Research Article

Temporal Modulation Detection Depends on Sharpness of Spatial Tuning

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ABSTRACT

Prior research has shown that in electrical hearing, cochlear implant (CI) users' speech recognition performance is related in part to their ability to detect temporal modulation (i.e., modulation sensitivity). Previous studies have also shown better speech recognition when selectively stimulating sites with good modulation sensitivity rather than all stimulation sites. Site selection based on channel interaction measures, such as those using imaging or psychophysical estimates of spread of neural excitation, has also been shown to improve speech recognition. This led to the question of whether temporal modulation sensitivity and spatial selectivity of neural excitation are two related variables. In the present study, CI users' modulation sensitivity was compared for sites with relatively broad or narrow neural excitation patterns. This was achieved by measuring temporal modulation detection thresholds (MDTs) at stimulation sites that were significantly different in their sharpness of the psychophysical spatial tuning curves (PTCs) and measuring MDTs at the same sites in monopolar (MP) and bipolar (BP) stimulation modes. Nine postlingually deafened subjects implanted with Cochlear Nucleus® device took part in the study. Results showed a significant correlation between the sharpness of PTCs and MDTs, indicating that modulation detection benefits from a more spatially restricted neural activation pattern. There was a significant interaction between stimulation site and mode. That is, using BP stimulation only improved MDTs at stimulation sites with broad PTCs but had no

effect or sometimes a detrimental effect on MDTs at stimulation sites with sharp PTCs. This interaction could suggest that a criterion number of nerve fibers is needed to achieve optimal temporal resolution, and, to achieve optimized speech recognition outcomes, individualized selection of site-specific current focusing strategies may be necessary. These results also suggest that the removal of stimulation sites measured with poor MDTs might improve both temporal and spectral resolution.

Keywords: modulation detection thresholds, psychophysical tuning curves, spatial selectivity of neural excitation, stimulation rate, stimulation mode, focused stimulation

INTRODUCTION

Modern cochlear implants (CIs) use envelope-based sound processing strategies, where the primary information extracted from the acoustic signal is the channel-specific slowly varying amplitudes (temporal envelope). The fine structure of the signal is discarded and replaced with constant-rate carriers that are unrelated to the signal. The spectral resolution of modern CIs may be limited by factors such as the number of physical channels (active electrodes), electrode-neuron interface, and the condition of the auditory nerve. It has been shown that, because of these limiting factors, the average number of effective channels was only approximately eight (Friesen et al. 2001). Due to the limited spectral resolution, CI users rely heavily on information within the temporal envelope. The slow-varying modulations (<20 Hz)

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provide useful speech information, especially for consonants (Fu 2002; Rosen 1992; Xu et al. 2005).

Modulation detection threshold (MDT) is a psychophysical measure that assesses an individual's ability to detect temporal modulation. In CI users, MDTs have been shown to vary with stimulation parameters and stimulation sites (Galvin and Fu 2005, 2009; Green et al. 2012; McKay and Henshall 2010; Zhou and Pfingst 2012). MDTs were found to be consistently better when carrier rates were lower (Galvin and Fu 2005, 2009; Green et al. 2012; McKay and Henshall 2010). In theory, transmission of the temporal envelope cue and thus its detection should be improved by increasing the carrier rate of the signal, since a higher carrier rate would better sample the temporal envelope. However, multiple studies have shown the opposite, especially at lower intensity levels. These patterns of the results were attributed to the slower growth of loudness associated with higher stimulation rates and wider dynamic ranges (DRs), where a larger change in current was necessary to elicit a perceptible change in loudness (Galvin and Fu 2009; Green et al. 2012). Modulation detection has also been shown to depend on stimulation level (e.g., Galvin and Fu 2005, 2009; Galvin et al. 2014; Luo et al. 2008; McKay and Henshall 2010). MDTs generally improve with increasing level up to 70 % DR, beyond which there is no further improvement (Fu 2002; Pfingst et al. 2008). Previous studies have not reported consistent effects of stimulation mode on MDTs at equal loudness. Improvement in MDT in narrow bipolar (BP) stimulation relative to wide BP or monopolar (MP) stimulation was seen at single stimulation sites in some individuals but not others (e.g., Galvin and Fu 2005). MDT averaged across the entire electrode array was comparable between MP and BP stimulation in most of the subjects tested by Pfingst et al. (2008), with a few outliers in both tails of the distribution.

In CI users, temporal modulation sensitivity has been shown to predict speech performance (e.g., Fu 2002; Garadat et al. 2012; Luo et al. 2008). Fu (2002) and Luo et al. (2008) showed a strong correlation between subjects' speech recognition performance and MDTs averaged across stimulation levels at a single stimulation site in the middle of the electrode array. More recent studies showed that CI users' modulation detection ability was not equal across the electrode array (Garadat et al. 2012, 2013; Zhou and Pfingst 2012). Moderate correlations have also been reported between modulation sensitivity averaged across the stimulation sites and speech recognition performance (e.g., Garadat et al. 2013). In addition, speech performance was significantly better when using stimulation sites with relatively good rather than poor modulation sensitivity (Garadat et al. 2012).

Deactivating or increasing the minimum stimulation levels on sites with poor MDTs has also been shown to improve speech recognition (Garadat et al. 2013; Zhou and Pfingst 2012, 2014).

It is not entirely clear what contributes to the across-site variations in MDTs. Studies that deactivated poor-MDT stimulation sites attributed better speech performance to an overall improvement in temporal acuity (e.g., Garadat et al. 2013). A few other investigators developed fitting strategies in which the sites for deactivation were selected based on spatial measures. This was done by identifying electrodes distant from the modiolus using CT-based 3D reconstructions of implanted cochlea (Labadie et al. 2016) or electrodes estimated to produce broad neural excitation as assessed by psychophysical measures (Zhou 2016). In these studies, deactivation of electrodes, where broad current or neural excitation spread might have occurred (and most likely, greater channel interaction), also improved speech recognition (Labadie et al. 2016; Zhou 2016). As site removal based on MDT and the spatial measures both resulted in improved speech recognition, it led to the question of whether stimulation sites with poor MDTs were also those that produced broad neural excitation.

There are a few studies that suggest that temporal sensitivity, such as that measured in strength-duration functions (threshold vs. phase duration), forward-masking recovery, and multipulse integration functions (threshold vs. stimulation rate), benefits from broad stimulation of the cochlea (e.g., Brown et al. 1996; Miller et al. 2009; Smith and Finley 1997; Zhou and Dong 2017; Zhou and Pfingst 2016). Faster forward-masking recovery, steeper strength-duration functions, and greater multipulse integration were found in psychophysically estimated broader neural excitation patterns or when measured with MP relative to BP electrode configuration. If modulation detection sensitivity is mediated by a similar process as the loudness-related temporal measures discussed above, broad stimulation should similarly facilitate rather than reduce modulation sensitivity. Some evidence also suggests the opposite. For example, better electrode discrimination at soft levels was correlated with better modulation sensitivity measured at the same level (Chatterjee and Yu 2010), which supports the idea that good modulation sensitivity requires restricted rather than broad activation of the auditory nerve. The relationship between MDT and the spatial activation pattern within which the modulated signal is coded remains unknown.

The present study aimed to explore this relationship in CI users by examining MDT at stimulation sites estimated to produce narrow vs. broad neural excitation patterns. If MDTs are better at stimulation

sites with sharper spatial tuning, this would suggest that good modulation sensitivity may require spatially restricted stimulation. Further, this would suggest that the previously reported benefits of removing sites with poor MDTs for speech recognition was possibly due to improved temporal acuity and improved spectral resolution. It would also indicate that modulation detection is not mediated by the same processes as other loudness related psychophysical acuities such as multipulse integration (Zhou and Pfingst 2016; Zhou and Dong 2017). If modulation detection requires spatially restricted stimulation, it follows that it should also benefit from a more focused stimulation mode, compared to MP stimulation. As discussed before, previous studies have not found consistent benefit of introducing narrow electrode configuration on MDT. Such benefit measured at single stimulation sites often varied between subjects (Galvin and Fu 2005) or between stimulation sites within a subject (Pfingst et al. 2008). We hypothesized that using narrow electrode configuration would have an effect on MDT, only if neural activation at the site was broad to begin with, such as in cases of large electrode-neuron distance (Goldwyn et al. 2010), but the effect would be minimal if neural activation was already narrow. In this study, we examined the effects of and interactions among spatial tuning, stimulation mode, and stimulation rate on modulation sensitivity in CI users. The results of the current study may further our understanding of the neural mechanisms for modulation detection in electrical hearing. The results may also provide rationale to design not only individual-specific but site-specific current-focusing strategies for optimized speech recognition outcomes.

METHODS

Subjects and Hardware

Nine postlingually deafened individuals implanted with Cochlear Nucleus® devices (Cochlear Corporation, Englewood, CO) participated in the study. Subject demographic information is shown in Table 1. Subjects were required to have had their implant for a minimum of 1 year to be eligible for the study. Ten ears were tested in the experiment. S1 was bilaterally implanted and both ears were tested. All subjects provided written informed consent to take part in the study. The use of the human subjects was approved by the East Carolina University Institutional Review Board.

All psychophysical tests were performed using a Nucleus Freedom® processor (Cochlear Corporation, Englewood, CO). The experiments were controlled by MATLAB programs interfacing with the NIC II

research software. Clinical units (CUs) were converted to current levels in dB re 1 mA.¹

Overview of the Psychophysical Procedures

Selected stimulation sites, estimated to have narrow and broad neural spatial activation patterns, were measured for forward-masked psychophysical spatial tuning curves (PTCs) in MP stimulation (MP 1+2). These sites were further measured for temporal modulation detection at various stimulation rates and stimulation modes. The stimulation levels for measuring MDTs were loudness balanced to a sensation level in the middle of the DR.

Selecting Stimulation Sites

For each ear, two stimulation sites, predicted to contrast in spatial tuning, were selected based on their detection thresholds (Ts) for pulse trains stimulated at 80 pulses per second (pps). MP thresholds measured at 80 pps have been shown to correlate with psychophysically estimated spatial selectivity of neural excitation, with higher thresholds associated with broader excitation (Zhou 2016). Thresholds were measured using the method of adjustment (MOA) for all functional electrodes in MP stimulation using 250-ms biphasic pulse trains with a phase duration of 25 μ s and an interphase gap of 8 μ s. The subjects were instructed to adjust the stimulus level in increments of 25, 5, or 1 CU to find the current level at which they could just detect the stimulus. This was achieved by first increasing stimulus level to a comfortable audibility, decreasing the level to approach threshold, and then adjusting the level up and down using finer step sizes until the stimulus was just detectable. The stimulation sites with the highest and lowest thresholds were selected for further testing, except for S1R, for whom we had extra testing time and two sets of stimulation sites with relatively high and low 80-pps thresholds were selected (S1R and S1R2).

Measuring Forward-Masked Psychophysical Tuning Curves (PTCs)

Spatial activation patterns at the selected sites were quantified by measuring PTCs. Stimuli were presented as biphasic pulse trains with a 25- μ s phase duration and an interphase gap of 8 μ s, stimulated at 900 pps in MP mode. There were seven maskers for each probe, one at the same stimulation site as the probe, three

¹CI24R (CS) devices: current level (dB re 1mA) = $20 * \log \left(\frac{F * 10 * 17.5^{0.25}}{1000} \right)$.
CI24RE devices: current level (dB re 1mA) = $20 * \log \left(\frac{17.5 * 100^{0.25}}{1000} \right)$.

TABLE 1

Subject demographic information. Asterisk denotes estimated value

Subject	Gender	Age (years)	Duration of implant (years)	Duration of deafness (years)	Device type
S1L	M	76	13.8	0.1	CI24R (CS)
S1R	M	76.8	7.8	6	CI24RE (CA)
S4L	F	56.6	5.3	0.4	CI24RE (CS)
S6R	F	84	4	65.2	CI24RE (CS)
S10R	F	65.6	2.7	12.4	CI24RE (CS)
S17R	F	71.6	1	60*	CI24RE (CS)
S18L	F	63.9	1.2	3.6	CI24RE (CA)
S19L	F	69.1	1	6*	CI24RE (CA)
S22R	F	70.9	3.1	0.4	CI24RE (CA)
S25R	F	58.6	7.4	1.4	CI24RE (CA)

apical, and three basal to the probe location, when spatially allowed. DRs were estimated for each of the probe and masker stimuli. Thresholds were measured using MOA as described above. To measure the maximum comfort levels (Cs), subjects were instructed to slowly increase the stimulus level in increments of 25, 5, or 1 CU, until they reached a level which they would be comfortable listening to for an extended period of time. Subjects were advised to curtail use of the 25-CU step size in favor of smaller step sizes to avoid overstimulation. The MOA thresholds and C levels (or DRs) were used to set the starting points for the adaptive procedures described below.

The unmasked threshold of the probes was measured using a 3-alternative-forced-choice (3AFC) adaptive paradigm, in which the signal was presented in one of the three intervals, chosen at random. Subjects were instructed to choose the interval that contained the signal. Stimulation started at 50 % of the probe's DR and was adapted based upon the subject's response, following a two-down one-up rule. The levels of the last six reversals, out of a total of ten reversals, were averaged and taken as the unmasked threshold. The adaptive procedure was repeated twice for each probe and the two thresholds were averaged to derive the final estimate of the unmasked probe threshold.

A 3AFC forward-masking paradigm was used to measure spatial tuning at each probe location, in which a 300-ms masker was presented followed by a 20-ms probe, with a masker-probe delay of 10 ms. The probe level was set at 2 dB above its unmasked threshold and the masker level started at 20 % of its DR. The probe signal followed the masker in one of three intervals at random. The other two intervals contained the maskers only. The subjects were instructed to select the interval with a "chirp" at the end. Masker levels were adapted following a two-up one-down rule based on the subject's response. The masker level increased when the subject correctly identified the signal twice consecutively and decreased when an interval containing only the masker

was selected. The masker levels of the last six reversals out of a total of ten reversals were averaged to quantify the masker level required to just mask the probe. The masker level at threshold, expressed in % of the masker's DR, was measured for each masker location, in random order. The PTC was measured twice and results were averaged. A linear model was fit to each side of the tuning curve and the two slopes were then averaged (% DR/electrode). Because PTCs were often not linear, the slopes were only able to approximate the shape of the functions.

Measuring MDTs

The selected sites were then measured for MDTs in MP (1 + 2) and BP (0) stimulation modes and at the stimulation rates of 250 and 1000 pps. The phase duration rather than amplitude of the stimulus was modulated to achieve finer stimulus resolution. Stimuli were 300-ms biphasic pulse trains with a reference phase duration of 200 μ s and phase gap of 8 μ s. DRs of the eight MDT stimuli (2 sites $\times$ 2 rates $\times$ 2 modes) were estimated following the MOA procedure described above. All stimuli were loudness balanced in random order to the 50 % DR level of the reference 250-pps MP stimulus at the broadly tuned site. Subjects listened to the reference stimulus and familiarized themselves with its loudness, then listened to the signal and adjusted its level until the two stimuli were equivalent in loudness. Subjects were instructed to compare the reference and the signal stimuli for as many times as they needed and were reminded to match the loudness but not the pitch. The T and C levels, DR, and loudness balanced stimulation level for each tested condition and electrode are given in Table 2. Note that for three cases (all under the BP 250-pps condition), DRs were incomplete due to C levels exceeding compliance; however, the stimulation level loudness balanced to the reference was obtained below compliance in all cases. MDTs were measured using the loudness-

TABLE 2

TABLE 2															
T level (dB re 1 mA), C level (dB re 1 mA), DR (dB), and stimulation level (dB re 1 mA) for MDTs. Asterisk denotes incomplete DR															
Tuning	Rate	Mode	T _{S1L}	C	DR	Level	T _{S1R}	C	DR	Level	T _{S1R2}	C	DR	Level	
Sharp	250	MP	-23.85	-14.90	8.94	-19.37	-28.39	-17.88	10.51	-23.14	-24.94	-17.41	7.53	-21.34	-27.69
		BP	-17.73	-6.75	10.98	-13.02	-23.53	-11.61	11.92	-17.41	-13.49	-5.49	8.00	-10.12	-24.94
	1000	MP	-28.24	-16.94	11.29	-20.24	-31.22	-20.86	10.35	-24.47	-26.67	-18.35	8.31	-22.20	-29.18
		BP	-20.39	-9.10	11.29	-13.81	-24.63	-12.08	12.55	-19.30	-15.53	-6.59	8.94	-10.90	-25.34
Broad	250	MP	-20.55	-12.39	8.16	-16.47	-23.85	-17.57	6.27	-20.71	-24.32	-15.37	8.94	-19.85	-25.73
		BP	-3.92	4.08	*8.00	-0.71	-5.81	1.25	7.06	-4.00	-13.49	-0.94	12.55	-9.57	-5.34
	1000	MP	-24.47	-13.02	11.45	-19.22	-27.92	-17.73	10.20	-22.35	-28.08	-16.47	11.61	-21.18	-28.47
		BP	-8.79	3.45	12.24	-2.98	-9.41	1.41	10.82	-4.47	-16.79	-4.24	12.55	-10.35	-8.08
Sharp	250	MP	-32.00	-19.45	12.55	-25.73	-32.94	-27.77	5.18	-30.35	-29.34	-19.30	10.04	-24.16	-24.71
		BP	-31.22	-6.28	24.94	-18.75	-26.51	-19.77	6.75	-21.73	-20.08	-6.43	13.65	-13.57	-5.49
	1000	MP	-34.98	-21.34	13.65	-28.16	-35.14	-30.43	4.71	-32.47	-34.83	-19.61	15.22	-27.69	-28.94
		BP	-32.00	-8.16	23.84	-20.08	-30.12	-21.02	9.10	-23.06	-22.59	-10.35	12.24	-16.79	-9.73
Broad	250	MP	-30.59	-19.30	11.29	-24.94	-30.28	-23.53	6.75	-26.90	-28.08	-17.41	10.67	-22.75	-23.92
		BP	-16.32	-11.30	5.02	-13.81	-21.65	-11.92	9.73	-21.18	-13.49	4.55	*18.04	-4.47	-8.79
	1000	MP	-34.98	-20.71	14.27	-27.85	-32.63	-27.45	5.18	-32.08	-33.10	-18.51	14.59	-26.28	-27.53
		BP	-20.55	-8.94	11.61	-14.75	-22.59	-14.75	7.84	-21.81	-16.63	0.31	16.94	-9.88	-13.65
Sharp	250	MP	-29.49	-25.41	4.08	-27.45	-29.96	-20.55	9.41	-25.26	-31.69	-25.88	5.80	-29.57	-24.8/3.1
		BP	-27.61	-9.57	18.04	-22.35	NaN	NaN	NaN	NaN	-26.83	-17.73	9.10	-23.06	-16.5/6.5
	1000	MP	-34.20	-26.98	7.22	-30.43	-31.37	-22.75	8.63	-26.28	-34.98	-25.10	9.88	-30.83	-26.8/3.5
		BP	-27.77	-16.79	10.98	-24.94	NaN	NaN	NaN	NaN	-29.81	-19.14	10.67	-25.57	-18.5/6.1
Broad	250	MP	-28.24	-22.59	5.65	-24.00	-29.65	-17.10	12.55	-21.81	-27.45	-18.98	8.47	-23.22	-22.3/2.7
		BP	-4.86	-1.57	3.29	-3.37	-11.77	-3.14	8.63	-6.98	-9.88	-2.67	7.22	-6.43	-6.3/3.7
	1000	MP	-33.41	-24.32	9.10	-28.55	-33.10	-18.98	14.12	-25.26	-33.10	-19.61	13.49	-26.35	-25.3/3.3
		BP	-11.92	-4.86	7.06	-5.73	-18.20	-7.22	10.98	-10.35	-14.43	-4.86	9.57	-9.65	-9.0/3.8
Mean/± Std across subjects															
Sharp	250	MP	-29.49	-25.41	4.08	-27.45	-29.96	-20.55	9.41	-25.26	-31.69	-25.88	5.80	-29.57	-24.8/3.1
		BP	-27.61	-9.57	18.04	-22.35	NaN	NaN	NaN	NaN	-26.83	-17.73	9.10	-23.06	-16.5/6.5
	1000	MP	-34.20	-26.98	7.22	-30.43	-31.37	-22.75	8.63	-26.28	-34.98	-25.10	9.88	-30.83	-26.8/3.5
		BP	-27.77	-16.79	10.98	-24.94	NaN	NaN	NaN	NaN	-29.81	-19.14	10.67	-25.57	-18.5/6.1
Broad	250	MP	-28.24	-22.59	5.65	-24.00	-29.65	-17.10	12.55	-21.81	-27.45	-18.98	8.47	-23.22	-22.3/2.7
		BP	-4.86	-1.57	3.29	-3.37	-11.77	-3.14	8.63	-6.98	-9.88	-2.67	7.22	-6.43	-6.3/3.7
	1000	MP	-33.41	-24.32	9.10	-28.55	-33.10	-18.98	14.12	-25.26	-33.10	-19.61	13.49	-26.35	-25.3/3.3
		BP	-11.92	-4.86	7.06	-5.73	-18.20	-7.22	10.98	-10.35	-14.43	-4.86	9.57	-9.65	-9.0/3.8

balanced levels, with and without level roving, as detailed below.

MDTs were measured using a 4-alternative-forced-choice (4AFC) paradigm in which three stimuli were steady state (0 % modulation depth) and the signal, placed in a random interval, was modulated in phase duration at 10 Hz. Subjects were instructed to select the interval that contained the modulated signal. Modulation depth (m) started at 50 % and was adapted based on the subject's response, in which the modulation depth decreased when the subject correctly identified the modulated signal twice consecutively and increased with an incorrect response, following a 2-down 1-up rule. Step sizes were 6 dB for the first reversal, 2 dB for the second and third reversals, and 1 dB for the remaining reversals. The m values at the last eight reversals out of a total of ten reversals were averaged. MDTs were quantified as dB re 100 % modulation depth.

MDTs were also measured with roving levels using a 4AFC paradigm similar to the procedure described above. The amplitudes of the three unmodulated stimuli were roved with the same sign and with a magnitude ranging from 0 to 5 % of the stimulus DR during a given presentation. The sign of the roving was randomized from presentation to presentation. MDTs with both roving and non-roving levels were measured twice and the average was taken. S6R and S22R did not participate in the tests with roving levels due to time constraints.

Statistical Procedure

All statistical procedures and analyses were conducted using IBM® SPSS® Statistics 24 (IBM, Armonk, NY). There were missing data for subject S22R, where BP stimulation of electrode 22 was not possible. Due to this missing data, linear mixed models were used to evaluate the main effects of and interactions among stimulation site, stimulation mode, and rate on MDTs. Univariate general linear models were used to examine whether there was a linear relationship between MDTs measured in MP stimulation at 1000 pps and the slopes of PTC measured also in MP stimulation at 900 pps, with MDTs as the dependent variable, subject as the random factor, and slopes of the PTC as covariate. Pearson's correlations and t tests were used to further examine the relationship between DR and MDT as well as the relationship between stimulation level and MDT for both the non-roving and roving data.

RESULTS

Figure 1 shows the forward-masked PTCs for selected stimulation sites for all subjects. An independent

samples t test revealed that sites with low 80-pps thresholds had significantly sharper tuning curves than the sites with high thresholds [$t(20)=5.70$, $p<.001$]. Missing data in the PTCs were due to either probe location being close to the apical or basal ends of the array (e.g., S4, S6R, S22R) or the level required to mask the probe exceeding the masker's C level (e.g., S1L, S4L).

MDTs for all testing conditions (2 sites $\times$ 2 rates $\times$ 2 modes) were measured using both non-roving and roving levels (Fig. 2). A repeated-measures ANOVA was performed to examine whether level roving had an effect on MDTs. Results showed a significant main effect of roving [$F(1, 8)=8.06$, $p=0.022$], a significant interaction between roving and rate [$F(1, 8)=9.87$, $p=0.014$], and a significant interaction between roving and mode [$F(1, 8)=10.26$, $p=0.013$]. The interactions suggest that the effect of roving was greater at the lower rate relative to higher rate and BP relative to MP conditions. Comparing the non-roving and roving data under each of the eight conditions (2 sites $\times$ 2 rates $\times$ 2 modes), none of the comparisons however reached statistical significance after Bonferroni corrections for family type I error ($p>0.006$).

A three-way mixed model ANOVA was used to examine the main effects of the test parameters: stimulation mode (MP, BP), stimulation rate (250 and 1000 pps), and stimulation site (sharp, broad) on MDTs. For non-roving data, the main effect of stimulation mode was significant [$F(1, 11.11)=5.77$, $p=0.035$], with BP stimulation resulting in better MDTs than MP stimulation. There was a significant main effect of stimulation rate [$F(1, 10.75)=74.79$, $p<0.001$], with the low stimulation rate resulting in significantly better MDTs than the high rate. The main effect of stimulation site was found to be significant [$F(1, 11.11)=32.54$, $p<0.001$], with better MDTs observed at sites with sharper tuning than at sites with broader tuning. Analysis of the roving data also revealed a similar main effect of stimulation site [$F(1, 9)=6.01$, $p=0.037$], with sharply tuned stimulation sites producing better MDTs. The main effects of stimulation rate and mode for roving data on MDTs were not significant [$F(1, 9)=2.12$, $p=0.180$] and [$F(1, 9)=0.15$, $p=0.701$], respectively. Figures 3 and 4 show the MDT data for all subjects across all conditions using the non-roving and roving levels, respectively.

Results of the non-roving data revealed a significant interaction between stimulation site and stimulation mode [$F(1, 11.21)=10.06$, $p=0.009$], indicating that the effect of stimulation mode on MDTs was different depending on the spatial tuning of the site. In Fig. 5a, at the sharply tuned sites, there was no significant difference in MDTs measured using MP compared to

Fig. 1. Psychophysical tuning curves (PTCs) for selected probe locations. Masker levels at threshold in % DR are shown as a function of masker-probe separation. Each panel shows PTCs for selected stimulation sites from one subject. The zero position

represents probe location. Blue lines represent PTCs measured at the low 80-pps threshold probes (sharply tuned sites), and the red lines represent PTCs measured at the high threshold probes (broadly tuned sites)

BP stimulation [$t(19) = -0.34$, $p = 0.731$], whereas at sites with broad tuning, MDTs improved with BP stimulation relative to MP stimulation [$t(21) = 3.86$, $p = 0.001$]. A similar interaction was identified between stimulation site and rate (Fig. 5b), [$F(1, 11.26) = 7.02$, $p = 0.022$]. While at both the sharply and broadly tuned sites, MDTs were better at low rates compared to high rates [$t(20) = -2.51$, $p = 0.021$], [$t(20) = -7.06$, $p < 0.001$], the effect of rate was significantly larger at broadly tuned than sharply tuned sites [$t(20) = 2.17$, $p = 0.041$]. Figure 5c shows the significant interaction between stimulation site and mode for roving data [$F(1, 9) = 7.92$, $p = 0.02$]. MDTs

appeared to be better with BP stimulation at the broadly tuned sites and worse at the sharply tuned sites, relative to those measured in MP stimulation, although neither difference was statistically significant [sharp: $t(17) = -1.53$, $p = 0.144$], [broad: $t(17) = 0.81$, $p = 0.428$]. Roving data showed no significant interaction between stimulation site and rate [$F(1, 9) = 2.07$, $p = 0.184$].

As the main effect of stimulation site on MDTs was significant, a univariate general linear model was used to examine whether a linear relationship existed between the slopes of the PTCs (measured in MP at 900 pps) and MDTs measured in MP at 1000 pps

Fig. 2. Scatterplots of MDTs measured with roving levels against those with the non-roving levels under various conditions. Symbols represent subjects. Filled symbols show MP data and open symbols show BP data

across subjects and across sites within subjects. Results showed that the PTC slopes accounted for the across-site variance [$F(1, 11) = 9.99$, $p = 0.009$], as well as the across-subject variance in MDTs with non-roving levels [$F(9, 11) = 4.36$, $p = 0.01$], with sharper tuning predicting better modulation sensitivity. PTC slopes accounted for the across-site variance but not across-subject variance in MDTs with roving levels [$F(1, 9) = 13.86$, $p = 0.005$; $F(7, 9) = 3.46$, $p = 0.12$]. These data are shown in Fig. 6, where MDTs measured from the same subjects but different sites are connected by lines. The r^2 values shown in Fig. 6 were adjusted for including both sources of variance.

Previous studies have shown that MDTs deteriorated with increasing stimulation rate, which is thought to be caused by an expanded DR but no improvement in intensity resolution (Galvin and Fu 2005, 2009). Two correlational analyses were performed for both the roving and non-roving data with rates fixed at one level at a time, to examine if variances in MDTs measured at different sites and stimulation modes could be accounted for by DR that co-varied with these manipulations. Analysis of the non-roving data

indicated that DR could not explain the variances in MDTs measured at either 250 pps [$r = 0.076$, $p = 0.62$], or 1000 pps [$r = 0.026$, $p = 0.87$]. Analysis of the roving data returned a similar conclusion, indicating that DR could not explain the variances in MDTs measured at either 250 pps [$r = 0.125$, $p = 0.46$], or 1000 pps [$r = -0.170$, $p = 0.32$].

Figure 8 shows MDTs as a function of the absolute stimulation levels. For the non-roving data, correlational analysis showed strong a relationship between stimulation level and MDT [$r = -0.32$, $p = 0.002$], but no such relationship was found for the roving data [$r = -0.006$, $p = 0.96$].

DISCUSSION

The major finding of this study was the significant relationship between temporal modulation sensitivity and spatial tuning. More spatially selective excitation was associated with better MDTs. The significant main effect of stimulation mode was primarily attributed to improvement in MDTs observed at stimulation sites estimated to produce

Fig. 3. MDTs with non-roving levels for all subjects across all conditions. Blue bars represent MDTs measured at a sharply tuned site and the red bars represent MDTs measured at a broadly tuned site. Each panel shows MDTs from one subject. The bottom right panel shows the group-mean MDTs for each condition. Error bars represent standard deviation

broad neural excitation in MP stimulation mode. Little benefit or, in some individuals, detrimental effects were seen when BP stimulation replaced MP stimulation at sites that were already sharply tuned. A similar interaction was found between stimulation rate and stimulation site, in that the magnitude of the rate effect also depended on the site's sharpness of tuning, with the more sharply tuned sites demonstrating less effect of stimulation rate.

Effect of Level Roving

Previous studies indicated that amplitude modulated pulse trains can be perceived louder than unmodulated pulse trains of equal amplitude, thus providing a loudness cue for identifying the modulated signal (e.g., McKay and Henshall 2010). Pulse trains that are modulated in phase durations could also produce a loudness bias. In the present study, this possible bias was controlled for by roving the levels of the

Fig. 4. MDTs with roving levels for all subjects across all conditions. Blue bars represent MDTs measured at a sharply tuned site and the red bars represent MDTs from a broadly tuned site. Each panel shows MDTs from one subject. The bottom right panel shows the group-mean MDTs for each condition. Error bars represent standard deviation

unmodulated pulse trains with magnitudes ranging from 0 to 5 % DR in either direction. Consistent with the literature, MDTs measured using roving levels were significantly poorer than those with non-roving levels and the difference was particularly apparent in BP stimulation where the absolute stimulation levels were high (McKay and Henshall 2010). Effects on MDT that were consistently found in CI users, such as those of stimulation rate, were not found in the data with roving levels. It is possible that the roving level produced significant distractions for the subjects such that the expected effects were masked.

Effect of Sharpness of Spatial Tuning in MP Stimulation

For each subject, two stimulation sites, one demonstrating significantly sharper PTC than the other (in MP stimulation), were measured for modulation sensitivity. Our results showed that the variances in MDTs could be explained by differences in the PTC slopes across stimulation sites within a subject. The mechanism underlying the relationship between MDT and spatial selectivity of neural excitation is not immediately clear. Modeling studies have predicted that neural coding of temporal modulation

Fig. 5. Mean MDTs as a function of stimulation site. Data were averaged across subjects and rates for panels **a** and **c** and averaged across subjects and modes for panel **b**. Panels **a** and **b** show that for

non-roving MDTs, stimulation mode and stimulation rate interacted with stimulation site. Panel **c** shows that for roving MDTs, stimulation mode interacted with stimulation site. Error bars represent standard

would be better if excitation occurs at the peripheral processes of the auditory neurons rather than a more central site (Joshi et al. 2017). This could explain why modulation was better coded with more spatially restricted neural activation, because restricted activation is thought to more likely excite the peripheral processes rather than the cell body or central axon. This is however based on the assumption that the peripheral processes have not degenerated and are excitable. Another possible explanation is that modulation detection requires activation of auditory fibers of similar characteristic frequencies. There is some evidence in the normal-hearing psychoacoustics literature that supports this theory. For example, amplitude modulation is better detected when the modulation is superimposed on

noise carriers with bandwidth narrower than the modulation frequency, compared to noise carriers with a wider bandwidth (Dau et al. 1999), although these differences were understood in terms of the noise carriers producing inherent fluctuations in their envelopes. In CI users, Galvin et al. (2014) reported that multichannel MDTs measured at widely spaced electrodes, when adjusted for multichannel loudness summation, were significantly poorer than single-channel MDTs measured at the same electrodes. The authors attributed the poorer multichannel performance to the low component stimulation level at the single electrodes, but it is also possible that their results were due to the modulation pattern being coded at places of drastically different frequencies. It appears that targeted exci-

Fig. 6. Correlations between MDTs and the slopes of the PTCs. MDTs with non-roving (panel **a**) and roving levels (panel **b**) measured at 1000 pps in MP stimulation are plotted as a function

of the slopes of the PTCs measured in MP stimulation at 900 pps. Data points connected with the line were those from one subject. Symbols represent subjects

Fig. 7. MDTs are shown as a function of stimulus DR for non-roving (panel **a**) and roving (panel **b**) conditions. The top of each panel shows correlation coefficients and their respective p values. The dashed lines in both panels represent the linear trends for the 250 (blue) and 1000 pps (red) stimulation conditions

tation at the peripheral processes or a narrow-band processing of the modulation could both be plausible explanations for the dependence of MDT on spatially restricted stimulation. The present results suggest that improved speech recognition after deactivating stimulation sites with poor MDTs (Garadat et al. 2013; Zhou and Pfingst 2012) may be partly due to improved spectral resolution.

Effect of Stimulation Mode

It is difficult to ascertain the role of stimulation mode on MDTs and the relation to sharpness of tuning because tuning was obtained using MP mode and because there has not been clear evidence that tuning is significantly sharper in BP compared to MP

stimulation (e.g., Kwon and van den Honert 2006). It is also unknown whether neural excitation produced by a BP electrode, assuming to be narrow, demonstrates the same pattern as that produced by a MP modiolar electrode. The fact that BP stimulation only improved MDTs at the sites with broad tuning but not those that were already sharply tuned, nonetheless, supports the idea that switching from MP to BP stimulation indeed changed the spatial neural activation patterns at those sites. Specifically, BP stimulation might have reduced the “off-channel” contributions at the broadly tuned sites to coding the modulation patterns. For some individuals, BP stimulation at the sharply tuned sites led to deteriorated MDTs (Fig. 3, e.g., S1L, S19L). This detrimental effect of BP stimulation was more salient when level was

Fig. 8. MDTs are shown as a function of stimulation level for non-roving (panel **a**) and roving (panel **b**) conditions. The top of each panel shows correlation coefficients and their respective p values. The dashed lines in the panels represent the linear trend of the data. See Fig. 7 for legend

roved (Fig. 5c). These data suggested that modulation detection may require a spatially restricted stimulation pattern, but the width of neural excitation must still exceed a criterion value. That is, the width of excitation in BP stimulation at the sharply tuned sites may have been so narrow in some cases that the population of excited neurons was too small to code the modulation. Thus, it is possible that applying current focusing on sharply tuned sites offsets the advantage of good modulation sensitivity/spectral resolution.

Broad neural excitation may be due to distant electrode position (relative to the targeted neural region) and/or neural degeneration. The broadly tuned sites tested in the current study were typically in the middle of the array and were likely to be those that were located at a great distance from the modiolus (lateral wall electrodes) rather than having poor neural survival (Long et al. 2014). For stimulation sites that are broadly tuned because of poor neural survival (instead of lateral wall electrodes), BP stimulation might reduce, rather than improve, modulation sensitivity. We speculate the reason may be that using BP stimulation may not necessarily reduce the width of neural excitation at the poor-survival sites due to elevated stimulation level to achieve a given loudness, or, if neural excitation does narrow with BP stimulation, the narrowing of excitation may fail to meet a criterion number of excitable neurons due to sparseness in survival. Previous research has shown that when switching from MP to BP stimulation, the change in modulation sensitivity could be in either direction, and the effect was site and ear specific (Galvin and Fu 2005; Pfingst et al. 2008). The unclear pattern in the previous findings may be due to testing a mixture of electrodes that were near poor neural survival regions as well as those that were at a great distance from the neural target. The insertion pattern of the electrode array and the overall neural survival status of an ear might then determine whether the across-site-mean MDT improves for that ear when switching from MP to BP stimulation. This would mean that if an individual has moderate neural survival but is implanted with a lateral wall array, using focused stimulation might improve the overall modulation sensitivity, which in turn might lead to better speech recognition outcomes. On the other hand, if an implant user has a severely degenerated auditory nerve, or tuning is already sharp, using focused stimulation might hurt speech recognition outcomes. These hypotheses warrant further investigation.

Effect of Rate, DRs, and Stimulation Level

The results from the present study are consistent with previous reports showing better MDTs with lower pulse rates (e.g., Galvin and Fu 2005, 2009; Green et al. 2012; McKay and Henshall 2010). The unique finding of the current data was that the effect of rate

depended on PTC slopes of the stimulation sites, as did stimulation mode. This could indicate that lowering of stimulation rate has a current focusing effect similar to that of switching to a more focused electrode configuration. While this is possible, there has not been clear evidence to indicate that neural excitation is more spatially selective at lower than at higher rates (Dong et al. 2017).

Previous studies suggested that poor MDTs might be due to slow loudness growth within large DRs because a larger change in amplitude is needed to elicit a change in loudness (Galvin and Fu 2009; Green et al. 2012). In the present study, phase duration was modulated rather than amplitude. If we assume that loudness growth with increasing current level and that with increasing phase duration follow a similar pattern under a specific condition, phase-duration MDT might have a similar relationship with (current level) DR. The question was whether variation in DR as a result of the manipulation of stimulation mode and site could explain variation in MDT observed in the current data. As can be seen in Table 2 and Fig. 7, DR was not smaller for conditions that produced better MDT, which supported the earlier discussed notion that the variation in MDT was attributed to the spatial neural excitation patterns.

Our data suggest that there is a relationship between MDTs and the absolute stimulation levels across conditions (Fig. 8). The significant correlation between the non-roving MDTs with stimulation levels was mainly driven by the significant effect of stimulation mode on MDT, since MDT was better in BP stimulation and BP stimulation required a higher current level. One should however caution the argument that high absolute current level leads to better modulation sensitivity. First, the relationship between stimulation level and MDT disappeared with roving levels (on the unmodulated stimuli) (Fig. 8, right panel). Secondly, the sharply tuned sites generally required less current than the broadly tuned sites, as shown in Table 2 and Fig. 8, but MDTs were found to be better at the sites requiring less current.

Clinical Implications

The findings of the current study provided an alternative explanation for the benefit of site deactivation based on the MDT measure reported in previous studies. That is, the deactivated poor-MDT sites may also be those that produced broad neural excitation, and therefore the removal of those stimulation sites may have resulted in not only improved temporal acuity but also improved channel independence. Further, current focusing may improve a CI user's ability to detect speech modulation patterns, but the benefit may only be site specific or subject specific.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest The authors declare that they have no conflict of interest.

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