A relation between electrode discrimination and amplitude modulation detection by cochlear implant listeners

Monita Chatterjee^{a)} and Jian Yu

Cochlear Implants and Psychophysics Laboratory, Department of Hearing and Speech Sciences, University of Maryland, College Park, Maryland 20742

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The objective of this study was to examine the relation between measures of spectral and temporal resolutions in cochlear implant listeners at a particular electrode location. The hypothesis was that a common underlying factor, such as the health of local groups of neurons, might partially determine patients' sensitivity to both spectral and temporal cues at specific tonotopic locations. Participants were adult cochlear implant listeners. A significant correlation was found between electrode discrimination measured at soft levels (20% and 30% of the dynamic range) and modulation sensitivity at those levels, for stimulation in bipolar mode and a 100 Hz modulation rate. Correlations between the two measures were weaker under monopolar stimulation, or when the modulation rate was 10 Hz. At a higher stimulation level (40% of the dynamic range), no significant correlations between these measures were observed. It is hypothesized that the more restricted excitation pattern at lower levels and/or with a narrower stimulation mode allows the measurement of locally driven sensitivity to spectral and temporal cues, particularly under more challenging listening conditions. Thus, psychophysical measures obtained under conditions that evoke a narrower excitation pattern may serve as a useful indicator of the functional health of local neural populations. © 2010 Acoustical Society of America. [DOI: 10.1121/1.3257591]

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I. INTRODUCTION

Speech perception with a cochlear implant (CI) is thought to require good resolution in both spectral and temporal domains. As far as the relation between speech perception and spectral resolution is concerned, the picture is not entirely clear. While earlier studies exploring the relation between place-pitch coding and speech perception by CI listeners have reported mixed results (Nelson *et al.*, 1995; Collins *et al.*, 1997; Throckmorton and Collins, 1999; Zwolan *et al.*, 1997; Donaldson and Nelson, 2000; Henry *et al.*, 2000), more recent investigations employing more complex stimuli have demonstrated significant correlations between spectral pattern processing abilities and speech perception by CI listeners (Henry and Turner, 2003; Henry *et al.*, 2005; Litvak *et al.*, 2007; Won *et al.*, 2007). It seems reasonable to assume that spectral pattern processing would require good electrode discrimination, but direct evidence for this is not clearly present in the literature.

On the other hand, temporal resolution has been found to have a positive relation with speech perception by CI listeners. Cazals *et al.* (1994) found that vowel and consonant recognition scores were significantly correlated with the slope of the high-frequency cutoff of the modulation transfer function measured in CI listeners at the most apical electrode. Fu (2002) showed that the mean modulation detection threshold (of 100 Hz modulated pulse trains) of CI listeners, calculated across the dynamic range, was strongly correlated with their phoneme recognition scores. As modulation sensi-

tivity in CI listeners tends to be strongly level-dependent, the mean of modulation thresholds measured at various levels provides a more representative measure of listeners' performance than a single measurement at a fixed level. The correlations observed by Fu (2002) and Cazals *et al.* (1994) between the measures of modulation sensitivity and vowel recognition are somewhat difficult to explain, given that fast temporal cues have been shown to play a relatively minor role in vowel recognition (Xu *et al.*, 2005). As correlation does not necessarily imply causation, interpretation of the results should be undertaken with some caution. It is possible, for instance, that CI listeners who have excellent modulation sensitivity, also have excellent spectral (spatial) resolution: the overall health and number of surviving auditory nerve neurons might dictate both. Thus, the correlations observed between either spectral resolution or temporal sensitivity and speech perception measures might well be a reflection of the contribution of overall spectro-temporal sensitivity to speech perception, rather than the importance of temporal sensitivity or spectral resolution alone.

Work by Shepherd and colleagues indicates that as duration of deafness increases, auditory nerve neurons in the cat decrease in number; further, the surviving neurons show poorer phase-locking to the temporal patterns of electrical stimuli owing to longer refractory periods (Shepherd and Javel, 1997; Shepherd *et al.*, 2004). Smaller numbers or irregular patterns of surviving neurons may be expected to result in weak or uneven pitch salience, thus contributing to poorer electrode discrimination. At the same time, poorer phase-locking of the surviving neurons would result in poorer temporal discrimination. It is thus possible that the pattern of nerve survival and the health of surviving neurons

^{a)}Author to whom correspondence should be addressed. Electronic mail: mchatterjee@hesp.umd.edu

TABLE I. Relevant information about subjects. Note that “Early/perilingual” onset of deafness indicates cases in which the subjects was not congenitally deaf; but may have had some auditory exposure prior to the onset of deafness. “Stimulation Mode” refers to the experimental mode used in the current study.

Subject	Onset of deafness	Stimulation mode	Device	Gender	Age at implantation	Age at testing
S1	Early/perilingual	MP1+2, BP+1	N-24	F	46	49
S2	Prelingual	MP1+2, BP+2	N-24	M	16	23
S3	Postlingual	MP1+2, BP+2	N-24	M	57	60
S4	Postlingual	BP+2	N-22	M	35	49
S5	Postlingual	BP+2	N-22	M	49	65
S6	Postlingual	BP+2	N-22	M	51	65
S7	Early/perilingual	MP1+2, BP+2	N-24	F	47	56
S8	Postlingual	MP1+2, BP+2	N-24	F	60	64
S9	Postlingual	MP1, BP+1	Freedom	F	63	64
S10	Postlingual	MP1, BP+2	Freedom	F	66	67
S11	Postlingual	MP1, BP+1	Freedom	F	69	71
S12	Postlingual	MP1	Freedom	M	64	67
S13	Postlingual	MP1	Freedom	F	63	64

is related to electrode discrimination (sensitivity to changes in the spectral pattern) as well as modulation detection (sensitivity to changes in the temporal pattern). Thus, measures of modulation sensitivity may be correlated with measures of electrode discrimination.

The strength of such a relationship may also depend on the stimulation mode. With monopolar (MP) stimulation (the mode of choice in present-day devices), the electric field is thought to be broader than with bipolar (BP) stimulation. By stimulating smaller groups of neurons using the bipolar stimulation mode, it should be possible to evoke responses from more localized regions of the auditory nerve array than in monopolar mode. In this case, the strength of the relation, if any, between spatial discrimination and temporal sensitivity may be stronger in bipolar mode than in monopolar mode.

In the present study, we explored the relation between electrode discrimination and sensitivity to amplitude modulation at a medial electrode location in a group of cochlear implant listeners. Effects of stimulation mode, stimulus level, and the rate of amplitude modulation were also examined.

Both electrode discrimination and amplitude modulation sensitivity improve with stimulus level in CI users, reaching ceiling performance at moderate loudness levels (Pfungst *et al.*, 2007; Galvin and Fu, 2005; Fu, 2002; Pfingst *et al.*, 1999; McKay *et al.*, 1999). The excellent performance achieved by most CI listeners in these tasks at moderate stimulation levels (e.g., at 40% of the dynamic range and above) means that the relative range of variation in performance across subjects is reduced as stimulation level is increased. It is therefore more likely that if there is indeed a relation between listeners’ performance in these two tasks, it might be observed at low stimulation levels rather than at high levels. In support of this expectation, preliminary results indicated a relation between amplitude modulation sensitivity and electrode discrimination at soft stimulation levels, but not at high stimulation levels. The goal of the study was to examine the relations between measures of electrode discrimination and amplitude modulation sensitivity under

conditions that were likely to produce the greatest inter-subject variability. Therefore, the focus of this investigation was placed on performance at relatively soft levels of stimulation (i.e., 20%–40% of the dynamic range).

Bipolar stimulation requires higher current levels than monopolar stimulation. To obtain a measurable dynamic range while remaining within the compliance limits of the device, it was necessary to (i) increase the pulse phase duration and inter-phase gap in bipolar mode over that in monopolar mode and (ii) in some instances, to increase the distance between the active and return electrodes in bipolar mode (to BP+1 or BP+2 as needed). These steps, while necessary, may have reduced the effective difference between the two modes of stimulation in this study. These constraints have likely weakened the strength of the observations reported here. This suggests that studies conducted under more ideal conditions might yield even stronger findings than the present study.

Sensitivity to amplitude modulation at both a slow (10 Hz) and a fast (100 Hz) rate was measured in this study. While slow envelope fluctuations are likely to be primarily limited by intensity discrimination limens, fast fluctuations are additionally limited by the temporal resolution of the system (phase-locking of auditory nerve neurons, etc.). As phase-locking has been shown to be compromised in animals with prolonged duration of deafness, it is expected that the 100 Hz modulation would be more poorly encoded than the 10 Hz modulation by the auditory system in locations of damage.

II. METHODS

A. Subjects

A total of 13 adult CI users (S1–S13) participated in this study. Of these, 11 were post-lingually deafened, and the remaining two (S2 and S7) were early deafened. Relevant information about the subjects is provided in Table I. All participants used CIs manufactured by Cochlear Corporation (N-22, N-24, or Freedom devices). Eight participants were

involved in measurements with both monopolar and bipolar modes. An additional three were stimulated in bipolar mode only. Two others were stimulated in monopolar mode only.

B. Stimuli

The nucleus cochlear implant arrays described in this study comprise 22 intracochlear electrodes, numbered 1–22 from base to apex. Henceforth, stimulation in BP+1 or BP+2 modes will be collectively referred to as BP or bipolar stimulation, while stimulation in MP1 or MP1+2 modes will be collectively referred to as MP or monopolar stimulation. A custom research interface (House Ear Institute Nucleus Research Interface: [Shannon et al., 1990](#); [Robert, 2002](#)) was used to generate electrical stimuli. All stimuli were 300-ms long trains of biphasic current pulses, presented at 1000 pulses/s. For modulation detection tasks, stimuli were presented to electrode 10 (a centrally located electrode in the array) in either bipolar or monopolar stimulation mode. For electrode discrimination tasks, the reference stimulus was presented on electrode 10 and the comparison stimuli were presented on neighboring electrodes. In bipolar mode, pulses were 100–200 μ s in phase duration, with a 20 μ s interphase gap. In monopolar mode, pulses were either 25 or 40 μ s in phase duration, with interphase gaps of 6 or 8 μ s. In the electrode discrimination experiment, stimuli were unmodulated pulse trains. In the modulation detection experiment, a sinusoidal modulation was applied to the amplitude of the pulses. Stimuli were presented in BP+1 or BP+2 mode for the BP experiments, and in MP1 or MP1+2 mode in the MP experiments. In the BP experiments, the narrowest mode that allowed us to measure the full dynamic range was selected. In the MP experiments, the N-24 users were tested in MP1+2 mode. For technical reasons, the Freedom users were tested in MP1 mode.

C. Procedures

1. Threshold and dynamic range

Threshold was obtained using a two-down, one-up, two-interval, forced-choice, adaptive procedure, converging at the 70.7% correct point on the psychometric function ([Levitt, 1971](#)). The mean of two runs was calculated as the threshold. The maximum acceptable level (MAL) was measured using a procedure in which the subject adjusted the level of the stimulus by pressing the “up arrow” or “down arrow” keys in the computer keyboard until the level of the sound was at the upper end of comfortable loudness. The dynamic range (DR) was calculated as the difference in microamperes between the MAL and the threshold. Stimuli were presented at various % DRs.

2. Modulation detection thresholds

The threshold modulation depth (MDT) was measured using a two-down, one-up, three-interval, forced-choice (3IFC) adaptive procedure, converging at the 70.7% correct point on the psychometric function ([Levitt, 1971](#)). Two of the three intervals (randomly) contained the unmodulated reference stimulus, while the remaining interval contained the modulated one; the subject’s task was to indicate which in-

terval sounded different. The MDT was measured at levels of the carrier ranging from 20% to 80% of the DR, in 10% DR increments. Measurements were made at modulation frequencies of 100 and 10 Hz. In each condition (e.g., bipolar mode and 100 Hz modulation frequency), measurements at different carrier levels were made in random order. At least two independent measurements were made at each level, and the mean of the two was calculated as the modulation threshold at that carrier level.

3. Electrode discrimination

Electrode discrimination was measured using a three-interval, forced-choice procedure, in which two of the intervals (randomly) contained the stimulus on the reference electrode, and the remaining interval contained the comparison electrode. The subject’s task was to indicate which of the three intervals sounded different from the other two. Each comparison electrode was presented 20 times. Blocks were created with a number of comparison electrodes, and the order of presentations was randomized. Results were obtained as percent correct. The percent correct scores were converted into d' measures for further analyses ([Macmillan and Creelman, 2005](#)). For a particular trial, stimuli were presented at the same % DR level.

It is to be noted that stimulus level was not varied in the electrode discrimination task. In preliminary experiments, we observed large variations in performance when small level variations were introduced, perhaps because performance asymptotes rapidly with level in this task. However, as several electrode comparisons were included in each block and the presentations were randomized, stimuli presented in successive trials would have had slightly different loudness levels (some slightly louder and some slightly softer), which would have resulted in a natural rove. Subjects were asked about loudness cues, and all except two (subjects S7 and S8) reported that the stimuli were equally loud. In their case, loudness was reported by the subject to be an important cue in the task, and the stimuli were loudness-balanced (adjusted until the subjects reported them to be equally loud).

Initially, electrode discrimination was measured at a range of levels in some of the subjects (S2, S5, S6, and S7). Preliminary analyses indicated a correlation between electrode discrimination at soft levels and measures of modulation sensitivity in the bipolar stimulation mode. Therefore, we elected to constrain the remaining measures to the lower levels (20%–40% DR). At higher levels of stimulation, performance in electrode discrimination approached ceiling levels, and inter-subject variation was relatively reduced.

III. RESULTS

A. Level dependence of the MDT

Consistent with previous findings ([Fu, 2002](#); [Shannon, 1992](#); [Chatterjee and Robert, 2001](#); [Chatterjee and Oba, 2005](#); [Pfungst et al., 2007](#)), modulation sensitivity at both 100 and 10 Hz showed considerable level dependence in all subjects. The top left-hand panel of Fig. 1 shows the modulation detection thresholds obtained in all 11 subjects in the medial location (electrode 10) using the bipolar stimulation mode

FIG. 1. Threshold modulation index (in %) plotted as a function of stimulus level. Upper and lower panels show results obtained in bipolar and monopolar modes, respectively. Left- and right-hand panels show results obtained using the 100 Hz and the 10 Hz modulation rates, respectively. Within each panel, different symbols refer to different subjects. The thick solid line indicates the mean calculated across the seven subjects, in each case. Error bars show ± 1 s.d. Note that the subject pools for bipolar and monopolar modes are overlapping, but not identical.

and the 100 Hz modulation rate, plotted as a function of level. The top left-hand panel shows data obtained using identical conditions, but with a 10 Hz modulation rate. Results in monopolar mode, but with a somewhat different group of subjects, are shown in the lower panels. Note that the vertical scale is different between the upper and lower panels. Although there was considerable inter-subject variation in the absolute modulation detection thresholds, the shape of the function relating modulation sensitivity to carrier level was similar across subjects and conditions, and is captured by the mean function (thick solid line in each panel). Thresholds decreased (sensitivity increased) with increasing carrier level following a nonlinear curve, asymptoting at generally excellent performance at moderate to high carrier levels. The carrier level at which performance reached the asymptote varied across subjects. As expected from the low-pass-filter shape of the temporal modulation transfer function (Shannon, 1992), the mean sensitivity of subjects to the 10 Hz modulator was greater than the mean sensitivity to the 100 Hz modulator in each stimulation mode. A two-way repeated measures analysis of variance (ANOVA) was conducted on the results obtained in each mode. In BP mode (using a Greenhouse–Geisser adjustment for violation of the sphericity assumption), the results showed a significant main effect of level [$F(1.243, 12.429) = 40.067$, $p < 0.001$] and modulation frequency [$F(1, 10) = 18.49$, $p < 0.005$], and a significant interaction between the

two [$F(1.748, 17.476) = 22.136$, $p < 0.001$]. An identical analysis conducted on the results obtained in MP mode (also using the Greenhouse–Geisser adjustment) also showed significant main effects of level [$F(1.147, 10.324) = 16.897$, $p < 0.001$] and modulation frequency [$F(1, 9) = 10.074$, $p < 0.02$] and a significant interaction between the two was again observed [$F(1.426, 12.831) = 8.866$, $p < 0.001$]. The interaction between carrier level and modulation frequency stems from the greater sensitivity to the slower modulation rates at lower carrier levels. At high carrier levels, the two mean functions converge. The temporal modulation transfer function (TMTF) of cochlear implant listeners reflects these differences as well: at low carrier levels, the TMTF often appears to be more low-pass (larger differences in sensitivity to low and high modulation rates), while at high carrier levels, the function tends to flatten out (smaller differences between sensitivity to low and high modulation rates: Shannon, 1992; Chatterjee and Robert, 2001).

Although the above results obtained with monopolar and bipolar stimulations were not obtained with the same set of subjects, eight of the participants provided data with both stimulation modes. The effect of stimulation mode, and its interactions with modulation frequency and level, could thus be directly tested on the results obtained with these subjects. Mean results are shown in Fig. 2, with open and closed symbols representing bipolar and monopolar stimulations, re-

FIG. 2. Mean modulation detection thresholds plotted as a function of stimulus level, for bipolar and monopolar stimulation modes (open and filled symbols, respectively), and 100 and 10 Hz modulation rates (circles and squares respectively). Results are shown for the eight subjects who were tested in both stimulation modes.

spectively, while circles and squares represent 100 and 10 Hz data. Error bars are omitted for clarity. A three-way repeated measures ANOVA was conducted on these results. Despite considerable variation in the results, analyses showed a small but statistically significant main effect of stimulation mode [$F(1,7)=8.61$, $p=0.049$], a significant main effect of modulation frequency [$F(1,7)=11.655$, $p<0.02$], and a significant main effect of level [$F(1.15,8.03)=23.796$, $p<0.005$]. The Greenhouse–Geisser correction was applied for violation of sphericity. Significant interactions were observed between stimulation mode and level [$F(1.32,9.26)=4.73$, $p<0.05$] and between modulation frequency and level [$F(1.423,9.963)=12.27$, $p<0.005$]. No interactions were observed between stimulation mode and modulation frequency, and no three-way interactions were observed. As is seen in Fig. 2, mean thresholds in bipolar mode were consistently higher than mean thresholds in monopolar mode: however, these differences were not large. There was also considerable inter-subject variation in the data, likely contributing to the small level of significance for the effect of mode.

B. Level dependence of electrode discrimination

Figure 3 shows results obtained in the electrode discrimination task by the 11 subjects using bipolar stimulation. The abscissa shows the location of the comparison electrode, and the ordinate shows percent correct in the 3IFC task. The horizontal solid line shows chance performance. Figure 4 shows similar results obtained with the ten subjects using the monopolar stimulation mode. Performance improved moderately with level in all subjects and stimulation modes, with one exception: subject S7's performance declined with increasing level in the monopolar stimulation mode. The dependence of electrode discrimination on level is consistent with previous observations by Pfingst *et al.* (1999) and McKay *et al.* (1999). 8 of the 11 subjects who provided data with the bipolar stimulation mode also participated in the measurements using the monopolar stimulation mode. Figure 5 provides a side-by-side comparison of the results obtained in these eight subjects with the two stimulation modes. The

ordinate represents the average of the values of d' obtained on electrodes located at equal distances from the reference electrode on the basal and apical side. The abscissa represents the relative distance of the comparison electrodes from the reference electrode. Within each panel, the parameter is the stimulus level (in % DR). The left-hand column shows results obtained with bipolar stimulation, and the right-hand column shows results obtained with monopolar stimulation.

For purposes of analysis, sensitivity indices were developed for electrode discrimination. As most subjects reached excellent performance at a three-electrode distance from the reference electrode, the one- and two-electrode distances were selected as ones that would yield poor to excellent performance without reaching ceiling effects in most subjects. Performance (in percent correct) at a distance of two electrodes (both in the apical end and in the basal direction) from the reference electrode was converted into a d' score for each electrode location and stimulation mode tested. The mean of the two values of d' (basal and apical) was taken as the measure of electrode discrimination. This measure will be henceforth referred to as the EDI₂ (electrode discrimination index at the two-electrode distance). A similar measure of sensitivity at the one-electrode distance was also developed (EDI₁). Figure 6 shows the mean d' obtained at distances of one and two electrodes away from the reference electrode in the bipolar and monopolar stimulation modes, at 20%, 30%, and 40% DR. The measures of EDI₁ were somewhat larger with bipolar than with monopolar stimulation. A paired t-test showed a statistically significant difference between the one-electrode d' obtained at 20% and 40% DR ($p<0.05$) but not at 30% DR. No significant difference was observed between the two-electrode d' obtained in the two modes at any of the levels.

C. Measures of dispersion for modulation detection and electrode discrimination

Inspection of the results suggested that at higher amplitudes of stimulation, the inter-subject variation in electrode discrimination and modulation detection would be reduced as a result of performance approaching ceiling levels. The coefficient of variation was selected as an appropriate, normalized measure of the dispersion in the data in each case. Analysis showed that indeed, the coefficient of variation in both the EDI₁ and EDI₂ measures reduced systematically with increasing level in both stimulation modes [Fig. 7(a)]. The coefficients of variations computed for modulation sensitivity ($1-m$, where m =modulation index at threshold) were much smaller than those calculated for electrode discrimination [Fig. 7(b)]. However, these coefficients also declined with increasing level in both stimulation modes [inset of Fig. 7(b): expanded vertical axis]. The increased inter-subject variation in the results at the lower stimulus levels suggests that any correlations between performance in the two tasks may be stronger at lower levels.

FIG. 3. Percent correct in the electrode discrimination task, obtained using the bipolar stimulation mode. Each panel shows results obtained with a different subject. Within each panel, the parameter is stimulus level (in % DR). The abscissa shows the location of the comparison electrode (the reference was always at electrode 10).

D. Relation between measures of electrode discrimination and modulation sensitivity

The EDI measures described above were used as indices of sensitivity in electrode discrimination. The MDT obtained at the corresponding level served as an index of modulation

sensitivity. The data were analyzed for correlations between the EDI obtained at a particular level and the MDT obtained at that same level.

Figure 8 shows results obtained in bipolar stimulation mode. Figure 8(a) shows a scatterplot of the EDI₂ obtained at

FIG. 4. Percent correct scores in the electrode discrimination task obtained using the monopolar stimulation mode. Otherwise, identical to Fig. 2.

20% DR against the 20% DR MDT obtained at the 100 Hz modulation frequency. The intermittent line indicates the result of a linear regression. The two measures were significantly correlated ($r=-0.621$, $p=0.042$). Figure 8(b) shows the 30% DR EDI₂ measure plotted against the 30% DR 100-Hz MDT. These two measures were again significantly

correlated ($r=-0.709$, $p=0.015$). When the modulation frequency was 10 Hz, the correlations fell below significance at both the 20% and 30% DR levels.

Similar analyses performed using the EDI₁ mode showed a significant correlation at the 20% DR level: that is, the 20% DR EDI₁ and the 20% DR 100 Hz MDT were sig-

FIG. 5. Performance in the electrode discrimination task as a function of (absolute) distance from the reference electrode (in numbers of electrodes). The ordinate shows the average d' taken across results obtained on equidistant electrodes on the basal and apical sides of the reference. Left-hand panels show results obtained using bipolar stimulation, and right-hand panels show results obtained using monopolar stimulation. Right-hand pairs of panels show results obtained in subjects S8, S9, S10, and S11. Within each panel, the parameter is stimulus level.

nificantly correlated with each other ($r=-0.696$, $p=0.025$). However, the corresponding measures were not significantly correlated at the 30% DR level.

The mean of the EDI_1 and EDI_2 measures obtained at

FIG. 6. EDI_1 (left-hand panel) and EDI_2 (right-hand panel) averaged across all eight subjects who provided data in both stimulation modes, plotted against the stimulus level. Dark and light bars represent results obtained in bipolar and monopolar modes, respectively. Error bars show ± 1 s.d. Asterisks indicate significant differences between means (paired t -test).

20% DR and 30% DR was computed (EDI_{mean}). The mean of the 100 Hz MDTs measured at 20% and 30% DR (MDT_{mean}) was also computed. These two measures were significantly correlated with each other [$r=-0.689$, $p=0.029$; see Fig 8(c)].

Analyses of data obtained at the 40% DR level showed no significant correlations between any of the measures of electrode discrimination and corresponding measures of modulation sensitivity.

In monopolar mode, significant correlations were observed only in two cases. A significant correlation was observed between the EDI_2 measure at the 20% DR and the 20% DR 100 Hz MDT ($r=-0.678$, $p=0.031$) and also the 20% DR 10 Hz MDT ($r=-0.668$, $p=0.035$). However, no significant correlations were observed between the 20% EDI_1 and either of the 20% MDTs. Similarly, no significant correlations were observed between the EDI_2 index at 30% DR and the 30% DR MDTs, either at 100 Hz or at 10 Hz.

FIG. 7. The coefficient of variation for electrode discrimination measures (upper panel) and modulation detection thresholds (lower panel) plotted as a function of carrier level, for 20%, 30% and 40% DR levels.

Consistent with these findings, the EDI_{mean} and MDT_{mean} computed for data in monopolar mode were not significantly correlated with each other.

In summary, the most significant correlations between electrode discrimination and modulation sensitivity were observed at the lower levels, particularly in bipolar stimulation mode and when the modulation rate was 100 Hz. Correlations observed between the EDI measures and modulation sensitivity were generally weaker when the modulation frequency was 10 Hz rather than 100 Hz. At the higher stimulation level of 40% DR, the strength of the correlations weakened. Finally, measures obtained using the monopolar stimulation mode only showed a significant correlation at the lowest level. No other significant correlations were observed in monopolar mode.

Adjustments to the criterion alpha value for significance are sometimes recommended when multiple comparative analyses are conducted on independent variables to investigate several independent hypotheses. Such adjustments should be made cautiously, particularly in studies with small n , because as the risk for Type 2 errors declines, the risk for Type 1 errors may increase. In the present case, independent (but related) measures of sensitivity were compared to answer a single question. In this instance, adjustments are not necessary and therefore, no adjustment was made for the criterion significance level (Motulsky, 1995, Chap. 13).

IV. DISCUSSION

The experiments included in this report were designed to examine the relation between modulation sensitivity and

FIG. 8. Scatterplots of EDI_2 obtained at 20% and 30% DRs (A and B, respectively) plotted against the MDT obtained at each level. Panel C shows the EDI_{mean} plotted against the MDT_{mean} .

electrode discrimination. Effects of stimulation mode, level, and modulation rate on the individual measures and the relations between them, were also investigated. Consistent with previous findings (Shannon, 1992; Fu, 2002; Chatterjee and Oba, 2005; Pfingst *et al.*, 2007; 1999; McKay *et al.*, 1999), results indicate that both modulation sensitivity and electrode discrimination improve with increasing stimulus level. McKay *et al.* (1999) found only small improvements in electrode discrimination between 40% and 70% DRs. This is consistent with our present findings indicating that the largest changes in electrode discrimination occur below 40% DR. The present results are also consistent with the observation of Pfingst *et al.* (1999) showing moderate improvements in electrode discrimination with increasing level in some instances.

Small effects of stimulation mode were observed in the electrode discrimination and modulation detection measures. Significantly improved performance was observed in one of the electrode discrimination measures (EDI_1) in the bipolar mode over the monopolar mode. However, the EDI_2 measure, taken two electrodes away from the signal electrode, did not reveal significant differences between the two modes. When modulation detection thresholds were compared across stimulation mode, a small but significant difference was observed, with mean thresholds in bipolar mode being slightly better than corresponding thresholds in monopolar mode. It is to be noted that Galvin and Fu (2005) did not observe significant effects of stimulation mode on modulation detection thresholds in their study. However, the narrowest bipolar stimulation mode they used was BP+3. It is likely that the effect of stimulation mode becomes even smaller when the bipolar mode is broadened.

At the lower levels of 20% and 30% DRs, significant correlations were observed between 100-Hz modulation thresholds and the EDI_2 measure in the bipolar mode. Observed correlations were weak and generally not significant when the modulation rate was 10 Hz, or in monopolar mode.

At the lower levels and in bipolar stimulation mode, the spread of excitation was likely contained to a small group of neurons: in this case, performance in the electrode discrimination task may have more truly reflected the status/response of local groups of neurons. At higher levels (i.e., 40% DR), excitation possibly spread to other areas, and the psychophysical measures no longer reflected the responses of a small group of neurons. In addition, as stimulation level increased, performance in both tasks approached ceiling. Accordingly, the coefficients of variation in the electrode discrimination and modulation detection threshold data decreased systematically (Fig. 7). This decline in inter-subject variation likely contributed to the lack of observed significant correlations among the measures at the 40% DR level.

The fact that more significant correlations were observed in the bipolar mode than in the monopolar mode supports the hypothesis that more focused stimulation modes may target the response properties of local groups of neurons, and possibly contribute to the diagnosis of local regions of damage. In partial support of the assumption that bipolar stimuli provide a more focused field, we observed larger values of d' in the electrode discrimination task in bipolar stimulation than in monopolar stimulation at two of the three stimulation levels analyzed. Note also that the one significant correlation obtained in monopolar mode was observed at the lower level (20% DR), which would be expected to correspond to a narrower stimulating field.

An important caveat to note is that the human data (psychophysical or physiological) do not provide clear support for the idea that the bipolar stimulation mode does, in fact, elicit a narrower excitation pattern than the monopolar mode. Although this has been shown to be the case in animal studies (e.g., Bierer and Middlebrooks, 2002; Snyder *et al.*, 2004), psychophysical results obtained in human CI users are mixed. Some studies suggest that similar widths of the excitation pattern are evoked by bipolar and monopolar stimula-

tion modes (Kwon and van den Honert, 2006; Cohen *et al.*, 2001). However, differences between psychophysical tuning curve shapes obtained in the two modes were noted by Nelson *et al.* (2008). Cohen *et al.* (2001) also noted that the peaks of forward masking patterns obtained in monopolar mode were flatter than those obtained in bipolar mode. The methodology used in some of the human psychophysical experiments makes the results somewhat difficult to interpret. For instance, Kwon and van den Honert (2006) and Nelson *et al.* (2008) used different probe stimulation modes to measure the forward masking pattern/psychophysical tuning curve in monopolar vs bipolar stimulation, making it difficult to compare the masked threshold shifts directly from one to the other mode. Ideally, the probe in a forward masking experiment should be as restricted in spatial/spectral spread as possible, and the same probe should be used to map out the masking pattern or psychophysical tuning curve. Cohen *et al.* (2001) did use a fixed BP+1 probe stimulation mode in their study. However, the masker level was fixed at the MCL: at this relatively high level, differences between the two modes of stimulation may be minimal owing to spread of excitation. Despite the mixed results observed in the psychophysical experiments, the fact remains that the human psychophysical data do not show the dramatic differences in spread of excitation between the two modes that are observed in the animal neurophysiological data. Cohen *et al.* (2003) and Hughes and Stille (2009) demonstrated good correspondence between psychophysical forward masking patterns obtained in humans and parallel measurements obtained using the physiological ECAP response in the same listeners. This suggests that, at least in humans, psychophysical masking patterns provide a good estimate of physiological spread of excitation, and partially rules out the psychophysics-physiology difference as the source of the discrepancy between animal and human data. While methodological differences (electrode design, stimulus parameters, etc.) may be partly to blame, it is difficult to conceive of convincing reasons for the difference in findings. Recently, Schoenecker *et al.* (2009) reported that, in contrast to spatial broad onset responses, steady-state physiological responses recorded in the central nucleus of the inferior colliculus to long-duration, high rate pulse trains are narrower in spatial extent in both monopolar and bipolar stimulations. This indicates that the difference between the two modes depends on the stimulus characteristics. Further research clearly needs to be done to clarify these issues. Overall, the human psychophysical data show—at best—more subtle effects of stimulation mode than those observed in the animal neurophysiological data.

Technical constraints resulted in less-than-ideal conditions in the present experiment. For instance, the bipolar stimulation mode was broader than desired in most cases, bringing it closer to the monopolar mode. Further, there is some evidence that stimuli with shorter pulse phase durations may elicit narrower excitation patterns than those with longer pulse phase durations (Grill and Mortimer, 1996), which would imply that the bipolar stimuli in our experiment were less spatially focused than desired. The computational model used by Grill and Mortimer (1996) produced results

that were supported by experimental data obtained from stimulation of the sciatic nerve and recordings of the torque generated at the ankle joint of adult cats. Stimuli were also different from those used in the present study. Psychophysical results from our own laboratory suggest that excitation patterns do not change greatly with changing pulse phase duration (Chatterjee *et al.*, 2001), but more research is needed to further clarify the issue. If it is the case that shorter pulse durations yield narrower excitation patterns, then in our experiment, the monopolar stimuli produced more spatially focused patterns than desired. Thus, the difference between monopolar and bipolar stimuli would have been reduced further. These limitations may have reduced the strength of the findings: if the experiments had better controlled for pulse phase duration, the bipolar mode would have produced more focused patterns and perhaps resulted in stronger correlations.

It is also true that changing the pulse phase duration and the inter-phase gap can introduce changes in the nature and site of spike initiation, particularly in individuals with surviving peripheral processes (Shepherd *et al.*, 2001; Shepherd and Javel, 1999; van den Honert and Stypulkowski, 1984). It has also been shown that sensitivity to changes in the inter-phase gap and pulse duration is related to spiral ganglion survival in guinea pigs (Prado-Guitierrez *et al.*, 2006). If so, then aspects of temporal coding may be sensitive to the pulse phase duration, as well as the number and health of surviving neurons. For all these reasons, it would be desirable to better control the pulse phase duration in future studies.

A possible explanation for the lack of significant correlations observed when the modulation frequency was 10 Hz, is that encoding the slower modulation frequency does not pose a significant challenge to the auditory system. This is reflected in the greater mean sensitivity observed in the 10 Hz modulation detection task than in the 100 Hz task. Ceiling performance was reached at relatively low stimulus levels in the modulation detection task at 10 Hz modulation rate. At 100 Hz, phase-locking is likely to be less efficient; thus, this task may have been more useful as an indicator of nerve damage; if the correlation between the two measures reflects the status of the nerve, it is reasonable to expect that the 100 Hz task would be more predictive than the 10 Hz task.

Unlike the EDI₂ measure, the EDI₁ measures did not show strong correlations with the MDT measures at the 30% DR level in bipolar mode. We do not have a convincing explanation for this observation at this time.

To summarize, the results presented here suggest that locally specific measures of spatial and temporal resolutions are correlated in CI listeners. The fundamental mechanism underlying the correlation is not known: however, we speculate that auditory-nerve survival at specific locations may dictate performance in both kinds of measures.

The present results provide support for the notion that the correlations reported between measures of modulation sensitivity or spectral resolution and phoneme recognition scores may reflect the contribution of both temporal and spectral cues to speech perception with CIs. It is to be noted that the subjects in Fu's (2002) study were all tested in the

bipolar stimulation mode; based on the results of the present study, the correlation between spectral and temporal resolutions is strongest under these conditions.

Although the correlations observed here were significant only at the lower stimulation levels and with relatively simple stimuli, the results have implications for CI listeners' performance in speech perception. The electrode discrimination and modulation detection tasks presented here define the least challenging task listeners may face in the spectral and temporal domains, respectively. In everyday listening, CI users must perform far more challenging tasks involving the discrimination and identification of multi-channel stimuli that are only subtly different in their spectro-temporal patterns.

Difficulties revealed in a simple electrode discrimination task are likely to be amplified when listeners are faced with the need to analyze more complex signals such as speech. Also, multi-channel loudness summation generally results in lower levels of per-channel stimulation; thus, listeners' psychophysical performance at low levels of stimulation may be more predictive of their performance in multi-channel auditory perception.

We would caution against the conclusion that no relationship exists between electrode discrimination and modulation sensitivity in monopolar stimulation: it is possible that a weaker relationship does exist between the two measures, which a study with a large pool of subjects might discover. The present results merely indicate that the relationship between the two is stronger in bipolar stimulation than in monopolar stimulation. The observed relationship between spatial and temporal resolutions in the bipolar mode also does not imply that temporal and spectral cues are processed by the same neural coding mechanisms. All that we can infer from the findings of the present study is that both measures may be limited by some common underlying factor. Further research is needed to discover whether this "factor" is linked to nerve survival, as we speculate, or not. We further speculate that suprathreshold measures of spatial/spectral and/or temporal resolution, such as those used in this study using lower stimulation levels and/or narrow stimulation modes, would serve as useful indicators of the functional health of local populations of neurons in cochlear implant patients.

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