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Rate modulation detection thresholds for cochlear implant users

Running Head: Rate modulation detection with cochlear implants

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The perception of temporal amplitude modulations is critical for speech understanding by cochlear implant (CI) users. The present study compared the ability of CI users to detect sinusoidal modulations of the electrical stimulation rate and current level, at different presentation levels (80% and 40% of the dynamic range) and modulation frequencies (10 Hz and 100 Hz). Rate modulation detection thresholds (RMDTs) and amplitude modulation detection thresholds (AMDTs) were measured and compared to assess whether there was a perceptual advantage to either modulation method. Both RMDTs and AMDTs improved with increasing presentation level and decreasing modulation frequency. RMDTs and AMDTs were correlated, indicating that a common processing mechanism may underlie the perception of rate modulation and amplitude modulation, or that some subject-dependent factors affect both types of modulation detection.

I. INTRODUCTION

It is important to maximize the transmission of temporal information to improve speech outcomes for cochlear implant (CI) users. In most CI speech processors, the implanted electrodes are activated with a fixed-rate biphasic pulse train whose current level is modulated by the temporal envelope of the assigned acoustic frequency band. In this study, we examined the potential for using rate modulation (RM) to transmit temporal envelope information. The primary aim of the study was to measure how well RM is perceived by CI users, and how the perception of RM changes with presentation level and modulation frequency. Further, we compared the patterns of results between amplitude modulation (AM) detection and RM detection.

A number of studies have shown that the ability to detect amplitude modulations in temporal envelopes is correlated with speech recognition among CI users (Brochier *et al.*, 2017; De Ruiter *et al.*, 2015; Fu, 2002; Gnansia *et al.*, 2014; Luo *et al.*, 2008; Won *et al.*, 2011). Researchers have investigated the effects of many stimulation parameters on AM detection threshold (AMDT) performance, including current level, stimulation rate, and modulation frequency. All studies agree that AMDTs are best at high current levels and low modulation frequencies (Busby *et al.*, 1993; Chatterjee and Oba, 2005; Chatterjee and Oberzut, 2011; Fraser and McKay, 2012; Fu, 2002; Galvin III and Fu, 2005; Galvin III *et al.*, 2014; Galvin and Fu, 2009; Galvin *et al.*, 2014; Pfingst *et al.*, 2007; Pfingst *et al.*, 2008; Shannon, 1992; Shannon *et al.*, 1995; Zhou and Pfingst, 2014).

Typically, a CI encodes temporal amplitude modulations in each frequency band by varying the current level of a fixed-rate pulse train at the electrode assigned to that frequency band. An electrical hearing model has been developed to explain how central temporal integration can account for many temporal processing phenomena, including AM detection

(McDermott *et al.*, 2003; McKay and McDermott, 1998; McKay *et al.*, 2001; McKay *et al.*, 2013) . In the model, the neural excitation elicited by each pulse is summed in a sliding integration window that weights the activity occurring at different times. The characteristics of the integration window are similar to those in normal acoustic hearing models (Oxenham and Moore, 1994; Oxenham, 2001; Plack *et al.*, 2002), with an equivalent rectangular duration of 7 ms, and exponential functions accounting for forward masking and backward masking.

An implication of this electrical hearing model is that temporal characteristics, such as variations in stimulation rate, could potentially be used to encode acoustic temporal envelopes. Since both RM and AM result in modulation at the output of the temporal integration window, both may produce similar auditory sensations for CI users. A study by Luo and Fu (2007) supported the idea that a temporal integration mechanism underlies RM and AM detection. Their experiment showed that applying AM at the same time as RM, but with different modulation frequencies, interfered with the RM detection. They suggested that RM and AM at least partly share a common coding mechanism in the central auditory system that involves temporal integration.

Other studies suggest the presence of an additional mechanism that is sensitive to interpulse interval information. A study by Fielden *et al.* (2014) found that the discrimination of interpulse intervals did not worsen at low levels compared to high levels. Interpulse interval discrimination refers to a CI user's ability to detect differences in temporal pulse patterns, and requires precise coding of neural spike intervals. In the reference stimulus, the interpulse intervals alternated between 1 ms and 9 ms. In the test stimulus, the interpulse intervals alternated between $1 + \Delta t$ ms and $9 - \Delta t$ ms. Subjects in the study of Fielden *et al.* (2014) were able to differentiate between loudness-balanced pulse trains containing different interpulse intervals equally well at a high presentation level (70% of the dynamic range) and a low presentation level (30% of the dynamic range). The mean noticeable difference for *Δt* at all levels was around 3 ms, corresponding to a pulse train whose interpulse intervals constantly alternated between 4 ms and 6 ms.

RM detection can theoretically be achieved via a central temporal integration mechanism as described above or via a mechanism sensitive to neural spike intervals. Sinusoidal RM detection was measured by Chen and Zeng (2004) in 3 CI users. RMDTs, which were measured as the difference between the peak rate and the central rate, were proportional to the central rate. They increased from 10 Hz at a central rate of 75 pps to 100 Hz at a central rate of 1000 Hz. No effect of level on RMDTs was observed between levels of 70% of the DR and 30% of the DR. Since AM detection greatly deteriorates at lower levels, these results suggest that the central auditory processing involved in the tasks in the Fielden *et al.* (2014) and the Chen and Zeng (2004) studies may not be the same as that involved in an AM detection task. Using RM rather than, or as well as, AM to encode temporal envelopes could be advantageous, because RM may be detectable by an additional or alternative mechanism that encodes neural spike intervals. This additional mechanism may provide a perceptual advantage, if it limits the deterioration of modulation detection with decreasing level.

In this study, RMDTs and AMDTs were measured for presentation levels of 80% DR and 40% DR and modulation frequencies of 10 Hz and 100 Hz. A two-way repeated measures analysis of variance (ANOVA) was used to test the effect of level and modulation frequency on RMDTs and AMDTs. A strong effect of level and modulation frequency was expected for AMDTs, based on results from past literature. It was hypothesized that RMDTs would show the same pattern of level and modulation frequency effects as AMDTs, if they share the same mechanisms. Alternatively, if the mechanism which detects RM utilizes an additional interpulse interval cue, it was hypothesized that RMDTs would not show the same level effects as AMDTs.

II. METHODS

A. Participants

Seven postlingually deafened adult CI users completed the study. Participants were recruited from the clinical population of the Royal Victorian Eye and Ear Hospital. Permission to conduct the studies was obtained from the Human Research and Ethics Committee of the Royal Victorian Eye and Ear Hospital, and each participant provided written informed consent. Participants were tested over the course of three to four sessions of 2 hours. Details about the participants are described in *Table I.*

TABLE I. Relevant information about the cochlear implant users who participated in the study.

	Gender	Age (years)	Duration of hearing loss before implantation (years)	Duration of implant use (years)	Implant Type	Etiology
P1	Male	78	23	15	CI24M	Genetic
P2	Male	75	42	7	CI24RE	Unknown, progressive hearing loss
P3	Male	57	23	7	CI24RE	Unknown, Genetic
P4	Female	65	16	5	CI24RE	Unknown, progressive hearing loss
P5	Male	44	5	5	CI512	Unknown, Genetic
P6	Male	70	13	7	CI24RE	Unknown, Genetic
P7	Female	70	60	3	CI24RE	Measles

B. Equipment

Psychophysical procedures were performed and behavioural responses were recorded using ImpResS software. The software interfaced with the implant using a SPEAR research processor (Azadpour and McKay, 2012; Fraser and McKay, 2012). Pulse parameters were defined in the software and sent directly to the implant using a radio frequency link. The responses of each participant were collected using a response box.

C. Stimuli and Procedure

The stimuli consisted of biphasic pulse trains, each 500-ms in duration. Each biphasic pulse had a phase duration of 26 μs and an interphase gap of 8.4 μs. The mode of stimulation was monopolar (MP1 + 2), and the active electrode was electrode 14. A reference stimulation rate of 1200 pps was used for all stimuli. The electrical current values are reported in clinical current-level units (CL steps). For the CI24M and CI512 implants each CL step represents a 0.176 dB change in current, and for the CI24RE implant each CL step represents a 0.157 dB change in current.

The maximum comfortable loudness (MCL) for the 1200 pps unmodulated stimulus was found by presenting the stimulus with an ascending sequence of single CL steps. The subject was instructed to indicate on a loudness category scale the point at which the stimulus was ‘too loud.’ The MCL was set as the level one CL step below the ‘too loud’ point. The threshold level (T-level) for the same stimulus was measured using an adaptive two-interval forced choice, two-down one-up procedure. In each trial, the participant was presented with two 500-ms intervals: one of silence, and one containing a 1200-pps pulse train. One of two buttons on the response box was lit during each time interval. The participant was asked to identify the interval that contained the sound by pressing the associated button, and to guess when they were unsure. This procedure was carried out until 8 CL reversals were obtained.

Until the first two reversals, a step size of 4 CL steps was used, and for the last six reversals, a step size of 2 CL steps was used. The threshold was calculated as the mean of the last six reversals.

1. Reference Stimulus

The level for the unmodulated, 1200 pps reference stimulus was set using the measurements of MCL and T-level. Dynamic range (DR) was calculated as the difference between MCL and T-level in CL units. For the ‘high level’ stimuli, the reference stimulus was set at a current level of 80% of the DR. For the ‘low level’ stimuli, the reference stimulus was set at a current level of 40% of the DR.

2. Rate Modulated Stimuli

For the rate modulated stimuli (example shown in Figure 1), the stimulation rate was modulated sinusoidally on a ratio scale around the central stimulation rate of 1200 pps. At maximum modulation depth used in this experiment the rate varied between 2400 pps (double the central rate) and 600 pps (half the central rate). At zero modulation depth, the rate stayed fixed at 1200 pps.

Modulation frequencies of 10 Hz and 100 Hz were used. These modulation frequencies were chosen because they represent temporal envelope cues at 10 Hz, and periodicity cues at 100 Hz (Rosen, 1992). Since the stimulus duration was 500 ms, the 10 Hz modulated stimuli went through exactly 5 cycles between highest and lowest rate, and the 100 Hz modulated stimuli went through exactly 50 cycles between highest and lowest rate. RM was applied using Equation 1:

$$Rate = Central\ Rate \times 2^{ModDepth \cos(2 \pi t\, fMod)} \qquad (1)$$

The *ModDepth* variable represents the modulation depth and the *fMod* variable represents modulation frequency. At each time instant in the stimulus, the calculated rate was inverted to find the period. The biphasic pulse duration (2*pulse width + interphase gap) was subtracted from the period, giving a calculated interpulse delay (silent delay between pulse offset and next pulse onset). ImpResS software built the pulse trains pulse-by-pulse, so the same biphasic pulses were used throughout the stimulus while varying the interpulse interval to control the rate. A set of stimuli that differed in values of the *ModDepth* variable between 1 (leading to rate variation between double and half the reference rate) and 0 (no modulation) were used to obtain psychometric functions for RMDTs for each participant and each condition.

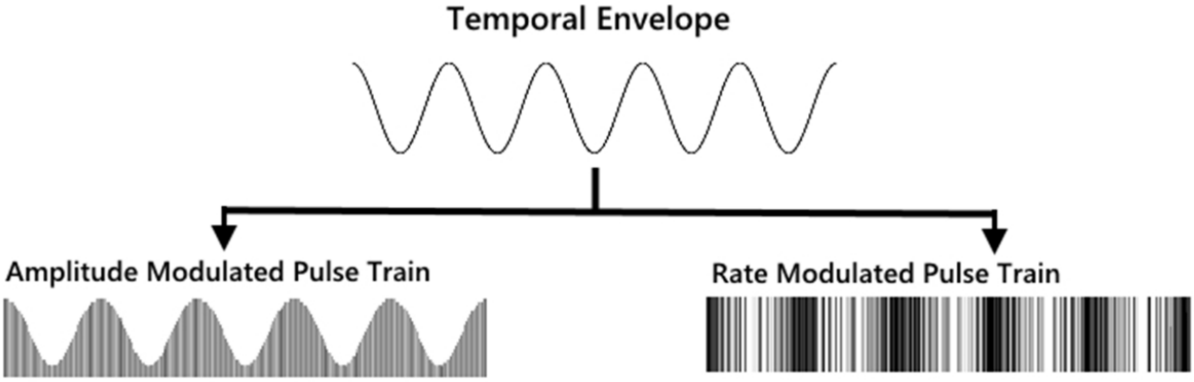

Figure 1. Sinusoidal temporal envelopes were encoded using amplitude modulated pulse trains (left) and rate modulated pulse trains (right).

3. Amplitude Modulated Stimuli

For amplitude modulated stimuli (example shown in Figure 1) a fixed stimulation rate of 1200 pps was used. The electrical current (in µA) was modulated sinusoidally. Again, modulation frequencies of 10 Hz and 100 Hz were used. Sinusoidal AM was applied using the Equation 2:

$$Current = Max\ Current - ModDepth\ (1 - \cos(2\,\pi\ t\ fMod)) \qquad (2)$$

As with the rate modulated stimuli, the *ModDepth* variable represents the modulation depth and the *fMod* variable represents modulation frequency. The peak-to-peak modulation depth was first set in current level (CL) steps to avoid quantization of *ModDepth*, and then peak and valley CLs were converted to electrical current (in µA) to calculate currents for all pulses. The peak-to-peak modulation depth was varied between 1 and 60 CL steps to obtain psychometric functions for AMDTs for each subject and each condition.

4. Loudness Balancing

Modulated stimuli are perceived as louder by CI users than unmodulated stimuli with the same average current (Chatterjee and Oberzut, 2011; Galvin III *et al.*, 2014; McKay and Henshall, 2010). Therefore, it was necessary to loudness balance each modulated stimulus to the unmodulated reference stimulus for each condition. Each modulated stimulus of differing modulation depth was loudness balanced to the unmodulated reference stimulus. During the experiments, the reference stimulus was set to the level corresponding to either 80% or 40% of the DR, and the loudness-balanced level was applied to the modulated stimuli.

Each loudness-balanced level was measured using an adaptive two-interval forced choice, one-up one-down procedure. In each trial, the participant was presented with two 500-ms intervals: one containing the modulated stimulus, and one containing the unmodulated reference stimulus. One of two buttons on the response box was lit during each time interval. The participant was asked to identify the interval that sounded louder by pressing the associated button, and to guess when they were unsure. Two rounds of loudness balancing were measured for each modulated stimulus. In the first round, the level of the reference stimulus was fixed at 80% or 40% DR. If the modulated stimulus was chosen as the louder sound, its level was reduced, and if it was not chosen as the louder sound, its level was increased. This process was continued until 8 reversals were obtained. The step size was 4

CL steps until the first two reversals, and 2 CL steps for the last six reversals. In the second round, the modulated stimulus was fixed at the measured loudness-balanced level from the first round, and the process was repeated with the reference stimulus being adjusted in each trial until 8 reversals were obtained. In each round, the difference between the reference level and modulated level was calculated. The final loudness-balanced level for the modulated stimulus was calculated from the average difference between modulated and unmodulated stimuli in the two rounds.

5. Applying Level Jitter

In addition to loudness balancing, level jitter was applied to remove the influence of any remaining loudness cues. The necessary current level jitter was calculated according to the standard error between the two rounds in the loudness balancing procedure, according to a method explained in Dai and Micheyl (2010) when using a three-interval oddity forced choice task. Separate jitter values were calculated for each presentation level, modulation frequency, modulation depth, and modulation method. The maximum jitter value across all modulation depths in each level/modulation frequency condition was used when obtaining the psychometric function. Across all subjects and conditions, the minimum jitter value used was ±1 CL step, and the maximum jitter value used was ±4 CL steps.

6. Determining Detection Thresholds

The method of constant stimuli was used to obtain psychometric functions for each carrier level, modulation frequency, and modulation method condition. Initially, the largest modulation depth to be tested in each condition was determined by playing the reference and modulated stimuli continuously in alternation, and incrementally raising the modulation depth until the participant could easily hear the difference between the two sounds. Then three additional smaller modulation depths were chosen between that modulation depth and zero modulation (for a total of four modulation depths), and each of the four modulated stimuli were then loudness balanced to the reference.

For each condition, two rounds of testing were completed. In each round, 10 trials at each of the four loudness-balanced modulation depths were completed, for a total of 40 trials. These 40 trials were randomized in order. Overall, 80 trials were completed for each condition (two rounds of 40 trials).

A three-interval forced choice task was used to assess modulation detection at the different modulation depths. Three stimuli in each trial were separated by 500-ms silent periods. One interval, randomly selected, contained the loudness-balanced modulated stimulus, while the other two intervals contained unmodulated reference stimuli. The participant was instructed to choose the interval which contained the different stimulus, and to guess if they could not easily differentiate between the three stimuli. For each modulation depth and each condition, a score of percent correct out of 20 trials was obtained. The modulation detection threshold was defined as the modulation depth that led to 70% correct discrimination, estimated by linear interpolation.

If the four chosen modulation depths did not complete the psychometric function after round 1 (i.e. there were not two modulation depths that led to 70% correct discrimination or greater, and two modulation depths that led to worse than 70% correct discrimination), a smaller (more difficult) or larger (less difficult) modulation depth was loudness balanced and added to round 2, as necessary. In that case, in the second round, 20 trials were completed for the new modulation depth, rather than 10 for the other modulation depths that had already been tested in the first round. When scores exceeded 70% correct at 1 CL modulation depth, the theoretical chance score of 33% at a modulation depth of 0 was used to interpolate a fraction of a CL for the 70% correct point.

III. RESULTS

Psychometric functions for AM and RM detection for each participant in each condition are provided in the supplementary materials.

A. Rate Modulation Detection Thresholds

Figure 2 shows RMDTs for different presentation levels and modulation frequencies. The units refer to the ratio between the highest rate and lowest rate at the RMDT. At maximum modulation depth, the ratio was 4 (2400 pps/600 pps), and at the minimum modulation depth, the ratio was 1 (1200 pps/1200 pps). P1 found the task too difficult to complete for either modulation frequency or modulation method at 40% DR. These data were denoted as ‘missing values’ in the statistical analysis. At 40% DR for the 100 Hz modulation frequency, P4 achieved a score of 70% and P7 got a score of 65% at the highest modulation depth (ratio of 4). For the subsequent analysis, both were assigned an RMDT at the ratio of 4. A two-way repeated measures ANOVA, using a general linear model with subject as a random factor, was used to assess the effect of presentation level and modulation frequency on RMDTs. A significant effect of level (F(1,6) = 10.03, p = 0.006) was found, with higher levels leading to better RMDTs. The effect of modulation frequency was also significant (F(1,6)=9.00, p = 0.008), with better RMDTs at the lower modulation frequency of 10 Hz.

The ANOVA revealed a significant interaction effect between presentation level and modulation frequency (F(1,6) = 5.38, p = 0.034). The interaction was further analyzed by investigating the effect of modulation frequency separately for levels of 80% and 40% DR, using a post-hoc paired t-test. At 80% DR, there was no significant effect of modulation frequency on RMDTs (t = 1.10, p = 0.314), and at 40% DR, the effect of modulation frequency was modestly significant (t = 2.55, p = 0.051). The effect of level was also analyzed separately for each modulation frequency using a post-hoc paired t-test. A significant effect of level was found at both modulation frequencies of 10 Hz (t = 2.61, p = 0.048) and 100 Hz (t = 3.15, p = 0.025). Overall, the interaction was due to the effect of level being greater at the higher modulation frequency and the effect of frequency being greater at the lower level.

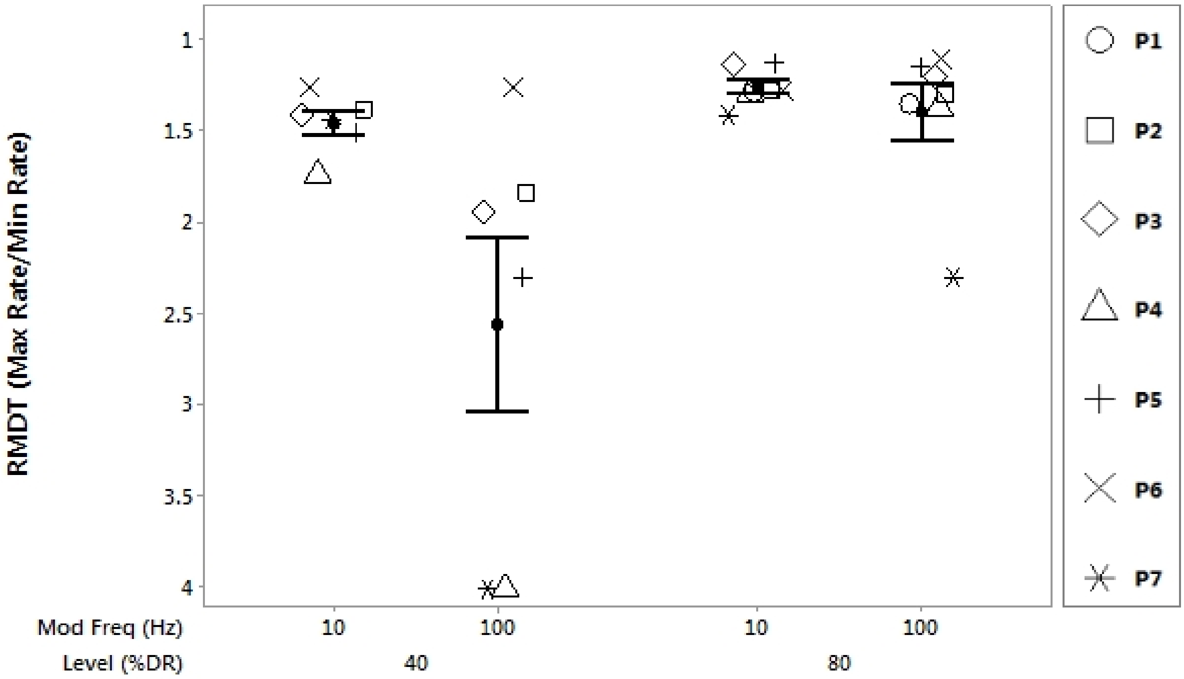

Figure 2. Rate modulation detection thresholds for different modulation frequencies and presentation levels. Individual subject data is shown along with the means in each condition (including P1 at 80% DR). Error bars represent ±1 standard error of the mean for each condition.

B. Amplitude Modulation Detection Thresholds

Figure 3 shows AMDTs for different presentation levels and modulation frequencies. Each participant’s AMDT was calculated as the modulation depth at the detection threshold (in peak-to-peak current level steps), divided by their dynamic range, giving units in percentage of the dynamic range (%DR). A two-way repeated measures ANOVA, using a general linear model with subject as a random factor, was used to analyze the effect of presentation level and modulation frequency on AMDTs. Significant effects of presentation level (F(1,6) = 18.31, p = 0.001) and modulation frequency (F(1,6) = 7.68), p = 0.014) were found, with better AMDTs at the higher presentation level and lower modulation frequency.

Ceiling effects were encountered for AMDTs at the high presentation level of 80% DR, due to the quantization of CL steps. The majority of subjects obtained a score greater than 70% discrimination at the lowest modulation depth (1 CL step) for modulation frequencies of 10 Hz (5 out of 7 subjects) and 100 Hz (4 out of 7 subjects) at 80% DR, and thus were assigned MDTs of less than 1 CL step. Therefore, the effect of modulation frequency at the higher level could not be assessed separately from the effect of modulation frequency at the lower level, making interaction effects difficult to assess.

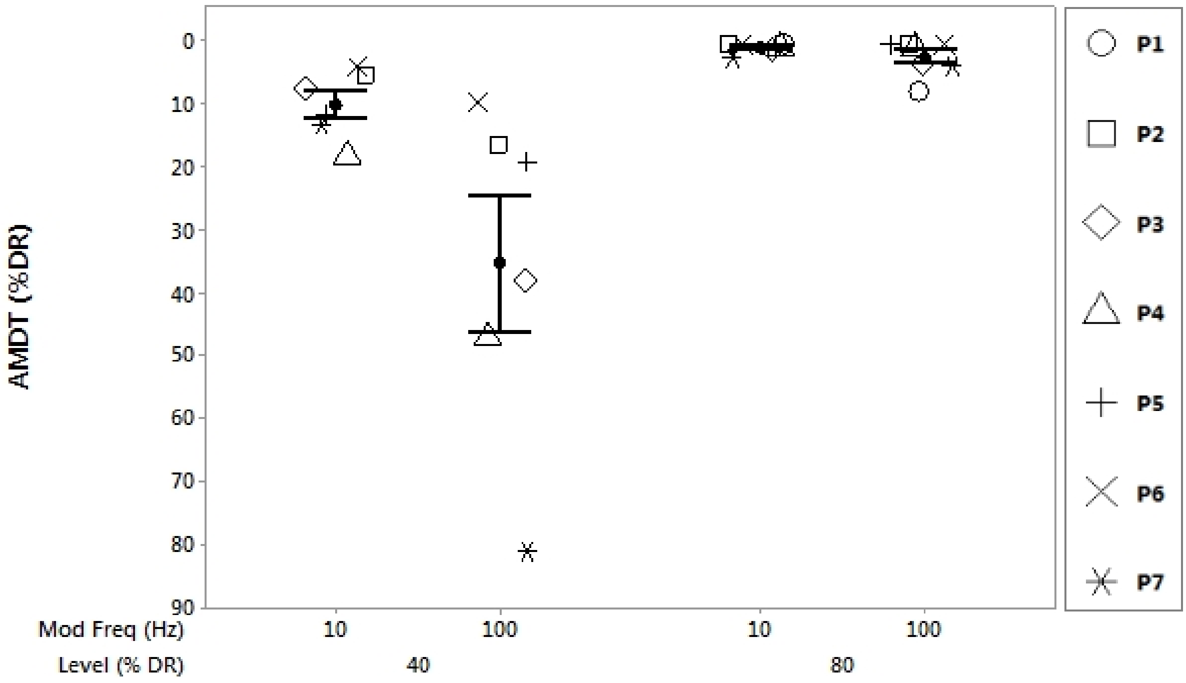

Figure 3. Amplitude modulation detection thresholds for different modulation frequencies and presentation levels. Individual subject data is shown along with the means in each condition (including P1 at 80% DR). Error bars represent ±1 standard error of the mean for each condition.

C. Correlation between RMDTs and AMDTs

Figure 4 shows the Pearson correlation analysis of RMDTs and AMDTs. Significant correlations were found between RMDTs and AMDTs at 40% DR and modulation frequencies of 10 Hz (R = 0.915, P = 0.010) and 100 Hz (R = 0.856, P = 0.030). For the data at 80% DR, no correlations were found, possibly due to ceiling effects for the AM stimuli. The strong relationship between RMDTs and AMDTs suggests that a common mechanism might be used to perceive RM and AM, or alternatively, that other subject-dependent factors influence both types of MDT.

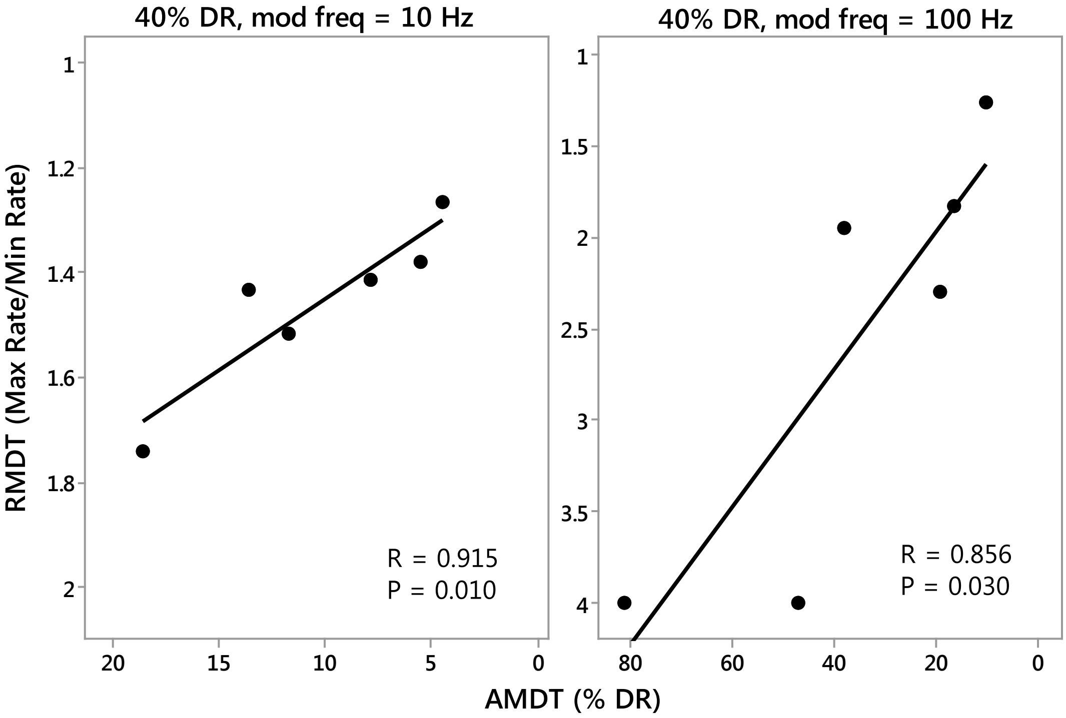

Figure 4. Pearson correlation analysis between RMDTs and AMDTs at 40% DR and modulation frequencies of 10 Hz (left panel) and 100 Hz (right panel).

D. Correlation between Dynamic Range and MDTs

Significant correlations were found between the electrical dynamic range and the RMDT at 40% DR with a modulation frequency of 10 Hz (R = 0.900, P = 0.014) and 100 Hz (R = 0.944, P = 0.005). The Pearson correlation analysis is shown in Figure 5. Participants with a higher dynamic range had better RM sensitivity at low levels. However, no significant correlations were found between RMDTs and DR at higher levels for modulation frequencies of 10 Hz (p = 0.471) or 100 Hz (p = 0.291).

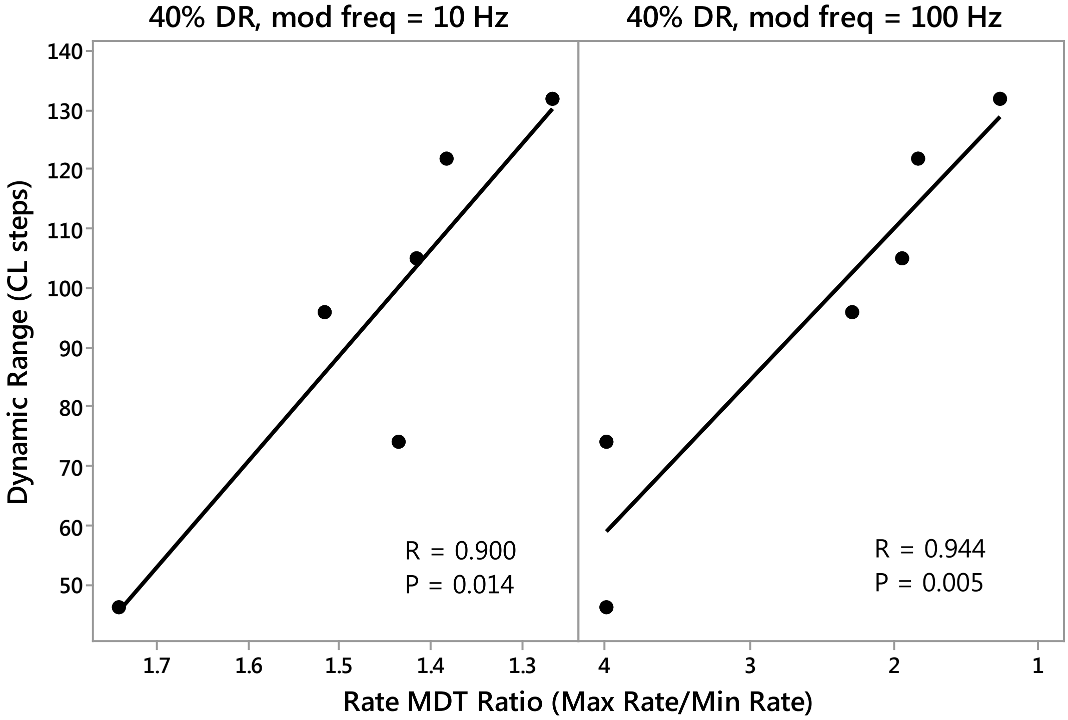

Figure 5. Pearson correlation analysis between electrical dynamic range and RMDTs at 40% DR and modulation frequencies of 10 Hz (left panel) and 100 Hz (right panel).

Similarly, a strong correlation was found between the electrical dynamic range and the AMDT at 40% DR with a modulation frequency of 10 Hz (R = 0.988, P < 0.001). At a modulation frequency of 100 Hz, there was a trend towards a correlation, but it did not reach significance (R = 0.709, P = 0.114). The Pearson correlation analysis is shown in Figure 6. Due to ceiling effects, the correlations were not analyzed at 80% DR.

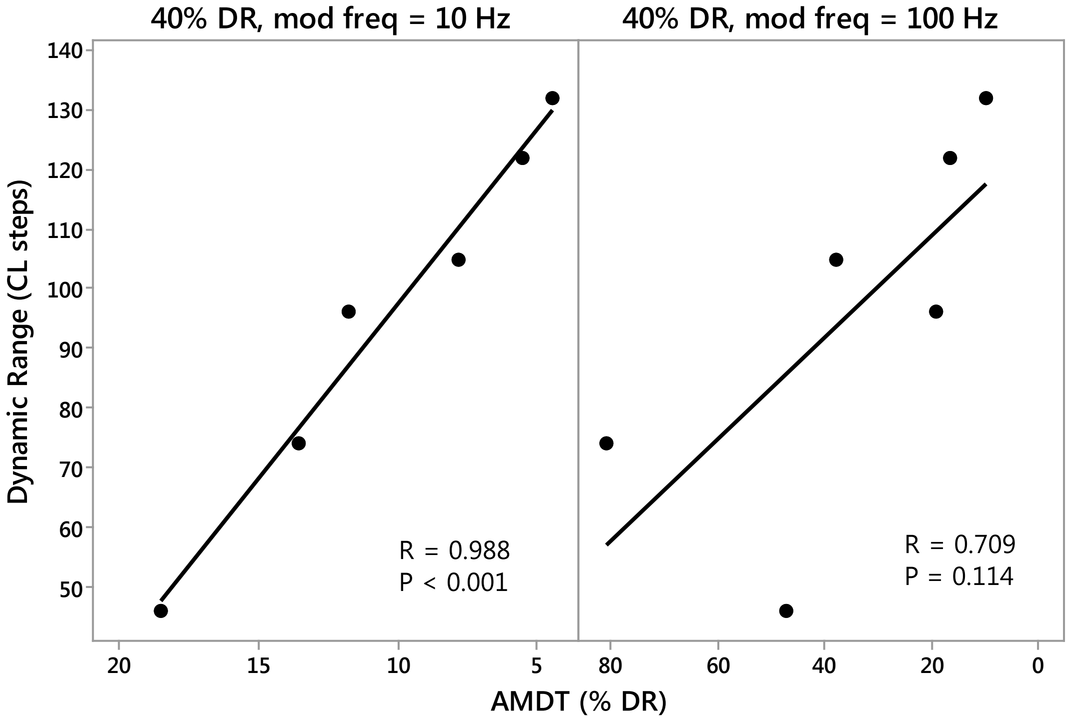

Figure 6. Pearson correlation analysis between electrical dynamic range and AMDTs at 40% DR and modulation frequencies of 10 Hz (left panel) and 100 Hz (right panel).

When Bonferonni corrections were applied to account for six multiple comparisons, only the correlation between DR and RMDT at 40% DR and 10 Hz became non-significant.

IV. DISCUSSION

The results showed that temporal envelopes can be transmitted through RM. Participants were able to differentiate between loudness-balanced fixed-rate pulse trains and rate modulated pulse trains. RMDTs exhibit similar rate and level effects to AMDTs, with modulation sensitivity increasing significantly at high presentation levels and low modulation rates.

It was not possible to directly compare RMDTs and AMDTs in absolute terms, due to the fundamental differences between the units in which the two measures were defined. However, the similar effects of level and modulation frequency between the two modulation methods suggests that a common mechanism might be used by the central auditory system to perceive AM and RM, consistent with the conclusions of Luo and Fu (2007). Furthermore, RMDTs were strongly correlated with AMDTs, demonstrating that participants who were most sensitive to RM were also most sensitive to AM.

There was not a clear advantage for either modulation method over the other for any specific conditions, as MDTs for both methods were similarly affected by level and modulation frequency. The similarities between AM and RM detection indicate that the main factor when perceiving temporal envelopes with CIs is the time-varying charge being delivered by the electrode, more so than the method by which the charge delivery is temporally modulated (by varying the current amplitude or the pulse rate). If the mechanism that detects RM utilizes an additional interpulse interval cue, it was hypothesized that the effect of level on RMDTs and AMDTs would be different. However, both RM and AM were affected similarly by presentation level. This result is consistent with a common mechanism that involves central temporal integration.

Fielden *et al.* (2014) showed that the perception of interpulse intervals did not worsen at low levels compared to high levels. However, the data from the present study show that RMDTs do worsen with lower levels. One main factor that may explain this discrepancy was the difference in methodology between the two experiments. As mentioned in the introduction, Fielden *et al.* (2014) found that subjects could distinguish between pulse trains which alternated interpulse intervals between 1 ms and 9 ms from pulse trains which alternated interpulse intervals between 4 ms and 6 ms. This task is roughly similar to distinguishing a pulse train of 100 pps (constant interpulse interval of 10 ms) from a pulse train of 200 pps (constant interpulse interval of 5 ms). Therefore, the results of Fielden *et al.* (2014) may be due to the relatively good rate discrimination at low rates. Since the present study uses a much higher central stimulation rate of 1200 pps, with rates never dropping below 600 pps, it is less likely that subjects could utilize the changing interpulse intervals.

Chen and Zeng (2004) observed a significant effect of modulation frequency on RMDTs at central rates of 500 pps and 1000 pps, consistent with the results of this study at a central rate of 1200 pps. However, they found no significant effect of level on RMDTs, in contrast to the results of the present study. A potential explanation for this difference could be that Chen and Zeng (2004) used mostly much lower central stimulation rates (75, 125, 250, 500, and 1000 pps) than the present study. Therefore, if subjects were able to utilize cues from the longer interpulse intervals (consistent with the use of the cues in the Fielden *et al.* (2014) study) and those cues did not deteriorate with level, as proposed by Fielden *et al.* (2014), then an overall lack of effect of level may have been found in that study because of the low rates used.

Considering that the results of Chen and Zeng (2004) and Fielden *et al.* (2014) may have been due to low central stimulation rates, the present study provides evidence that RM and AM utilize a common temporal integration mechanism at higher central rates (>1000 pps), and that the additional interpulse interval cue in RM stimuli may only be useful at lower central rates.

The electrical dynamic range was correlated with both RMDTs and AMDTs at low levels, demonstrating another similarity between RM and AM. When AMDTs were expressed in CL steps, without normalizing with respect to DR, they were not correlated with DR. This non-correlation suggests that loudness growth slope is not an important determinant of AMDTs (in CL) at the low modulation frequencies that were tested in this study, a result analogous to the non-correlation of intensity difference limens with DR (Kreft *et al.*, 2004). The significant correlation of AMDTs (in %DR) found in this study could therefore be due to the normalization to the %DR itself. The correlation of RMDTs with DR is of greater interest since there was no normalization with respect to DR. The fact that both RMDTs and AMDTs (in %DR) are correlated with DR may explain why the two detection thresholds are highly correlated with each other.

Several factors could influence the relationship between RM sensitivity and DR, including spiral ganglion nerve (SGN) density, the temporal properties of the surviving SGNs, or the quality of the electrode-neuron interface. Previous research has suggested that higher DRs are associated with higher SGN cell counts. In two experiments relating psychophysical data to histopathology in monkeys implanted with CIs, it was shown that DR and SGN count were correlated (Pfingst *et al.*, 1981; Pfingst and Sutton, 1983). In post-mortem histopathological examinations of five implanted human cochleas, Kawano *et al.* (1998) found that subjects with higher DRs also had higher SGN survival. However, Khan *et al.* (2005), also using post-mortem histopathological examinations, found a negative correlation between SGN counts and DR in two of five subjects, and no relation between SGN and DR in the other three. It is likely that the relation between SGN survival and psychophysical measures, such as DR and RMDT, extends beyond the number of SGNs, and also relies upon the temporal and intensity coding properties of those neurons (Pfingst *et al.*, 2015). Kawano *et al.* (1998) also showed that the quality of the electrode-neural interface influenced DR, observing higher dynamic ranges as the distance to the modiolus was reduced. These results are consistent with those of (Cohen *et al.* (2001)), who used plain film radiographs to estimate the electrode positions in three CI recipients, and then performed psychophysical measurements on those electrodes. It was found that electrodes closer to the modiolus had higher DRs, and that people had better current level discrimination at these electrodes. If these relations between DR, SGN survival, and electrode-neural interface apply for the subjects in our experiment, then a combination of these factors could contribute to better RMDTs and AMDTs for subjects with higher DRs. For example, a higher density of SGNs with good temporal coding properties could lead to better RMDTs because there would be more neurons available to respond to each individual pulse in the RM stimulus. Therefore, the modulations would be more accurately represented by the auditory system.

V. CONCLUSIONS

RM was used to encode sinusoidal temporal envelopes on single-electrode pulse trains. CI users were able to perceive RM at modulation frequencies of 10 Hz and 100 Hz at presentation levels of 80% and 40% DR. Both RMDTs and AMDTs improved with increasing presentation level and decreasing modulation frequency. The similar pattern of results, along with the strong correlation between RMDTs and AMDTs, indicates that a common temporal integration mechanism underlies the perception of RM and AM. RMDTs and AMDTs were both correlated with DR, suggesting that some subject-dependent factors, related to DR, might influence the correlation between RMDTs and AMDTs.

VI. ACKNOWLEDGEMENTS

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See supplementary material at [URL will be inserted by AIP] for psychometric functions for AM and RM detection for each participant in each condition.

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