Electrode ranking of "place pitch" and speech recognition in electrical hearing

David A. Nelson, Dianne J. Van Tasell, Anna C. Schroder, Sigfrid Soli,[a] and Samuel Levine
Clinical Psychoacoustics Laboratory, Department of Otolaryngology, Department of Communication Disorders, University of Minnesota, Minneapolis, Minnesota 55455

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The ability to distinguish electrical stimulation of different electrodes on the basis of "pitch or sharpness" was evaluated with an electrode ranking procedure in 14 individual users of the Nucleus cochlear implant. Prior to the electrode ranking test, absolute thresholds and maximum comfortable loudness levels were measured, and loudness balancing was accomplished across all usable electrodes. Performance on the electrode ranking task was defined in terms of d' per mm of distance between comparison electrodes. Large individual differences were found among cochlear-implant users. In subjects with good to excellent place-pitch sensitivity, the electrode ranking task was limited by a ceiling effect; however, in those with poor to moderate sensitivity d'/mm was relatively constant with spatial separation between electrodes. Place pitch was typically ordered from apical to basal electrodes, i.e., basal electrodes were judged to be higher in pitch than more apical electrodes. However, instances of reversals in place-pitch ordering were seen on some electrodes in some subjects. Instances were also seen of better electrode ranking in the apical half of the electrode array than in the basal half, and vice-versa. Analyses of the electrode ranking functions in terms of d' per stimulus indicated that, in some subjects, perfect performance was reached with as little as 0.75 mm between comparison electrodes, the minimum possible. In other subjects, perfect performance was not reached until the spatial separation between comparison electrodes was over 13 mm, more than three quarters of the entire length of the electrode array. Ten of the subjects also participated in a closed-set recognition task of intervocalic consonants. Although the maximum transmitted information for place of consonant articulation (which is based primarily on spectral speech cues) was only 34%, correlations between place-pitch sensitivity and transmitted speech information were as high as 0.71. This was surprising considering the excellent place-pitch sensitivity exhibited by some of the subjects, and may reflect limitations of the Nucleus speech coding strategy for representing spectrally coded speech information. The two prelingual subjects performed notably poorer on the speech task than the postlingual subjects, even though one of the prelingual subjects demonstrated very good place-pitch sensitivity. © *1995 Acoustical Society of America.*

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INTRODUCTION

One of the fundamental premises underlying the design of multiple-electrode cochlear implants is that selective stimulation of different electrodes, along an array of electrodes placed within the cochlea, will restore some semblance of what is commonly thought of as "place" pitch in the normal acoustically stimulated cochlea (Clark *et al.*, 1978; Eddington *et al.*, 1978; Tong *et al.*, 1982, 1983; Tong and Clark, 1985). Speech energy at different frequency regions is transformed into electrical current and then sent to different electrodes that presumably stimulate different populations of surviving neural elements.

Depending on the design of the speech processor and electrode array under consideration, the methods of encoding speech energy from different frequency regions and delivering it to separate electrodes may take several forms. For example, in the original processing scheme devised for the Symbion device (Eddington, 1980), the speech processor consisted simply of four bandpass filters, the analog outputs of which were delivered tonotopically to four separate electrodes in the implanted array (i.e., highest-frequency band to most basal electrode, and so forth). Processor designs subsequently developed to enable pulsatile stimulation of this electrode array (Wilson *et al.*, 1991) used the envelopes of the waveforms at the outputs of the bandpass filters to modulate a high-rate pulse train, with the same tonotopic organization of electrode stimulation. The series of processors developed for the 22-electrode array of the Nucleus device have also used a tonotopic relationship between stimulus frequency and stimulated electrode (Skinner *et al.*, 1991). The Nucleus processors in general use so far identify regions of maximal speech energy, usually corresponding to formant frequencies, and stimulate the electrode assigned to the corresponding frequency range in the patient's stimulation "map."

Although algorithms for encoding speech information in the stimulation of the electrode array differ dramatically, the outcome of each is that the distribution of speech energy across frequency is represented dynamically by the ongoing

[a]At the House Ear Institute, Los Angeles, CA.

TABLE I. Subject codes, ages at implant surgery (yrs), depth of insertion of electrode array (mm), number of years of deafness before surgery (yrs), number of months post surgery before initial testing began, processor type for those who participated in speech testing, pulse rate employed during pitch ranking, and the primary cause of deafness.

Subject code	Age	Insert depth	Years deaf	Initial testing	Processor type	Rate (pps)	Primary cause of deafness
AJA	42	20	10	6	WSP	125	Skull fracture
AMA	58	19	56	6	WSP	100	Congenital; prog. snhl (prelingual)
DVS	44	21	10	4	WSP	125	Congenital; progressive snhl
EES	54	17	4	14	MSP	100	Cogan's syndrome
JPB	56	24	4	36	MSP	125	Hereditary; progressive snhl
JRK	46	17	5	8		100	Encephalitis; progressive. snhl
JWB	51	20	4	13	WSP	100	Cochlear otosclerosis
KKS	39	17	18	8		125	Skull fracture
RFM	57	21	1	7	WSP	125	Meniere's disease
RRR	25	13	13	12		100	Autoimmune; ototoxicity
SYA	37	20	34	9	MSP	100	Meningitis (prelingual)
TVB	41	21	8	5	MSP	125	Progressive snhl
VVK	55	17	5	5		100	Coch. otosclerosis; progressive. snhl
WZM	66	20	30	4	MSP	125	Sudden hearing loss

pattern of stimulation across electrodes. Therefore, the perception of those speech cues that reside in the distribution of speech energy across frequency should be directly dependent on the ability of the user to differentiate among stimulation to different electrodes in the implanted array. It has been demonstrated that the phonemic feature of consonant place of articulation is represented primarily by the distribution of speech energy across frequency (Erber, 1972; Van Tasell *et al.*, 1987, 1992). Spectral shape information is of course contained in the temporal fine structure of the speech waveform, but the availability of the information in this form is limited by the temporal resolution of the auditory system. Consonant place therefore can be regarded as a mostly "spectral" speech cue, i.e., one for which very little information is extractable from the broadband speech waveform, and that therefore is not typically perceived by users of single-channel cochlear implants (Rosen *et al.*, 1989). It should be the case, therefore, that the ability of multichannel cochlear implant users to perceive spectral speech cues should be related to their ability to differentiate among stimulation to different electrodes in terms of the perception of the evoked pitch. The present study examines this fundamental premise in a population of users of the Nucleus 22-electrode cochlear implant.

The ability to differentiate stimulation on one electrode from neighboring electrodes was measured using an electrode ranking procedure (Townshend *et al.*, 1987) in which subjects ranked electrodes on the basis of "pitch or sharpness." Characteristics of electrode ranking were examined in some detail to discover how electrode ranking of place pitch varies among individual cochlear-implant users and to define the critical parameters that specify electrode-ranking performance in individual subjects. A subgroup of subjects participated in a closed-set consonant-recognition experiment, the results of which were analyzed to determine recognition of both temporally coded and spectrally coded speech features.

I. ELECTRODE RANKING BY PLACE PITCH

A. Method

1. Subjects

Fourteen users of the Nucleus cochlear implant participated in the electrode ranking experiment. Table I contains pertinent subject information. Two of the subjects were classified as prelingually deafened because their profound hearing losses existed at an early age. The remaining 12 subjects were classified as postlingually deafened.

2. Stimulus parameters

Each of the 14 subjects had a Nucleus 22-electrode array implanted into the cochlea. The electrodes within the array were separated from one another by 0.75 mm. For all subjects, except two, electrical stimulation was bipolar between every other electrode (referred to as BP+1), corresponding to a distance of 1.5 mm between electrodes. For subjects JRK and TVB, electrical stimulation was bipolar between adjacent electrodes, which is a spatial extent of 0.75 mm. This was the spatial extent dictated by the clinical protocols for these patients. Figure 1 illustrates the electrode numbering scheme. Individual electrodes were numbered from 1 to 22, beginning at the apical end of the electrode array. For convenience throughout this manuscript, each pair of bipolar electrodes will be referred to as a single electrode, and will be identified by the number associated with the more basal electrode. As illustrated in Fig. 1, the bipolar electrode pair consisting of electrodes #1 and #3 will be referred to as EL3, and the bipolar pair consisting of electrodes #2 and #4 will be referred to as EL4.

During the electrode-ranking procedure, sets of electrodes were chosen for pitch comparisons. In each set, one was denoted the apical EL and the other the basal EL. The distance between electrodes of each set specified the spatial separation between comparison electrodes. Figure 1 shows three examples of different spatial separations between comparison electrodes. For electrodes EL3 and EL4 the spatial

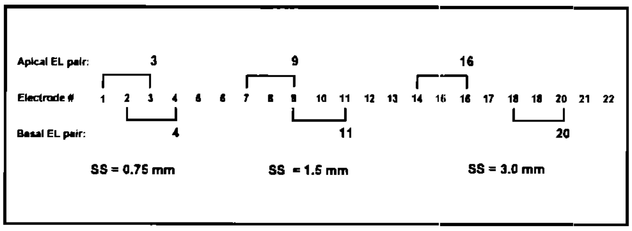

FIG. 1. Illustration of the electrode nomenclature used for these experiments. Numbering of consecutive electrodes begins at the end of the electrode inserted furthest into the cochlear duct, the apical end. The stimulation mode illustrated here is bipolar between every other electrode (BP+1), shown by the connecting lines between the two electrodes comprising a bipolar electrode pair. Since the physical distance between each electrode is 0.75 mm, the spatial extent between electrode pairs is 1.5 mm. For convenience, the two electrodes comprising a bipolar pair are referenced by only one electrode number, the number of the more basal of the two bipolar electrodes. For example, the bipolar pair consisting of electrodes #1 and #3 is referred to as EL3. For electrode ranking, place-pitch comparisons are made between stimulation on two such electrodes. One is the apical member and the other is the basal member of a comparison set. The physical distance between electrodes in each comparison set is referred to as the spatial separation (SS) between electrodes. Three spatial separations are illustrated. Comparisons between EL3 and EL4 have a spatial separation of 0.75 mm, those between EL9 and EL11 have a spatial separation of 1.5 mm, and those between EL16 and EL20 have a spatial separation of 3.0 mm.

separation is 0.75 mm, for EL9 and EL11 the spatial separation is 1.5 mm, and for EL16 and EL20 the spatial separation is 3.0 mm.

Electrical stimulation consisted of 500-ms stimulus bursts of biphasic 0.2-ms/phase current pulses, delivered at 100 or 125 pulses per second (as indicated in Table I). A silent period of 500 ms was maintained between stimulus bursts. Electrical stimuli were coded by a computer and delivered with the aid of a specially designed interface that transmitted the stimulus codes to the implanted electronics (Shannon *et al.*, 1990).

3. Psychophysical procedures

Prior to beginning the electrode ranking experiment, thresholds for detection were obtained for each electrode pair. Stimuli were trains of 500-ms stimulus bursts of 0.2-ms/phase biphasic pulses delivered at 100 or 125 pulses per second (indicated by subject in Table I), separated by silent intervals of 500 ms. An ascending method of adjustment procedure was used. Similarly, the maximum level at which a subject was willing to listen, referred to as the maximum acceptable loudness level (MAL), was measured for each electrode pair. That level was also determined with an ascending method of adjustment.

In order to minimize loudness cues across electrodes, stimulus levels were equated for loudness on each electrode. The loudness balance procedure began with a stimulus level that was comfortably loud on a reference electrode chosen to be in the middle of a subject's usable electrode array. Then stimuli on neighboring electrodes were presented alternately with stimuli on the reference electrode, and the current level on the neighboring electrode was adjusted by the experimenter until the stimulus on that electrode was judged by the subject to be equally loud to the stimulus on the reference electrode.

During the electrode ranking procedure, subjects listened to stimuli presented sequentially on two different electrodes in a two-alternative forced-choice procedure. The subject's task was to choose which stimulus was higher in "pitch" (or "sharper").[1] The subject indicated his/her choice by pressing one of two buttons on a computer mouse. No feedback was provided.

On a single trial, a set of two electrodes were chosen for comparison. One was the apical member of the set and the other was the basal member. For example, when comparing the pitch percepts on EL3 and EL4, as illustrated in Fig. 1, EL3 was the apical member and EL4 was the basal member. The order of presentation within the two listening intervals was chosen randomly from trial to trial. For each comparison set of electrodes, a subject's choice of the electrode with the higher pitch was recorded in an n-by-n matrix, where n was the total number of electrodes available for stimulation in that subject's electrode array. Each electrode was compared with every other electrode in the array. Ten comparison sets were chosen for testing during a single testing session in which each comparison set was presented ten times. Testing sessions continued until each electrode had been compared with every other electrode at least ten times. In those subjects for whom the task was particularly difficult, additional trials (up to 60 per comparison set) were accumulated.

B. Results and discussion

1. Electrode-ranking performance matrices

Raw data from the electrode ranking experiment consisted of a matrix describing the frequency with which a subject chose the basal member of a comparison set as being the one with the higher pitch. An example of a complete electrode ranking matrix for one subject (JWB) is shown in Table II. The most apical electrode available for pitch comparisons in this subject's array was EL5, the most basal electrode was EL20. In Table II, the entry in row five under column six shows the results for the EL5:6 comparison set. The more basal electrode, EL6, was judged to have a higher pitch percept than the more apical electrode, EL5, on 56% of 50 comparison trials. Since EL6 is closer to the base of the cochlea, one might expect that it would elicit a higher pitch percept if tonotopic organization within the cochlea were well preserved. In this case, EL6 was judged higher in pitch only 56% of the time. Chance performance in a two-interval task is 50%; therefore, this score does not indicate that a strong difference in pitch existed between EL5 and EL6. By contrast, for comparison set EL6:20 (row 6, col 20), EL20 was judged higher in pitch 100% of the time, which indicates that a strong pitch difference existed between EL6 and EL20. Other comparison sets show intermediate performance levels, such as EL7:10 where EL10 was judged higher in pitch than EL7 on 90% of the trials. Because EL10 is closer to the basal end of the electrode array than EL7, where surviving spiral ganglion cells were once associated with high-frequency acoustic stimulation, this pitch-ranking score is consistent with good tonotopic organization along the elec-

TABLE II. Electrode ranking matrix for one subject (JWB). Entries are the percentage of trials in which the basal member of the comparison set of electrodes (column electrode) was judged higher in pitch than the apical member of the comparison set (row electrode). Total trials per each comparison set was 50 for this subject.

		Basal electrode															
		5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	5		56	58	68	62	92	90	92	88	94	94	96	94	94	98	98
	6	···		84	58	70	64	76	84	72	98	90	94	100	90	86	100
	7	···	···		42	58	90	86	90	78	98	94	96	94	92	98	98
	8	···	···	···		58	62	70	80	82	88	96	86	86	80	90	98
	9	···	···	···	···		56	66	74	74	88	82	88	88	90	88	98
	10	···	···	···	···	···		58	74	68	84	76	84	60	82	88	96
Apical	11	···	···	···	···	···	···		72	58	68	62	76	86	70	76	96
electrode	12	···	···	···	···	···	···	···		40	64	60	62	64	56	60	92
	13	···	···	···	···	···	···	···	···		66	50	68	72	58	78	98
	14	···	···	···	···	···	···	···	···	···		50	60	52	42	40	90
	15	···	···	···	···	···	···	···	···	···	···		52	48	38	64	92
	16	···	···	···	···	···	···	···	···	···	···	···		30	40	56	84
	17	···	···	···	···	···	···	···	···	···	···	···	···		62	54	86
	18	···	···	···	···	···	···	···	···	···	···	···	···	···		68	86
	19	···	···	···	···	···	···	···	···	···	···	···	···	···	···		82

trode array. That was not always the case. Comparison set EL16:17 illustrates a reversal in expected tonotopicity. The more basal electrode, EL17, was judged higher than EL16 on only 30% of the trials, which means that on 70% of the trials the more apical electrode, EL16, was judged higher in pitch.

2. Perceptual sensitivity (d')

The electrode ranking matrix is simplified by transforming the pitch ranking scores into perceptual sensitivity units of d'. The rationale for this transformation is described in detail in the appendix of Townshend *et al.* (1987). Transformation of the electrode ranking matrix in Table II into d' units is shown in Table III. Here relatively poor place-pitch sensitivity was exhibited for the comparison set EL5:6, which yielded a d' score of only 0.21 (chance=0). Intermediate sensitivity performance was exhibited for EL7:10 with a d' score of 1.8. Perfect ranking of comparison sets on the basis of pitch, where the more basal electrode was always judged higher in pitch, was seen for EL6:20. Since the d' score for perfect performance is indeterminant, a d' score of 3.29 (rounded to 3.3 for the table) was assigned for perfect performance. This corresponds to an actual pitch ranking score of 99%, which assumes one error by chance would have occurred had 100 trials been tested. In cases where the more apical electrode pair was judged to be higher in pitch than the more basal pair, d' is negative (a reversal in electrode ranking from the physical ordering of the electrodes within the cochlea).

3. Cumulative sensitivity curves

In general, consecutive electrodes were ranked in pitch from the apex to the base of the electrode array. Since the electrodes were separated from one another by a constant distance, this suggests that the primary independent variable for place pitch might be the distance (in mm) between comparison electrodes. Therefore, electrode number was transformed into millimeters of distance along the electrode array by multiplying the difference between two electrode num-

TABLE III. d' performance matrix for subject (JWB). Entries are the d' values corresponding to the entries in Table II.

		Basal electrode															
		5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	5		0.21	0.28	0.66	0.43	2.0	1.8	2.0	1.7	2.2	2.2	2.5	2.2	2.2	2.9	2.9
	6	···		−0.3	0.28	0.74	0.50	1.0	1.4	0.82	2.9	1.8	2.2	3.3	1.8	1.5	3.3
	7	···	···		−0.3	0.28	1.8	1.5	1.8	1.1	2.9	2.2	2.5	2.2	2.0	2.9	2.9
	8	···	···	···		0.28	0.43	0.74	1.2	1.3	1.7	2.5	1.5	1.5	1.2	1.8	2.9
	9	···	···	···	···		0.21	0.58	0.91	0.91	1.7	1.3	1.7	1.7	1.8	1.7	2.9
	10	···	···	···	···	···		0.28	0.91	0.66	1.4	1.0	1.4	0.36	1.3	1.7	2.5
Apical	11	···	···	···	···	···	···		0.82	0.28	0.66	0.43	1.0	1.5	0.74	1.0	2.5
electrode	12	···	···	···	···	···	···	···		−0.4	0.50	0.36	0.43	0.50	0.28	0.36	2.0
	13	···	···	···	···	···	···	···	···		0.58	0	0.66	0.82	0.28	1.1	2.9
	14	···	···	···	···	···	···	···	···	···		0	0.36	0.07	−0.3	−0.4	1.8
	15	···	···	···	···	···	···	···	···	···	···		0.07	−0.1	−0.4	0.50	2.0
	16	···	···	···	···	···	···	···	···	···	···	···		−0.7	−0.4	0.21	1.4
	17	···	···	···	···	···	···	···	···	···	···	···	···		0.43	0.14	1.5
	18	···	···	···	···	···	···	···	···	···	···	···	···	···		0.66	1.5
	19	···	···	···	···	···	···	···	···	···	···	···	···	···	···		1.3

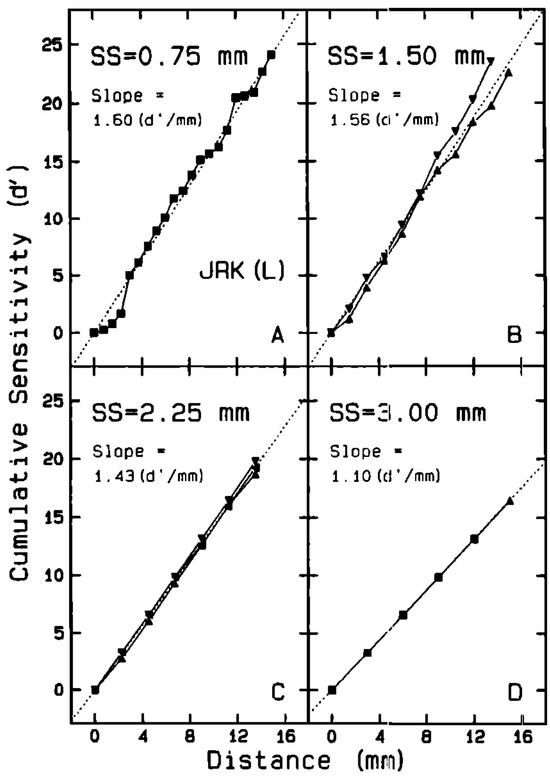

FIG. 2. Cumulative sensitivity curves from a single subject (JRK) for different spatial separations between electrodes. Cumulative sensitivity (d') is plotted on the ordinate as a function of the physical distance along the electrode array (in mm), which has been normalized to the most apical electrode available for pitch ranking. Each panel shows cumulative sensitivity curves for different spatial separations. Panel A contains the single curve resulting from a spatial separation of 0.75 mm. The slope of the least-squares best fit line (through zero) to the data indicates performance in sensitivity units per millimeter of physical distance between electrodes in a comparison set (d'/mm). The best fit line is shown by the dotted curve and the slope of that line is indicated in the panel. Panel B contains the two curves resulting from a spatial separation of 1.5 mm. In this case, to avoid overlapping of adjacent comparison sets, two curves are required to describe performance across the electrode array, with each curve normalized to the most apical electrode for each curve (see text). The best fit line to the average of those two curves is shown by the dotted curve, with the slope of that curve (in d'/mm) indicated in the panel. Panel C contains the three curves resulting from a spatial separation of 2.25 mm and panel D contains the four curves for a spatial separation of 3.00 mm. In both panels the best fit line to the average cumulative sensitivity curve is indicated by the dotted lines. The slopes of those curves are indicated in each panel.

bers by 0.75 mm, the physical distance between electrodes in the array. A convenient way of evaluating place-pitch perception as a function of distance along the electrode array is to examine cumulative sensitivity as a function of distance. The comparison sets of electrodes contained along the first negative diagonal in a d' performance matrix represent a constant spatial separation of 0.75 mm. If each successive d' score is added to its predecessor, a cumulative indication of perceptual sensitivity as a function of distance along the electrode array is realized. An example cumulative sensitivity curve for a spatial separation of 0.75 mm is shown by the filled squares in Fig. 2(a), for subject JRK. Cumulative sensitivity (d') is plotted as a function of the distance in mm from the most apical member of the electrodes available for pitch comparisons. We refer to this function as a *cumulative sensitivity curve*. The slope of the best fit line (through zero) to that curve, shown by the dotted line, specifies the average perceptual sensitivity per millimeter demonstrated across the available electrode array. For a spatial separation of 0.75 mm between comparison sets, that slope was 1.60 d'/mm for this subject, as indicated in the panel. The local slopes reflect local changes in sensitivity to place-pitch percepts along the electrode array.

Electrode ranking scores for spatial separations larger than 0.75 mm were treated in a similar manner. However, the number of curves increased as the spatial separation increased. For example, the second negative diagonal in Table III contains all of the d' scores for a spatial separation of 1.5 mm. That diagonal begins with a d' value of 0.28 for comparison set EL5:7, and ends with the d' value of 1.5 for EL18:20. In this case, adjacent comparisons sets EL5:7 and EL6:8) overlap in terms of cumulative distance along the electrode array; therefore, two cumulative sensitivity curves are required to specify perceptual sensitivity. One curve contains seven odd-numbered comparison sets (EL5:7, 7:9, 9:11, 11:13, 13:15, 15:17, and 17:19), and the other contains seven even-numbered comparison sets (EL6:8, 8:10, 10:12, 12:14, 14:16, 16:18, 18:20). The two cumulative sensitivity curves for a spatial separation of 1.5 mm are shown in Fig. 2(b). To obtain a single index of sensitivity for both comparison sets with a 1.5-mm spatial separation, cumulative distance was normalized to the most apical comparison set in each curve, and the two cumulative sensitivity curves were averaged into a single curve. The slope of the least-squares best fit line through zero of that averaged curve, shown by the dotted line in Fig. 2(b), was used to specify sensitivity per mm. The slope of that line is 1.56 d'/mm.

Larger spatial separations yielded an additional number of cumulative sensitivity curves from a decreasing number of d' values. A spatial separation of 2.25 mm yielded three curves (2.25/0.75) from 13 d' values. Those three curves are all plotted in Fig. 2(c) but are so close to perfect performance that they are barely distinguishable in the figure. The slope of the best fit line to the average of those three curves was 1.43 d'/mm. A spatial separation of 3.00 mm yielded four functions (3.00/0.75) from 12 d' values, which are all plotted in Fig. 2(d) but are indistinguishable because they were all perfect scores. The slope of the average curve was 1.10 d'/mm.

Figures 3 and 4 show cumulative sensitivity curves obtained from all twelve of the postlingual cochlear-implant users. Figure 5 shows the cumulative sensitivity curves from the two prelingual cochlear-implant users. Each panel displays the averaged cumulative sensitivity curves for an individual subject. The parameter is the spatial separation between comparison sets. The slopes of the curves in d'/mm are given within each panel.

Several features of these curves are noteworthy. Perhaps the most obvious is *the large variability in sensitivity to place pitch across subjects*. Sensitivity curves from five subjects who demonstrated excellent to moderately good place-pitch sensitivity, and from one subject who exhibited less acute sensitivity, are shown in Fig. 3. Among the subjects in Fig. 3, sensitivity to place pitch at a spatial separation of 0.75 mm varied from 3.16 d'/mm for subject RFM in the top left

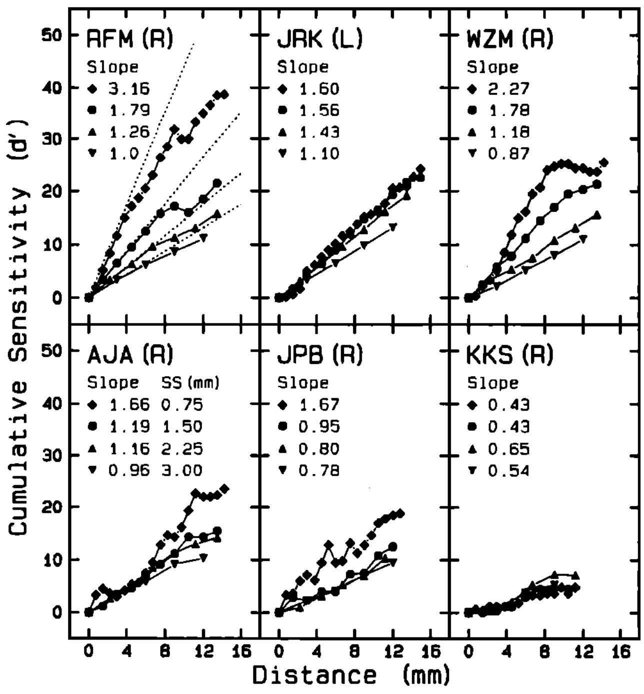

FIG. 3. Cumulative sensitivity curves for place pitch from six of the 12 postlingually deafened subjects with Nucleus cochlear implants. Cumulative sensitivity (d') is plotted on the ordinate as a function of the physical distance along the electrode array (in mm). Each panel shows cumulative sensitivity curves for a different subject. The parameter is spatial separation (SS) between comparison electrodes. Each curve is fitted (through zero) with a straight line and the slope of that line (in d'/mm) specifies sensitivity to place pitch across the entire electrode array for each spatial separation. Those slope values are indicated in each panel, with the symbol legend given in the lower left panel. Changes in sensitivity at local regions of the electrode array can be seen as local changes in the slopes of the curves. Dotted lines in the upper left panel for subject RFM show the cumulative sensitivity curves that would result if perfect performance were exhibited at each of the four spatial separations.

panel, to 0.43 d'/mm for subject KKS in the bottom right panel. Sensitivity curves from six additional subjects who demonstrated less acute place-pitch sensitivity are shown in Fig. 4, where d'/mm for a spatial separation of 0.75 mm ranged only between 0.69 and 0.12. Notice that Fig. 4 has an expanded ordinate to allow visualization of local details of the less acute sensitivity curves. Sensitivity curves from the two prelingual subjects are shown in Fig. 5. One scored moderately well with a d'/mm score of 1.76 (AMA) and the other (SYA) had extreme difficulty ordering electrodes on the basis of pitch with a d'/mm score of 0.06.

Similar cumulative sensitivity curves have been obtained by previous investigators from a few cochlear implant users, but such a wide range in sensitivity to place pitch has not been demonstrated before. Tong and Clark (1985) obtained cumulative sensitivity curves, based upon absolute electrode identifications of seven electrodes at a time, from three Nucleus implant users. Their results have been replotted in Fig. 6 as subjects P02, P04, and P07. Comparisons with the present results suggest that their electrode-identification procedure yielded results consistent with electrode ranking. Their subjects obtained d'/mm scores between 0.90 and 2.11 for SS=0.75 mm, which are in the range of the

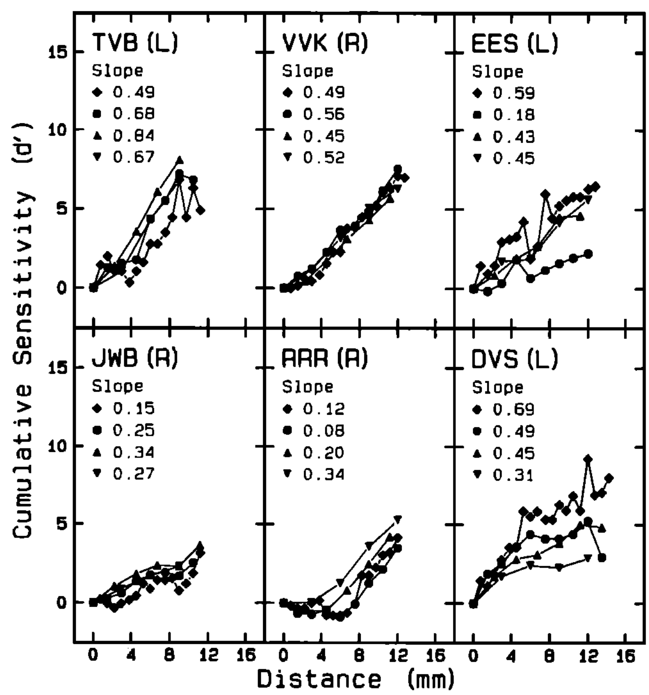

FIG. 4. Cumulative sensitivity curves for place pitch from the remaining six postlingually deafened subjects with Nucleus cochlear implants. Legend as in Fig. 3, except the ordinate has been expanded to allow visual resolution of less acute cumulative sensitivity curves.

better performers in the present study. Townshend (1987) reported electrode ranking results from one subject using a procedure very similar to that used here, but the stimulation mode was monopolar. Results from his subject AS are replotted in Fig. 6. In this case d'/mm was 0.55 for SS=2.50 mm, which suggests that place-pitch sensitivity was not much better than that demonstrated by the subjects least sensitive to place pitch in the present study for equivalent spatial separations. This could stem from the use of monopolar stimulation, or may reflect other subject-dependent factors as discussed below.

Such a wide range in sensitivity to place pitch across subjects may reflect differences in neural survival. Although little more than speculation at this point, subjects who dem-

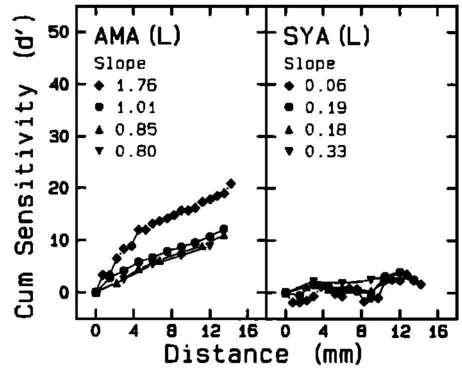

FIG. 5. Cumulative sensitivity curves for place pitch from the two prelingually deafened subjects with Nucleus cochlear implants. Legend as in Fig. 3.

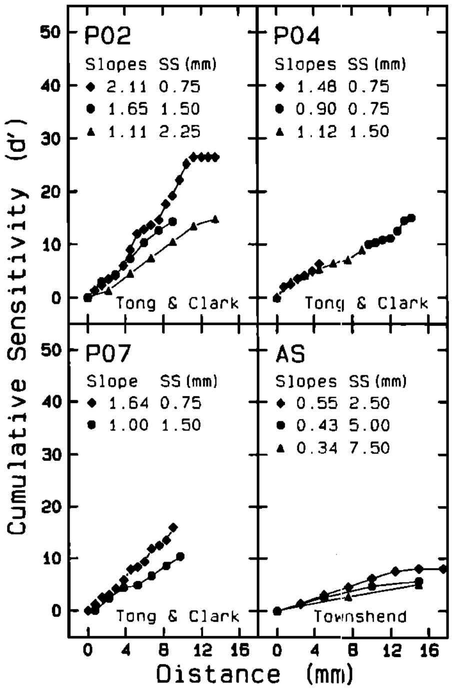

FIG. 6. Cumulative sensitivity curves for place pitch from individual subjects reported by previous investigators. Legend as in Fig. 3. Data for subjects P02, P04, and P07 were extracted from Figures 4–6 of Tong and Clark (1985), in which absolute identification of electrode number was performed on seven electrodes at a time using bipolar pulsatile stimuli similar to the present experiment. Data for subject AS were extracted from the electrode ranking matrix in Figure 1 of Townshend (1987), in which electrode ranking was performed using pulsatile stimuli but with monopolar stimulation.

onstrate steeper electrode ranking functions may possess a larger population of surviving neural elements, including functional cell bodies in the spiral ganglion and/or peripheral terminals, which remain functionally organized tonotopically. Those with poor place-pitch sensitivity may have a smaller population of surviving neural elements that might be more dispersed throughout the spiral ganglion. It might also be the case that the orientation between the electrode array and the target neural population is different among subjects. The electrode array of subjects with excellent place-pitch sensitivity might lie close to the lateral wall of the modiolus so that the geometry of current flow is conducive to stimulation of a small localized population of neural elements. Unfortunately, no independent measure of neural survival or electrode-target geometry is available on these patients, so the possible diagnostic value of electrode ranking performance remains only speculative.

A second feature of these cumulative sensitivity curves that is particularly noteworthy is the presence of local changes in sensitivity for adjacent electrodes (SS=0.75 mm). These local changes take two forms. *Large regions of very poor sensitivity* to place pitch in the basal half of the electrode array (distance >7 mm) are evident in the otherwise steeply sloping curves from subject WZM (Fig. 3, upper right panel) and subject AJA (Fig. 3, lower left panel). Subject AMA (Fig. 5, left panel) also demonstrated slightly poorer sensitivity in the basal half than in the apical half of the array. The reverse, poorer sensitivity in the apical half, can also be seen. Subject KKS (Fig. 3, lower right panel) and subject RRR (Fig. 4, lower middle panel) had virtually no sensitivity to place pitch in the apical half (distance <7 mm) but demonstrated some sensitivity in the basal half. Another type of local change in sensitivity can be seen as *reversals in place pitch ranking* for adjacent electrodes. In Fig. 3 such reversals were evident around 9.75 mm from the apical end for subject RFM, at 6.00 and 8.25 mm for subject JPB, and at 3.00 mm for subject AJA. In Fig. 4, reversals at 6.00 and 8.25 mm are evident for subject EES and between 11 and 13 mm for subject DVS. In Fig. 5, a reversal is evident at 8.25 mm for subject SYA. These regions of poorer place pitch sensitivity or place-pitch reversal may prove to be significant factors in speech recognition performance, and it may be possible to selectively disable electrodes from a patient's active array to improve speech recognition performance (Collins *et al.*, 1994; Collins *et al.*, 1994).

A third feature that is particularly noteworthy is the *change in slope with spatial separation* that can be seen in the cumulative sensitivity curves for some of the subjects but not others. The slopes of the sensitivity curves for subjects RFM, WZM, and JPB (Fig. 3) decrease dramatically as spatial separation increases beyond 0.75 mm. This decrease in slope with spatial separation is also evident between spatial separations of 2.25 and 3.00 mm for subject JRK (Fig. 3). For subjects AJA (Fig. 3) and AMA (Fig. 5), an average slope decrease is evident between spatial separations of 0.75 and 1.50 mm, but is mostly due to local slope changes for a spatial separation of 0.75 mm. For the remainder of the subjects the slopes of the curves are relatively constant with changes in spatial separation. This change in slope with spatial separation has important implications for assumptions about the underlying place-pitch dimension presumably measured by the sensitivity index d', as discussed in more detail in the next section.

4. Additivity of the place-pitch dimension

The slopes of the cumulative sensitivity curves specify performance in terms of sensitivity per mm of distance along the electrode array. If the pitch dimension that is reflected by the sensitivity index d' is unidimensional, if the distribution of perceptual sensitivity scores is Gaussian, and if no bias exists for one interval over the other in the 2AFC task, then the individual sensitivity scores on consecutive electrodes should be additive. This means that the sum of d' for two comparison sets 0.75 mm apart should be equal to d' for one comparison set 1.5 mm apart. For example, if the d' scores for comparison sets EL5:6 and EL6:7 are both 1.2, then the d' for EL5:7 should be 2.4. In that case the slopes of the cumulative sensitivity curves (in d'/mm) would remain constant as spatial separation increases, at 1.6 d'/mm (1.2 d'/0.75 mm, or 2.4 d'/1.5 mm), which was the case for subject JRK in Fig. 2. This additivity should continue until perfect performance ($d'=3.29$) is reached at some spatial separation. Once perfect electrode ranking of place pitch is reached, further increases in spatial separation cannot improve perceptual sensitivity as measured with this electrode ranking procedure.

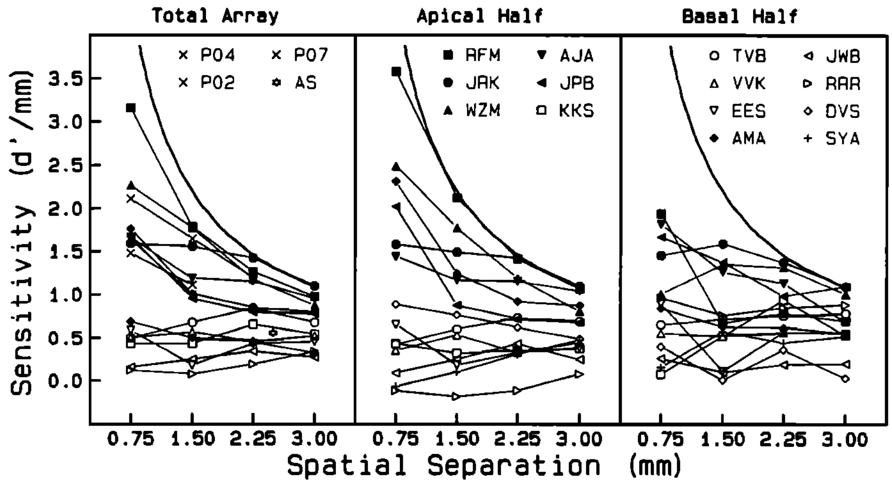

FIG. 7. Sensitivity to place pitch (in d'/mm) as a function of the spatial separation (SS) between comparison electrodes. The *left panel* shows data for the total electrode array, which are the slopes of the cumulative sensitivity curves given in Figs. 3–6 above. Open symbols show that sensitivity per mm is constant across spatial separation in those subjects who demonstrate less than excellent sensitivity to place pitch, which suggests that the place-pitch dimension measured with this technique is additive. The limits of sensitivity per mm imposed by perfect-pitch ranking ($d'=3.29$) are shown by the heavy negatively decelerating curve. Filled symbols show data from those subjects who demonstrated excellent sensitivity to place pitch at the smallest spatial separations. In those cases, near perfect performance for small spatial separations limited the possibility that sensitivity could double with doubling of spatial separation, which precluded additivity from being demonstrated. Results from previous investigations are also shown by the × symbols for data from Tong and Clark (1985) and by the ☆ symbol for data from Townshend (1987). The *middle* panel and the *right* panel show sensitivity to place pitch (in d'/mm), as a function of spatial separation, for electrodes in the apical half and the basal half of the electrode array, respectively. Symbols for individual subjects are the same in all three panels.

In the left panel of Fig. 7, slopes of the cumulative sensitivity curves (d'/mm) from previous figures are plotted as a function of the spatial separation between comparison electrodes. Notice that d'/mm is constant for spatial separations from 0.75 to 3.00 mm for the subjects whose data are indicated by unfilled symbols. For these subjects the place-pitch dimension is *additive*: doubling spatial separation maintains about the same sensitivity to place pitch per mm of distance along the electrode array. This supports the assumptions about place pitch enumerated above. On the other hand, for the subjects whose data are indicated by filled symbols, d'/mm decreases with increasing spatial separation. At first glance this appears to argue that place-pitch is not additive. However, one must consider that the absolute performance at any particular spatial separation is a limiting factor to sensitivity per mm, since the sensitivity index d' has a maximum of 3.29. Those subjects for which d'/mm decreased with spatial separation were those with the best sensitivity at small spatial separations. Because their performance was so good, it was not possible to double their score as spatial separation doubled. Their performance was limited by a ceiling effect, which is illustrated by the heavy negatively decelerating curve showing the maximum d'/mm score achievable if a subject scored 100% at each spatial separation. All but one of the subjects shown by solid symbols demonstrated negatively decelerating functions, which suggests their performance was limited by the ceiling effect. Subject JRK (solid circles) demonstrated a constant score around 1.6 d'/mm at 0.75 and 1.50-mm spatial separations, then hit the ceiling at 2.25- and 3.00-mm spatial separations where his scores decreased. Given this ceiling effect, the electrode ranking procedure cannot evaluate the additivity assumptions for subjects with excellent place-pitch sensitivity. The results of those subjects with poorer place-pitch sensitivity suggest that the place-pitch percept is additive.

5. Sensitivity in apical versus basal halves of the electrode array

Thus far, this analysis of sensitivity to place pitch has been based upon performance across the entire electrode array. As noted earlier, local changes in sensitivity along the electrode array were also seen in some subjects. The previous analyses tended to minimize local sensitivity changes because they averaged sensitivity across the entire electrode array. Such local changes in sensitivity might be particularly relevant for understanding why certain speech sounds are not recognized correctly. Therefore, separate analyses of sensitivity to place pitch were carried out on the results from electrodes in the apical and basal halves of the array. For each subject, the total electrode array was divided into two parts. Cumulative sensitivity curves were generated for electrodes comprising the apical half and the basal half of the electrode array. They were then fit in the same way as those curves illustrated in Fig. 2. This yielded two additional sensitivity scores (d'/mm) at each spatial separation, one for the apical half and one for the basal half as shown in the middle and right panels of Fig. 7, respectively.

Place-pitch sensitivity as a function of spatial separation for the *apical half* of the electrode array is shown in the middle panel of Fig. 7. Comparisons with results for the total array (left panel), indicates that sensitivity to place pitch in the apical half of the electrode array is similar to sensitivity to place pitch as reflected by the total array. For both analyses, the subjects tended to order themselves into the same two groups: Those who demonstrated excellent sensitivity to place pitch (filled symbols) and those who demonstrated less than excellent sensitivity (unfilled symbols).

Place-pitch sensitivity as a function of spatial separation for the *basal half* of the electrode array is shown in the right panel of Fig. 7. Here subjects ordered themselves differently than in the total array analysis. Some of the subjects with excellent sensitivity (filled symbols) in the total array analysis exhibited poorer sensitivity at small spatial separations in the basal half of the electrode array.

6. Changes in place pitch sensitivity with spatial separation

Conversion of the slopes of the cumulative sensitivity curves expressed as d'/mm (Fig. 7) into absolute performance at each spatial separation (d'/mm*SS) indicates that absolute performance grows with increased spatial separation between 0.75 and 3.00 mm. It is not clear from that analysis how sensitivity behaves for spatial separations larger than 3.00 mm. For those subjects with excellent sensitivity at spatial separations between 0.75 and 3.00 mm, it is not clear whether sensitivity remains high for larger spatial separations, or if sensitivity decreases for spatial separations larger than 3.00 mm. For those subjects with poorer sensitivity, it is also not clear if their sensitivity continues to improve with further increases in spatial separation. Therefore, to examine sensitivity to place pitch for larger spatial separations, the sensitivity scores associated with each spatial separation were averaged together. In Table III, this corresponds to the average of each negative diagonal in the sensitivity matrix, where the total number of cells in the average decreases as spatial separation increases.

Figure 8 shows the averaged sensitivity score (filled circles) plotted against spatial separation for each of the 12 postlingually deafened subjects. For comparison purposes the absolute sensitivity scores obtained by converting the slopes of the cumulative sensitivity curves (Figs. 3–5) into absolute sensitivity (d'/mm*SS) are also plotted (unfilled squares). Notice first that the estimates of absolute sensitivity obtained from the slopes of the cumulative sensitivity curves, which specify sensitivity for spatial separations up to 3.00 mm, agree fairly well with the averaged sensitivity scores. This is true for all subjects. The advantage of the cumulative sensitivity analysis over this analysis is that the cumulative sensitivity analysis reveals local changes in sensitivity along the electrode array.

The questions posed above, about place-pitch sensitivity for larger spatial separations, are addressed very explicitly by the individual curves in Fig. 8. First, those subjects with excellent sensitivity for small spatial separations reached asymptotic performance at some spatial separation and then remained at a high performance level for larger spatial separations. This is particularly evident in the curves for RFM, JRK, WZM, and AJA. Second, those subjects with relatively poor sensitivity to place pitch at small spatial separations eventually reached high performance levels when spatial separation was increased sufficiently. From these results, it appears that growth in sensitivity with spatial separation is a

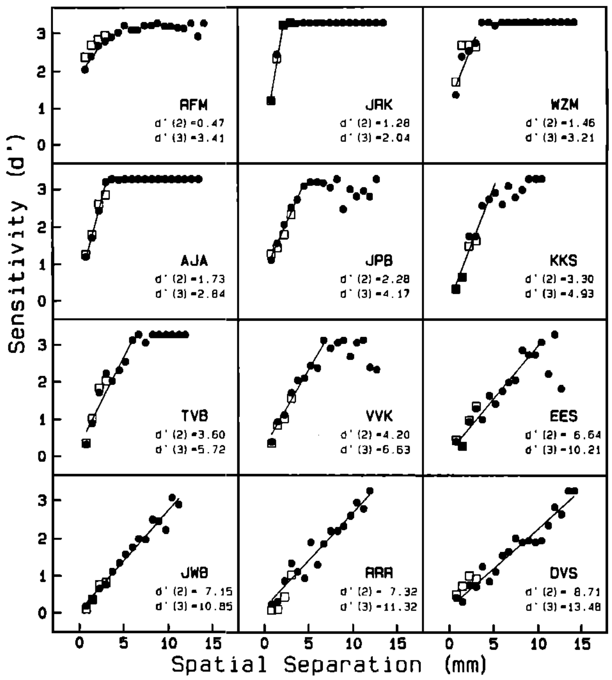

FIG. 8. Growth curves for absolute sensitivity to place pitch (d') as a function of the spatial separation (SS) between electrodes. Different panels show growth curves for individual subjects. Absolute place-pitch sensitivity (filled circles) was obtained by averaging the d' scores for each negative diagonal in the d' performance matrix of each subject (e.g., Table III for subject JWB). The slopes of the cumulative sensitivity curves (Figs. 3–6) were also converted to absolute sensitivity (d'/mm*SS) and are plotted (open squares) for comparison. For subjects with excellent sensitivity at small spatial separations, absolute sensitivity to place pitch asymptoted at perfect performance at some spatial separation and remained at perfect performance for larger spatial separations. For subjects with less than excellent performance at small spatial separations, absolute sensitivity continued to grow and finally approached perfect performance when spatial separation was large enough. The solid line shows the best-fit straight line through the growth portion of each subject's curve. The growth portion of each curve was fitted with least-squares procedures, which allowed calculations to be made of the spatial separation required to achieve a constant sensitivity score. The spatial separations required to achieve d' scores of 2.0 and 3.0 are indicated within each panel.

linear process that can be specified by a proportionality factor (slope). However, the best performers (RFM and WZM) reached near perfect performance at a spatial separation of 0.75 mm. Therefore, both a slope term and an intercept term were needed to adequately fit these growth curves. Least-squares fits to the growth portion of each curve are shown by straight lines. From these fits one can calculate the spatial separation that is required for each subject to reach a specific sensitivity criterion. Two criterion performance levels were chosen: $d' = 2.0$ and $d' = 3.0$. For the 12 postlingual subjects, the spatial separations required to reach those two performance levels are listed in each panel. For the two prelingual subjects (not shown in Fig. 8), the spatial separations at $d' = 2.0$ and $d' = 3.0$ were 2.67 mm and 5.05 mm for AMA (similar to JPB in Fig. 8) and 7.46 mm and 11.31 mm for SYA (similar to RRR in Fig. 8). For $d' = 2.0$, the required spatial separations ranged from as small as 0.47 mm (RFM) to as large as 8.71 mm (DVS). For $d' = 3.0$, the spatial separations ranged between 2.04 mm (JRK) to 13.48 mm (DVS).

II. SPEECH RECOGNITION

A. Method

1. Subjects

Ten of the 14 subjects who participated in the pitch-ranking experiment also participated in speech recognition testing. The two prelingually deafened subjects were included in this group. As indicated in Table I, five of the subjects used the MSP model speech processor. The remaining subjects used the WSP processor (see Skinner *et al.*, 1991, for a complete description of Nucleus processor designs).

2. Speech materials

The speech materials were a set of 21 /aCa/ disyllables uttered by a male talker, where C=/p,t,k,b,d,g,f,θ,s,ʃ,v,ð,z,ʒ,m,n,r,l,j,w,tʃ/. These same stimuli, minus the affricate /tʃ/ and /w/, formed the stimulus set used in two previous studies (Van Tasell *et al.*, 1987, 1992). The stimuli were digitized at a sampling rate of 10 kHz, with 12-bit resolution.

3. Testing procedures

Subjects were tested separately. They wore their speech processors for this experiment; each subject's processor was programmed with his or her regular map, which had been determined clinically and had been used daily for several months. The subject was seated in a sound-isolated room in front of a pair of high-quality audio loudspeakers and a video screen. Speech stimuli were played from computer memory at 10 kHz, amplified and sent to loudspeakers. Stimulus level was 75 dB SPL in the sound field at the subject's location. A test block consisted of four randomly ordered presentations of each of the 21 stimuli, for a total of 84 trials. On each trial, the stimulus was presented three times. The subject responded by using a computer mouse to highlight the appropriate item from the 21 alternatives shown on the video screen. No correct-answer feedback was provided. Data from each subject consisted of the pooled confusion matrix from the last five out of six blocks, or 20 observations per stimulus.

3. Speech information transfer analysis

Three statistics were calculated for each individual subject's confusion matrix:

a. Relative transmitted information for stimulus. This quantity was calculated as described by Miller and Nicely (1955). It is a measure of the information transmitted from stimulus to response, relative to the total amount of information available in the stimulus set; it therefore has a value from 0 to 1. It can be thought of as the proportion of available stimulus information that was transmitted to the subject.

b. Relative transmitted information for envelope. Normal-hearing subjects can, with a relatively high degree of accuracy, sort the items of the stimulus set used in this experiment into four categories based only on certain types of temporal information they contain (Van Tasell *et al.*, 1987, 1992). Because the temporal fine-structure cues had been removed from the speech-modulated noise stimuli presented to the normal-hearing listeners in those experiments, the two types of temporal cues remaining were, according to the classification system proposed by Rosen (1989): (1) "envelope" cues, conveying mostly information about phoneme duration, voicing, and manner, and (2) "periodicity" cues, conveying information about vocal fold vibration, and therefore voicing. Rosen *et al.* (1989) confirmed that users of the single-channel House/3M cochlear implant categorized consonant stimuli into the same temporal categories as did the subjects of Van Tasell *et al.* (1987). As in Van Tasell *et al.* (1992), we defined "envelope" as a single phonemic feature having four categories. Category membership is shown in Table IV. Relative transmitted information for the envelope features was calculated as described in Miller and Nicely (1955). It can be thought of as a measure of a subject's ability to extract and use the envelope and periodicity information in the speech waveform.

TABLE IV. Category membership of the speech stimuli under envelope and place features for the information transfer analyses.

Category #	Envelope feature	Place feature
1	[voiced fricatives and plosives] /b,d,g,v,ð,ʒ,z/	[front] /b,p,f,v,m,w/
2	[voiceless plosives] /p,t,k/	[mid] /d,s,j,t,n,z,ð,l,θ,tʃ/
3	[voiceless fricatives and affricates] /f,s,θ,ʃ,tʃ/	[back] /k,ʒ,ʃ,r,g/
4	[nasals and glides] /m,n,w,r,l,j/	

c. Conditional relative transmitted information for place. Sequential information analysis (SINFA: Wang, 1976) was used to calculate relative transmitted information for consonant place after removing the effects of envelope. Place category membership in the general categories of *front*, *mid*, and *back* is shown in Table IV. It was necessary to use SINFA to get an accurate representation of information transfer for place because the category membership of stimuli across the two features is not entirely orthogonal. Conditional relative transmitted information for place can be thought of as a measure of the subject's ability to recognize consonant place information. Therefore, this measure is as separate as possible from his or her ability to identify envelope category membership of the stimuli.

B. Results and discussion

1. Information transfer analysis

Table V contains the results of the information transfer analyses for each subject. The postlingually deafened subjects' relative transmitted information (RTI) scores for stimulus information were between 0.45 and 0.71. The range of RTIs for envelope cues for the postlingual subjects was similar at 0.39–0.77. The RTIs for the prelingually deafened subjects were substantially lower, with both subjects performing well below the range of the postlingually deafened subjects. It is likely that the incomplete phonological systems of the prelingually deafened subjects contributed significantly to their low scores on these measures. That is, the nonsense syllable recognition task assumes a normal English phono-

TABLE V. Information transfer quantities for individual subjects. Postlingually deafened subjects are ordered on the basis of their performance on the pitch ranking task at a spatial separation of 0.75 mm.

Subject	Relative transmitted information (RTI)		
	Stimulus	Envelope	Place*
RFM	0.65	0.56	0.29
WZM	0.57	0.59	0.22
JPB	0.71	0.77	0.34
AJA	0.60	0.67	0.31
EES	0.63	0.50	0.12
TVB	0.55	0.58	0.14
DVS	0.56	0.55	0.24
JWB	0.45	0.39	0.07
AMA**	0.29	0.08	0.11
SYA**	0.11	0.0	0.01

*conditional on envelope **prelingually deafened

logical system; this is probably not a valid assumption for the prelingually deafened subjects. Therefore, in the correlation analyses to be reported later, the speech scores from the prelingually deafened subjects were excluded, although data from these subjects are plotted in the figures with separate symbols.

The RTIs for envelope and stimulus for the postlingually deafened subjects compare in the expected way with the performance of normal-hearing subjects listening to temporal-only versions of the same stimuli (Van Tasell *et al.*, 1987, 1992). The implanted subjects in this study performed for the most part within the range of the normal subjects' scores in Van Tasell *et al.*, where only temporal envelope cues were available. This supports the conclusion that a subject who is good at extracting single-channel temporal speech information can do fairly well at identifying separate consonant phonemes.

The performance of the postlingual subjects for conditional RTI for place data was different from the normal data in Van Tasell *et al.* (1987, 1992), although not markedly so. The upper limit of conditional RTI for place for an untrained temporal-only listener is approximately 0.10 (Van Tasell *et al.*, 1992). It can be seen that several of the implanted patients performed above that limit, although none came close to his or her level of performance on the temporal feature. The performance of the two prelingual subjects was again very low, but not noticeably different from that of the postlinguals because the postlinguals' scores were also low. It seems clear that the subjects were not receiving much useful consonant place information from their implants. On the contrary, the picture that emerges from the data in Table V is that the *consonant identification performance of the subjects was more dependent on their extraction of temporal speech information than on extraction of spectral speech information*, even though they had "multichannel" cochlear implants.

2. Comparison of speech and pitch ranking data

The RTI data were compared with two measures of pitch sensitivity: (1) the slope of the cumulative sensitivity function in d'/mm (0.75 mm spatial separation), and (2) the spatial separation necessary to reach a performance criterion of $d'=2$. These two measures were chosen in order to avoid the ceiling effects described earlier for the larger spatial separations, and for the $d'=3$ spatial separation data. Only data from the postlingually deafened subjects were used in the correlations, although data from the prelingual subjects are plotted on the figures for information.

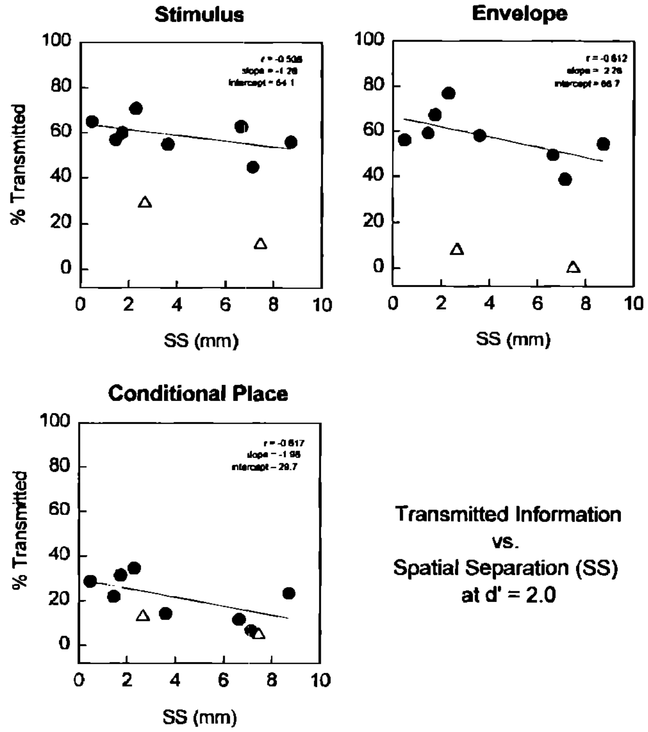

FIG. 9. Relative transmitted information (expressed in percent) for stimulus, envelope, and place conditional on envelope, as a function of the spatial separation necessary for a d' score of 2.0. Filled circles: postlingually deafened subjects. Open triangles: prelingually deafened subjects. Regression lines are fitted to data from postlingually deafened subjects only. Regression parameters are shown in each panel.

Figure 9 show RTIs for stimulus and envelope, as well as conditional RTI for place, plotted against the spatial separation required to reach a d' score of 2.0. It can be seen that better performance on either of the derived pitch-ranking measures was correlated with better performance on the speech measures, as expected. The correlations were somewhat higher for RTI for conditional place, at $r=-0.62$ for spatial separation at $d'=2$. It is interesting to note, however, that the pitch ranking measures were also correlated with RTI for envelope, with the higher correlation ($r=0.61$) observed between RTI for envelope and spatial separation at $d'=2$. The most informative aspect of the data, however, is probably not the correlation coefficients but the obviously restricted ranges of the speech data. The ranges of performance for stimulus and envelope were similar and somewhat restricted in the sense that all subjects performed fairly well on these measures, but not perfectly. Similarly, performance on conditional place was low, but the range was not large. Although the correlation coefficients were significant, the slopes of the regression lines were shallow. The same pattern of results was true for the speech data separately for the apical and basal electrodes in the array, except that for the basal data the pitch sensitivity data were also compressed into a smaller range.

In the case of conditional RTI for place, which one might think would be closely related to the pitch-ranking data, the conclusion is obvious. Although better pitch sensitivity definitely was related to better perception of consonant place information, even subjects with excellent pitch sensitivity were not able to extract enough consonant place information to produce even mediocre recognition of this feature. The data suggest strongly that the limitation on speech recognition performance is not the ability to perceive pitch changes across electrodes, but processor design and/or fitting.

The pattern of performance across features shows that subjects were already performing well on the envelope feature. Therefore, it was the poor place feature recognition that limited the information that could be transmitted about the stimulus set. Before consonant recognition performance can reach 100%, then, speech processor designs must be developed that can transmit place information at much higher levels than is apparently possible with the WSP and MSP processors used by these subjects. There is some recent evidence that new processor designs for use with the Nucleus electrode array will produce speech recognition improvements by increasing the richness of the display of frequency information across electrodes (McKay *et al.*, 1991; McDermott *et al.*, 1992; Whitford *et al.*, 1993).

III. CONCLUSIONS

(1) The ability to rank order electrodes consistently according to place pitch varies considerably among cochlear implant users.

(2) The electrode ranking task is limited by a ceiling effect in those subjects with excellent place-pitch perception. However, in those with poorer performance, the place-pitch dimension appears to be additive. Other scaling techniques are required to assess the additivity assumption in subjects with excellent place-pitch perception.

(3) Electrode ranking performance improves linearly with spatial separation between comparison electrodes. Those subjects with poor performance at small spatial separations can reach perfect performance if spatial separation is increased. This suggests that a reduction in the number of active electrodes might provide a better representation of place-pitch across electrodes for these subjects. Future research might explore the possibility of improving speech recognition performance by reducing the number of active electrodes in some subjects.

(4) Reversals in electrode ranking performance are evident on some electrodes in some subjects. In others, very flat electrode ranking functions for local regions of the electrode array indicate little or no place-pitch sensitivity. Future research should investigate whether or not improved speech recognition performance can be achieved by selectively removing electrodes from the active electrode array in regions where poor local performance is exhibited or where reversals occur.

(5) Prelingual subjects do not necessarily demonstrate poor place-pitch perception. While the two prelingual subjects in this study exhibited different place-pitch sensitivity, one performed moderately and the other poorly, their speech recognition performance was uniformly poor. Their lack of language development before becoming deaf might be a common factor for poorer speech recognition ability (Tong *et al.*, 1988).

(6) Relatively good transmission of consonant phoneme information does not necessarily require excellent place-pitch sensitivity. Subjects with very poor place-pitch sensitivity still received upward of 60% of stimulus information, primarily via the transmission of envelope information.

(7) The primary limitation on the transmission of larger amounts of consonant information appears to be the transmission of spectrally based speech information. None of the subjects performed beyond 34% relative transmitted information for consonant place, even though some of the subjects showed excellent place-pitch sensitivity. The place-pitch data were obtained using direct stimulation of selected electrodes, while the speech data were obtained using the subjects' speech processors. The disparity between place-pitch sensitivity and speech results suggests that the spectrally coded speech information provided by the speech processor may not have been sufficient to take advantage of the excellent place-pitch sensitivity shown by some subjects.

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[1]The use of the term "pitch" is used here with some caution. No one has demonstrated melody recognition for across electrode stimulations, which should be a requirement for the percept to be truly called "pitch." Neither is the use of "place pitch" intended to imply that the percepts experienced by implant users when stimulated on different electrodes are the same as those experienced by acoustically stimulated listeners when stimulated at different frequency regions, especially with pure tones. Some subjects report that stimuli sound "sharper" on adjacent electrodes, which may indicate that the appropriate perceptual dimension correlated with stimulation across electrodes is "timbre" rather than pitch (Plomp, 1970; Pols, 1970). The procedures used here do not distinguish between the dimensions of "pitch" and "timbre."

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