are in agreement with the results of Won et al. (2011), who found significant correlations between CNC phoneme scores and the AMDTs at higher modulation frequencies (75 to 300 Hz) but not with AMDTs at low modulation frequencies (10 and 50 Hz). Also in agreement with this study, they found significant correlations between the attenuation rate and CNC phoneme scores, where the attenuation rate, the b-component of the exponential fit, was primarily determined by the AMDTs at higher modulation frequencies (i.e. 200 and 300 Hz). The latter is also the case for the data in this study, where correlations with the attenuation rate were only significant for the modulation frequencies 50 to 200 Hz. Taken together, our current results and the study of Won et al. (2011) both suggest that when CI users have better amplitude modulation detection skills at higher modulation frequencies, they attain better speech understanding scores. Though only a 100-Hz modulation frequency was measured, and stimulation was done directly at the electrodes, Fu (2002) found highly significant correlations between the mean AMDT (averaged over various stimulus levels) and vowel and consonant recognition scores. On the other hand, a number of studies found correlations with lower modulation frequencies. Also using electric stimulation, Luo et al. (2008) found a significant correlation between AMDTs at both the 100-Hz and 20-Hz modulation frequency and consonant- and sentence recognition scores, but not vowel recognition scores. Recently, Gnansia et al. (2014) found a significant correlation between sound-field AMDTs at a modulation frequency of 8 Hz and consonant and vowel identification scores.

Further Considerations

Sound-field Stimulation

The sound-field TMTF can be seen as a representation of temporal performance in the daily life situation, when the CI is used. It describes the characteristics of the auditory system combined with the CI, including speech coding strategy and individual map settings. Since the attack time of a noise reduction system is relatively long compared to the stimulus duration, no effect of this feature is assumed. Compression is another factor that could affect the AMDT, however, Won et al. (2011) tested the influence of AGC on AMDTs in 7 CI users and did not find significant effects at 65 dB(A). In general though, it is difficult to control the modulation depth without stimulating directly at the electrode(s), especially when different speech coding strategies and different individual map settings are used.

Intensity and Loudness Cues

In this study, it is unlikely that intensity cues were used by the subjects to detect amplitude modulations, since a compensation for intensity increase coming with amplitude modulation was executed, as described in the methods section. However, it is possible that loudness cues were used, since loudness is more related to the peak-intensity than the RMS of the signal (McKay & Henshall 2010; Fraser et al. 2012). This could give the subject an additional cue to choose between modulated and unmodulated stimuli.

Loudness balancing and roving are ways to compensate for possible loudness cues. In research regarding amplitude modulation, the effect of these interventions has been investigated. McKay and Henshall (2010) performed loudness balancing of 250- and 500-Hz modulated stimuli and measured loudness differences. The effect on AMDTs was not measured. They concluded that modulated stimuli were perceived as louder than unmodulated stimuli. Fraser and McKay (2012) measured the effect of balancing and roving in 4 CI users. For the low modulation frequency (50 Hz), 2 out of 4 CI users showed worse AMDTs after balancing and roving. For the higher modulation frequencies (300-600 Hz), this effect was found in 3 out of 4 subjects. Galvin et al. (2014) measured AMDTs at 10 and 100 Hz in nine CI users, with and without a novel method to control for possible loudness cues. In an adaptive task, the stimuli were balanced and global roving was applied. The AMDTs were generally worse with this method, but controlling for loudness cues did not affect the general finding that AMDTs became worse when the modulation frequency increased. In another study with 5 CI users, Chatterjee and Oberzut (2011) found that there was a small but significant effect of roving (without loudness balancing) on the overall gain of the TMTF. The shape of the TMTF, however, was unaffected. On the other hand, Won et al. (2011) found that roving had no significant effect on AMDTs, as measured for modulation frequencies of 10, 100, and 200 Hz in 2 CI users. In conclusion, it was found that when applying roving, AMDTs were generally worse, but the overall shape of the TMTF was not affected. For sound-field stimulation though (see Won et al. 2011), these findings have not yet been confirmed.

In the current study, loudness balancing between the modulated and unmodulated stimuli was not performed. This task would be very difficult for the prelingually deafened CI users, especially for the low modulation frequencies, where changes in loudness are clearly noticeable during the stimulus. However, when no balancing is performed, an even larger amount of roving should be applied in order to correct for possible loudness cues, especially when modulation depths are larger than -15.92 dB re 100%, which is >16% (Chatterjee & Oberzut 2011). The latter occurs for most of the modulation frequencies of the prelingually deafened CI users (Figure 2). Since in this study neither roving nor loudness balancing was applied, the AMDTs might overestimate the sensitivity to amplitude modulations due to loudness cues, and this for the whole range of modulation frequencies. This means that there is a small, but unlikely, chance that the real AMDTs, and thus also the gain of the TMTFs, might be lower. In addition, this effect of loudness cues could be different for each subject group. If this were the case, this would have an impact on the results discussed in the previous sections, regarding the lower sensitivity of the prelingually deafened CI users to amplitude modulations, and the correlations between the speech measures and the individual and mean AMDTs. However, since it is also known that the shape of the TMTF would not be affected, this would not change the results where the main parameter was the attenuation rate. In other words, the significant difference that was found between the attenuation rate of the TMTF of the postlingually and prelingually deafened CI users, and the high correlations between the attenuation rate and various speech measures in all groups, would not likely have been influenced by loudness cues.

CONCLUSIONS

This study measured the temporal processing abilities of both prelingually and postlingually deafened CI users by means of the sensitivity to sound-field sinusoidal amplitude modulations of a broadband noise. It was found that prelingually deafened CI users were less sensitive to amplitude modulations than postlingually deafened CI users, and that their performance degraded more quickly with increasing modulation frequency.

High correlations were found between temporal modulation detection and speech recognition ability in both pre- and postlingually deafened CI users. Better modulation detection thresholds that degraded less quickly when the modulation frequency increased, were related to better speech understanding scores. For postlingually deafened CI users, such correlations were not found between modulation frequencies below 100 Hz and speech recognition. Although this has been observed in literature before, it is not clear what causes this effect, given that primarily slowly varying temporal cues are used for speech recognition.

Finally, although the influence of loudness cues on the absolute levels of the AMDTs cannot be ruled out, the significant correlations that were equally found with the shape-dependent measures of the TMTF, point to the authenticity of these findings.

REFERENCES

Arora, K., Vandali, A., Dowell, R., et al. (2011). Effects of stimulation rate on modulation detection and speech recognition by cochlear implant users. *Int J Audiol, 50*, 123-132.

Bacon, S. P., Viemeister, N. F. (1985). Temporal modulation transfer functions in normal-hearing and hearing-impaired listeners. *Audiology, 24*, 117-134.

Blamey, P., Artieres, F., Baskent, D., et al. (2013). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants: an update with 2251 patients. *Audiol Neurootol, 18*, 36-47.

Boons, K., Debruyne, J. (2011). Evaluatie van objectieve testmethodes voor prelinguaal dove volwassen CI-gebruikers. . *Logopedie - Informatiemedium van de Vlaamse Vereniging voor Logopedisten 24*, 48-52.

Bosman, A. J., Smoorenburg, G. F. (1995). Intelligibility of Dutch CVC syllables and sentences for listeners with normal hearing and with three types of hearing impairment. *Audiology, 34*, 260-284.

Busby, P. A., Tong, Y. C., Clark, G. M. (1993). The perception of temporal modulations by cochlear implant patients. *J Acoust Soc Am, 94*, 124-131.

Cazals, Y., Pelizzone, M., Saudan, O., et al. (1994). Low-pass filtering in amplitude modulation detection associated with vowel and consonant identification in subjects with cochlear implants. *J Acoust Soc Am, 96*, 2048-2054.

Chatterjee, M., Oberzut, C. (2011). Detection and rate discrimination of amplitude modulation in electrical hearing. *J Acoust Soc Am, 130*, 1567-1580.

Dau, T., Kollmeier, B., Kohlrausch, A. (1997). Modeling auditory processing of amplitude modulation. I. Detection and masking with narrow-band carriers. *J Acoust Soc Am, 102*, 2892-2905.

Dorman, M. F., Spahr, A.J. (2006). Speech Perception by Adults with Multichannel Cochlear Implants. In *Cochlear Implants*: Thieme Medical Publishers, Inc.

Erber, N. P., Alencewicz, C. M. (1976). Audiologic evaluation of deaf children. *J Speech Hear Disord, 41*, 256-267.

Francart, T., van Wieringen, A., Wouters, J. (2008). APEX 3: a multi-purpose test platform for auditory psychophysical experiments. *J Neurosci Methods, 172*, 283-293.

Fraser, M., McKay, C. M. (2012). Temporal modulation transfer functions in cochlear implantees using a method that limits overall loudness cues. *Hear Res, 283*, 59-69.

Friesen, L.M., Shannon, R.V., Cruz R.J. (1995). Effects of stimulation rate on speech recognition with cochlear implants. *Audiol Neurotol, 10,* 169-184

Fu, Q. J. (2002). Temporal processing and speech recognition in cochlear implant users. *Neuroreport, 13*, 1635-1639.

Galvin, J. J., 3rd, Fu, Q. J. (2005). Effects of stimulation rate, mode and level on modulation detection by cochlear implant users. *J Assoc Res Otolaryngol, 6*, 269-279.

Galvin, J. J., 3rd, Fu, Q. J. (2009). Influence of stimulation rate and loudness growth on modulation detection and intensity discrimination in cochlear implant users. *Hear Res, 250*, 46-54.

Galvin, J. J., 3rd, Fu, Q. J., Oba, S., et al. (2014). A method to dynamically control unwanted loudness cues when measuring amplitude modulation detection in cochlear implant users. *J Neurosci Methods, 222*, 207-212.

Garadat, S. N., Zwolan, T. A., Pfingst, B. E. (2012). Across-site patterns of modulation detection: relation to speech recognition. *J Acoust Soc Am, 131*, 4030-4041.

Gnansia, D., Lazard, D. S., Leger, A. C., et al. (2014). Role of slow temporal modulations in speech identification for cochlear implant users. *Int J Audiol, 53*, 48-54.

Hacker, M. J., Ratcliff, R. (1979). A revised table of d' for M-alternative forced choice. *Perception & Psychophysics, 26*, 168-170.

Lazard, D. S., Giraud, A. L., Gnansia, D., et al. (2012). Understanding the deafened brain: implications for cochlear implant rehabilitation. *Eur Ann Otorhinolaryngol Head Neck Dis, 129*, 98-103.

Lazard, D. S., Vincent, C., Venail, F., et al. (2012). Pre-, per- and postoperative factors affecting performance of postlinguistically deaf adults using cochlear implants: a new conceptual model over time. *PLoS One, 7*, e48739.

Leek, M. R., Hanna, T. E., Marshall, L. (1992). Estimation of psychometric functions from adaptive tracking procedures. *Percept Psychophys, 51*, 247-256.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *J Acoust Soc Am, 49*, Suppl 2:467+.

Luo, X., Fu, Q. J., Wei, C. G., et al. (2008). Speech recognition and temporal amplitude modulation processing by Mandarin-speaking cochlear implant users. *Ear Hear, 29*, 957-970.

Luo, X., Galvin, J. J., Fu, Q. J. (2010). Effects of stimulus duration on amplitude modulation processing with cochlear implants. *J Acoust Soc Am, 127*, EL23-29.

McDermott, H., McKay, C.M., Vandali, A.E. (1992). A new portable sound processor for the University of Melbourne/Nucleus Limited multielectrode cochlear implant. *J Acoust Soc Am, 91,* 3367-3371

McKay, C. M., Henshall, K. R. (2010). Amplitude modulation and loudness in cochlear implantees. *J Assoc Res Otolaryngol, 11*, 101-111.

Pfingst, B. E. (2011). Effects of electrode configuration on cochlear implant modulation detection thresholds. *J Acoust Soc Am, 129*, 3908-3915.

Pfingst, B. E., Xu, L., Thompson, C. S. (2007). Effects of carrier pulse rate and stimulation site on modulation detection by subjects with cochlear implants. *J Acoust Soc Am, 121*, 2236-2246.

Rosen, S. (1992). Temporal information in speech: acoustic, auditory and linguistic aspects. *Philos Trans R Soc Lond B Biol Sci, 336*, 367-373.

Santarelli, R., De Filippi, R., Genovese, E., et al. (2008). Cochlear implantation outcome in prelingually deafened young adults. A speech perception study. *Audiol Neurootol, 13*, 257-265.

Shannon, R. V. (1992). Temporal modulation transfer functions in patients with cochlear implants. *J Acoust Soc Am, 91*, 2156-2164.

Shannon, R. V., Zeng, F. G., Kamath, V., et al. (1995). Speech recognition with primarily temporal cues. *Science, 270*, 303-304.

Teoh, S. W., Pisoni, D. B., Miyamoto, R. T. (2004a). Cochlear implantation in adults with prelingual deafness. Part I. Clinical results. *Laryngoscope, 114*, 1536-1540.

Teoh, S. W., Pisoni, D. B., Miyamoto, R. T. (2004b). Cochlear implantation in adults with prelingual deafness. Part II. Underlying constraints that affect audiological outcomes. *Laryngoscope, 114*, 1714-1719.

Vandali, A.E. et al. (2000). Speech perception as a function of electrical stimulation rate: using the Nucleus 24 cochlear implant system. *Ear Hear, 21,* 608-624

Viemeister, N. F. (1979). Temporal modulation transfer functions based upon modulation thresholds. *J Acoust Soc Am, 66*, 1364-1380.

Won, J. H., Drennan, W. R., Nie, K., et al. (2011). Acoustic temporal modulation detection and speech perception in cochlear implant listeners. *J Acoust Soc Am, 130*, 376-388.

FIGURE LEGENDS

Fig. 1.TMTFs based on the mean sound-field AMDTs of the 8 prelingually deafened CI users (circles) and the 18 postlingually deafened CI users (triangles) measured in this study, as well as 24 CI users (reverse triangles, data adapted from Won et al. (2011)), and 4 normal-hearing listeners (diamonds, data adapted from Viemeister (1979)). Error bars indicate the 95% confidence interval; the thin lines are the mean exponential fits for the prelingually and postlingually deafened CI users measured in this study.

Fig. 2. Individual sound-field TMTFs of 8 late-implanted prelingually deafened CI users.

Fig. 3. Percentages of prelingually (black bars) and postlingually (white bars) deafened CI users that were sensitive to the different modulation frequencies.

Fig. 4. Mean sound-field TMTFs obtained with short stimuli (500 ms, filled symbols) and long stimuli (1000 ms, open symbols) of 8 prelingually (circles) and 6 postlingually deafened CI users (triangles). Error bars indicate the 95% confidence interval.

Figure 1

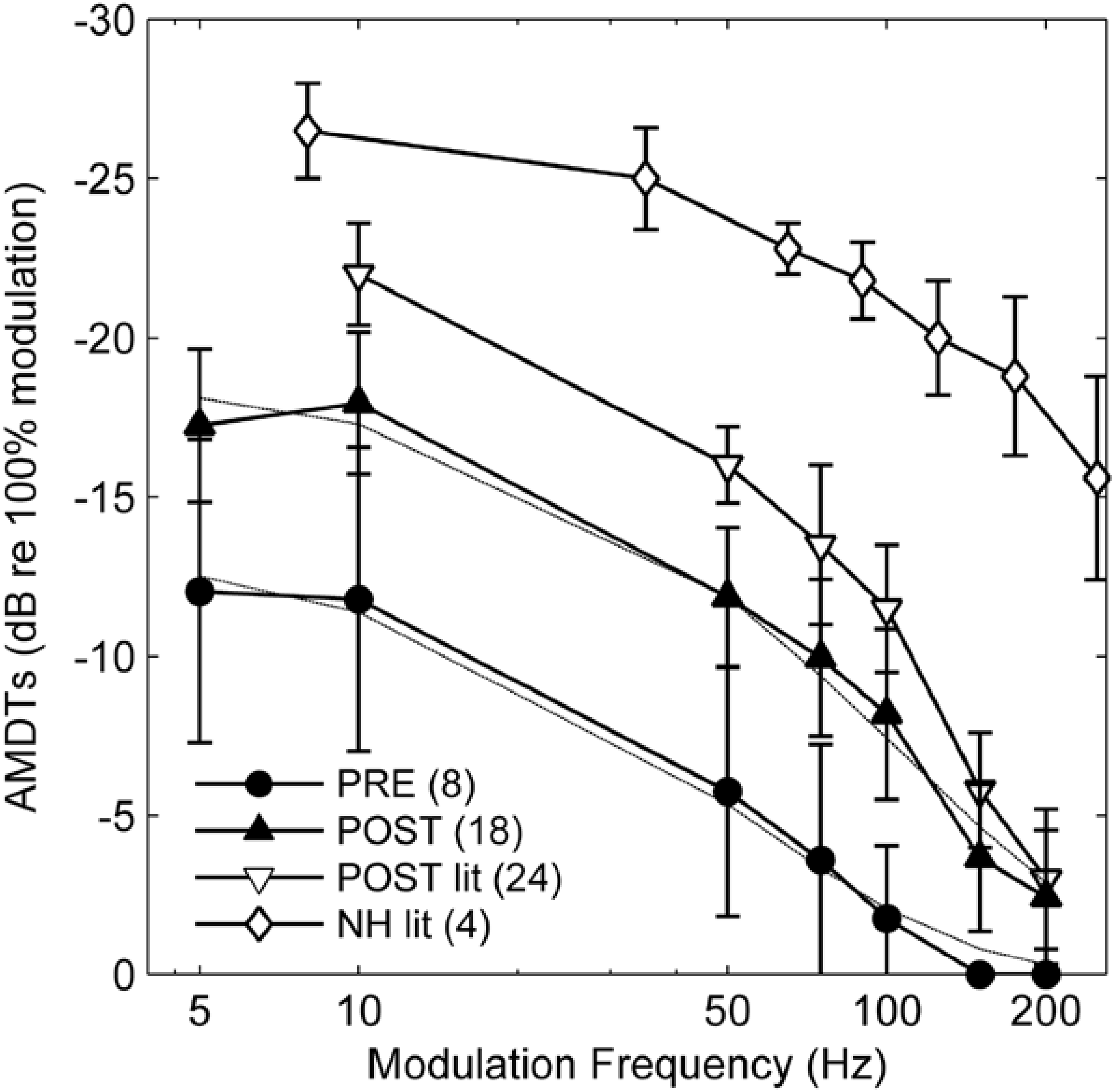

-30
-25
-20
-15
-10
-5
0
AMDTs (dB re 100% modulation)
PRE (8)
POST (18)
POST lit (24)
NH lit (4)
5
10
50
100
200
Modulation Frequency (Hz)

Figure 2

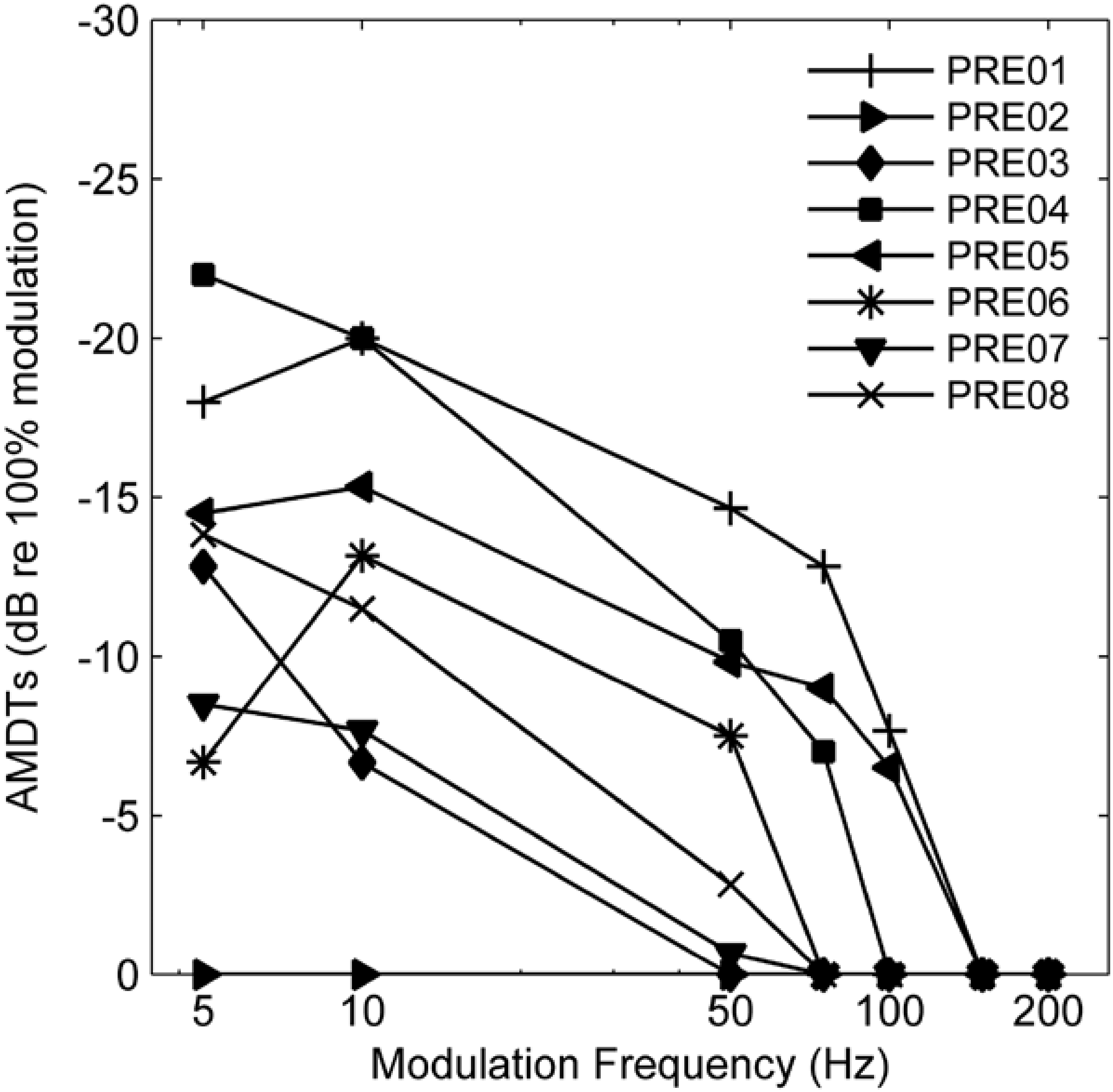
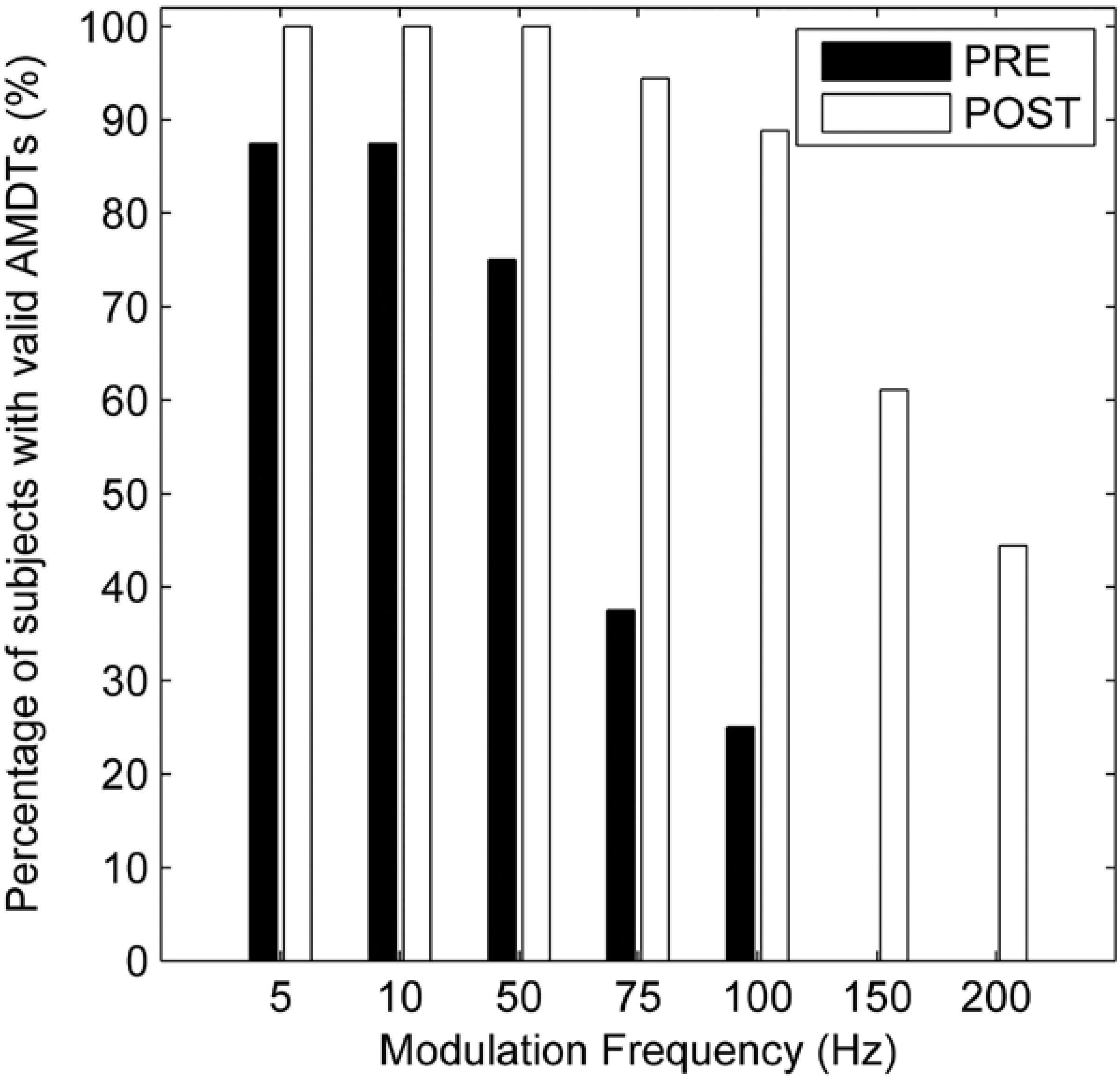

PRE01
PRE02
PRE03
PRE04
PRE05
PRE06
PRE07
PRE08
AMDTs (dB re 100% modulation)
-30
-25
-20
-15
-10
-5
0
5
10
50
100
200
Modulation Frequency (Hz)

Figure 3



PRE
POST
Percentage of subjects with valid AMDTs (%)
0
10
20
30
40
50
60
70
80
90
100
5
10
50
75
100
150
200
Modulation Frequency (Hz)

TABLE 1. Subject Characteristics

Subject	Age (yr)	Age at Onset of Deafness (yr)	Duration of Hearing Loss (yr)	Age at Implantation (yr)	Etiology	Implant Type
PRE01	49	3	42	45	Meningitis	HiRes 90k
PRE02	67	2	63	65	Meningitis	HiRes 90k
PRE03	47	Congenital	40	40	Rubella	HiRes 90k
PRE04	74	0.7	70	71	Meningitis	Nucleus CI512
PRE05	73	Congenital	71	71	Unknown	CONCERTO
PRE06	65	3	58	61	Meningitis	HiRes 90k
PRE07	40	Congenital	37	37	Unknown	HiRes 90k
PRE08	62	0.3	58	59	Meningitis	HiRes 90k
POST01	66	/	35	58	Hereditary	HiRes 90k
POST02	73.5	/	9	64	Hereditary + noise exposure	Nucleus 24R
POST03	72	/	22	53	Otosclerosis	HiRes 90k
POST04	66	/	10	61	Otosclerosis	Nucleus 24RE
POST05	73	/	15	69	Ménière's Disease	Nucleus 24RE
POST06	74	/	39	68	Unknown	HiRes 90k
POST07	61	/	26	55	Otosclerosis	Nucleus 24RE
POST08	79	/	15	74	Hereditary	Nucleus 24RE
POST09	58	/	8	55	Sudden deafness	SONATA
POST10	65	/	23	62	Unknown	HiRes 90k
POST11	56	/	17	52	Hereditary	Nucleus 24 RE
POST12	44	/	15	34	Meningitis	Nucleus 24 R
POST13	80	/	/	75	Otosclerosis	Nucleus 24 RE
POST14	57	/	20	52	Unknown	HiRes 90k
POST15	65	/	15	62	Temporal Bone Fracture	SONATA
POST16	66	/	2	61	Progressive Familiar	HiRes 90k
POST17	60	/	20	53	Hereditary motor and sensory neuropathy	HiRes 90k
POST18	70	/	23	66	Chronic Otitis Media	Nucleus 24RE

TABLE 2. Group Comparisons of Amplitude Modulation Detection Thresholds

	Prelingual (Mean ± SD)	**Postlingual (Mean ± SD)**	***p***
5 Hz	-12.04 ± 6.88	-17.24 ± 5.21	0.044*
10 Hz	-11.79 ± 6.88	-17.95 ± 4.82	0.015*
50 Hz	-5.75 ± 5.63	-11.86 ± 4.70	0.008*
75 Hz	-3.60 ± 5.22	-9.96 ± 5.33	0.009*
100 Hz‡	-1.77 ± 3.29	-8.18 ± 5.81	0.006*†
150 Hz‡	0.00 ± 0.00	-3.67 ± 4.98	0.013*
200 Hz‡	0.00 ± 0.00	-2.43 ± 4.56	0.08*
mean AMDT	-7.0 ± 4.71	-10.8 ± 6.05	0.007
attenuation rate, b ‡	-0.039 ± 0.029	-0.012 ± 0.005	0.021*†
surface area	543 ± 485	1636 ± 881	0.003*†

Amplitude Modulation Detection Thresholds expressed in dB re 100% Modulation
**: significant with $\alpha < 0.05$*
†: significant after Bonferroni correction
‡: Mann-Whitney U test was used instead of independent-samples t-test

TABLE 3. Spearman's Rho (r_s) Correlations Between Measures of Sound-Field Amplitude Modulation Detection and Speech Perception Scores (Mean ± SD; *range*)

	Prelingual				**Postlingual**	**All**
	MTS – word (57 ± 35%) *0 – 100%*	MTS – suprasegmental (80 ± 17%) *52 – 100%*	Speech Tracking (26 ± 13 words/min) *16 – 56 words/min*	CNC (28 ± 34%) *0 – 94%*	CNC (68 ± 20%) *23 – 99%*	CNC (56 ± 32%) *0 – 99%*
AMDT at 5 Hz	-0.786* (p = 0.021)	-0.548 (p = 0.160)	-0.714* (p = 0.047)	-0.862*[c] (p = 0.006)	-0.347 (p = 0.159)	-0.512* (p = 0.008)
AMDT at 10 Hz	-0.826* (p = 0.011)	-0.635 (p = 0.091)	-0.743* (p = 0.035)	-0.829* (p = 0.011)	-0.150 (p = 0.553)	-0.478* (p = 0.013)
AMDT at 50 Hz	-0.838*† (p = 0.009)	-0.659 (p = 0.076)	-0.790* (p = 0.020)	-0.855*† (p = 0.007)	-0.277 (p = 0.266)	-0.601*† (p = 0.001)
AMDT at 75 Hz	-0.791* (p = 0.019)	-0.627 (p = 0.096)	-0.873*† (p = 0.005)	-0.930*† (p = 0.001)	-0.371 (p = 0.130)	-0.645*† (p = 0.000)
AMDT at 100 Hz	-0.764* (p = 0.027)	-0.764* (p = 0.027)	-0.764* (p = 0.027)	-0.814* (p = 0.014)	-0.612*† (p = 0.007)	-0.740*† (p = 0.000)
AMDT at 150 Hz	-	-	-	-	-0.621*† (p = 0.006)	-0.624*† (p = 0.001)
AMDT at 200 Hz	-	-	-	-	-0.316 (p = 0.202)	-0.410* (p = 0.037)
mean AMDT	-0.929*† (p = 0.001)	-0.762* (p = 0.028)	-0.833*† (p = 0.010)	-0.913*† (p = 0.002)	-0.395 (p = 0.104)	-0.673*† (p = 0.000)
attenuation rate, *b*	-0.821* (p = 0.023)	-0.750 (p = 0.052)	-0.857*† (p = 0.014)	-0.778* (p = 0.039)	-0.589*† (p = 0.010)	-0.715*† (p = 0.000)
surface area	0.905*† (p = 0.002)	0.786* (p = 0.021)	0.786* (p = 0.021)	0.875*† (p = 0.004)	0.407 (p = 0.094)	0.688*† (p = 0.000)

**: significant with α < 0.05*
†: significant after Bonferroni correction