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Effects of Electrode Location on Speech Recognition with the Nucleus-22 Cochlear Implant

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Abstract

Speech recognition performance was measured as a function of electrode in two experiments with the Nucleus-22 cochlear implant using 4-electrode SPEAK speech processors. In experiment 1, the four stimulated electrode pairs were shifted in 0.75-mm steps over 3 mm in the apical-basal direction. In experiment 2, the four electrodes were closely spaced and positioned apically, medially, or basally. An additional condition spaced the four electrodes as widely as possible. In experiment 1, City University of New York sentence scores showed a significant decrease in performance as the electrodes were shifted basally; no other speech measures showed a significant change with electrode location. For experiment 2, all scores were the best with the processor that had the electrodes spaced as widely as possible. In both experiments, all 4-electrode SPEAK processors produced significantly poorer speech recognition than the subject's own 20-electrode processor. These results indicate that the location of electrodes is an important factor in implant performance.

Key Words: Cochlear implant, electrical stimulation

Abbreviations: C = maximum comfortable loudness levels, CI = cochlear implant, CUNY = City University of New York, NU-6 = Northwestern University Auditory Test No. 6, T = electrical thresholds

The normal cochlea is arranged tonotopically, with higher frequencies represented at the basal end and lower frequencies at the apical end. Multichannel cochlear implants such as the Nucleus-22 prosthesis filter sound into multiple frequency ranges, and the output of each filter is sent to different electrodes to simulate the normal tonotopic frequency-to-place mapping. However, in cochlear implants, there are many uncertainties regarding the pattern of activation along the nerve array. Electrodes that are not fully inserted will result in a basal shift in the tonotopic pattern of activation. Irregularities in the local nerve population could also cause local tonotopic perturbations in the pattern of activity along the nerve array.

Several experiments have explored the effects of alterations in the tonotopic location and spacing on speech recognition. In normal-hearing listeners, Shannon et al (1998) measured speech recognition with a four-band noise vocoder in which the noise-band carriers were shifted 8 mm basally from the speech analysis bands. Their results showed a large decrease in speech performance when the frequencies of the noise bands were not matched to the speech analysis bands. Dorman et al (1997) measured speech recognition with a five-channel sinusoidal vocoder as the sinusoidal carriers were systematically shifted in frequency from the frequency bands they were representing. They found that performance decreased steadily as the tonotopic shift increased.

Fu and Shannon (1999a) shifted the frequency representation in four-band SPEAK processors with Nucleus-22 implant subjects over a 13-mm cochlear distance and also simulated such shifts in normal-hearing listeners. Vowel and consonant recognition were relatively unaffected by frequency shifts of ±3 mm relative to the normal tonotopic map. However, for shifts

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of more than 3 mm, speech recognition performance dropped dramatically. Implant listeners showed peak performance with the frequency allocation that most closely matched the one they had been using in their clinical speech processor. This indicated that implant listeners had accommodated to the frequency allocation of their clinical processor even though in some cases this frequency assignment was shifted 6 to 10 mm relative to the normal acoustic tonotopic location of their electrodes.

Fu and Shannon (1999b) shifted four electrode pairs 3.0 mm toward the base from the most apical position in 0.75-mm steps, keeping the spacing between stimulated electrodes fixed at 3.75 mm. They also systematically changed the spacing between electrode pairs from 1.5 to 4.5 mm while holding the most apical electrode fixed. Vowel and consonant scores were best when the electrodes were in the most apical conditions and when electrode pairs were separated by 3 to 3.75 mm. Spectral cues (vowel recognition and consonantal place of recognition) were more sensitive to the manipulations than temporal cues (consonantal voicing and manner).

Geier and Norton (1992) evaluated the effects of varying the location of programmed electrodes on speech perception in five patients having the Nucleus-22 cochlear implant with an earlier feature-extraction signal processing strategy ($F_0F_1F_2$). Four conditions were tested: all 20 electrodes used, five apical electrodes eliminated, five middle electrodes eliminated, and five basal electrodes eliminated. Two subjects performed equally well, regardless of condition, and three subjects demonstrated poorer performance on all test measures when the five electrodes from the apical portion of the array were turned off. With the subjective rating scale used, all subjects rated their current processor the best and gave the lowest score to the processor with five apical electrodes eliminated.

The present study measured speech recognition as a function of electrode location and spacing in patients with the Nucleus-22 cochlear implant and a SPEAK processing strategy. All conditions use a four-band processor because using only four electrodes allows flexibility in the positioning and spacing of the stimulated channels. Experiment 1 examined the effect of moving the four stimulated electrodes along the tonotopic dimension of the listener's cochlea while holding the spacing between electrodes constant. Experiment 2 investigated the effect of both location and spacing of the four electrodes on speech recognition.

EXPERIMENT 1

Method

Listeners

Ten postlingually deafened adults (18 years and older) with at least 6 months experience using the Nucleus-22 cochlear implant with the SPEAK speech processing strategy participated in this study (Table 1). There were five females and five males, all native speakers of American English. Relevant information for the 10 subjects is presented in Table 1. All listeners had used their normal speech processor for at least 6 months and had 20 active electrodes available for use. Electrode insertion depths were determined from the surgical report in the listeners'

Table 1 Listener Data for Experiment 1

Listener	*Age*	*Gender*	*CI Ear*	*Etiology*	*Age at Onset of HL*		*Age at Onset Profound*		*Hearing Aid Use*		*Depth of Insertion (Rings Out)*	*Duration of Implant Use (Yr)*	*Frequency Allocation Table*
					L	*R*	*L*	*R*	*L*	*R*			
N2	64	F	R	Autoimmune	27	27	51	51	Y	Y	0	9	7
N3	56	M	R	Trauma/unknown	45	10	45	45	N	N	3	7	7
N4	40	M	R	Trauma	35	35	35	35	N	N	4	5	9
N5	81	M	R	Meningitis	52	52	52	52	N	N	6	7	7
N6	65	F	R	Ototoxicity	54	54	54	54	Y	Y	0	7	9
N7	55	M	R	Unknown	20	20	47	44	Y	N	0	2	9
N9	55	F	L	Hereditary	8	8	38	38	Y	Y	4	7	9
N14	63	M	R	Unknown	37	37	47	61	N	Y	0	1	9
N15	77	F	L	Cochlear oto	62	62	75	75	Y	Y	6	1	9
N17	71	F	R	Unknown	41	41	68	68	Y	Y	10	1	7

medical chart. Four listeners had all 32 platinum bands inserted (22 active electrodes plus 10 stiffening rings — a condition termed "0 rings out"), one listener had 29 bands inserted (3 rings out), two listeners had 28 bands inserted (4 rings out), two listeners had 26 bands inserted (6 rings out), and one listener had 22 electrodes inserted (10 rings out). Six listeners' normal processors used the default frequency division, frequency allocation table 9 (150–10,823 Hz), and four listeners' processors used frequency allocation table 7 (120–8658 Hz).

Speech Materials

Speech perception tests used to evaluate the experimental settings were all presented without lip-reading (sound only). The tests consisted of vowel and consonant discrimination, as well as open-set word and sentence recognition.

Vowel stimuli were presented using a custom stimulus presentation and scoring program (CONDOR; Robert, 1998). Medial vowels produced by 10 different male talkers and 10 different female talkers were drawn from the materials recorded by Hillenbrand et al (1995). Vowel recognition was measured in a 12-alternative identification paradigm, including 10 monophthongs (/ɔ u ɛ i o e ɪ ʊ ʌ ɑ/) and 2 diphthongs (/æ ɜ/), presented in an /h/vowel/d/ context (heed, hid, head, had, who'd, hood, hod, hud, hawed, heard, hoed, hayed). Chance performance level for this test was 8.33 percent correct, and the 95 percent confidence level was 27.0 percent correct.

Consonant stimuli were taken from the soundtrack of the Iowa audiovisual laser videodisk (Tyler et al, 1987). A single male talker produced the consonants. Consonant confusion matrices were compiled from 10 presentations of each of 16 medial consonants (/b d g p t k l m n f s ʃ ð v z/), presented in an /a/-consonant-/a/ context. Chance performance level for this test was 6.25 percent correct, and the 95 percent confidence level was 15 percent correct.

The Northwestern University Auditory Test No. 6 (NU-6) was used to evaluate open-set phoneme and word recognition (Tillman and Carhart, 1966). The Auditec tape recordings included four lists of 50 monosyllabic words containing 150 phonemes. Listener responses were scored separately for words and phonemes correctly identified. Since there are only four NU-6 lists, a practice set was not given. Because there were five test conditions in the electrode location experiment, one of the NU-6 lists was repeated — the list with the poorest score in the initial four test conditions.

Recognition of words in sentences was measured using the soundtrack from the City University of New York (CUNY) laser videodisk everyday sentences (Boothroyd et al, 1985). For each condition, data were collected for 12 sentences, representing 102 key words, from each listener. The sentences were of easy-to-moderate difficulty and presented with no context, and no sentences were repeated to an individual listener.

To assess subjective benefit of the experimental processors in a variety of environments, a cochlear implant benefit questionnaire, modified from the Profile of Hearing Aid Benefit (Cox and Gilmore, 1990), was given. The questionnaire consisted of 20 questions describing hypothetical listening situations, and listeners were asked to estimate the percentage of time that the situation would present a communication difficulty with that processor. The overall score is reported as an average percentage of the 20 questions. A low score represents good perceived benefit in all situations and a high score represents poor perceived benefit in many listening situations.

Experimental Speech Processor Conditions

Each listener was tested with his/her normal clinical speech processor and five experimental speech processors that were worn for 2 days each prior to testing. In the Nucleus-22 implant, the 22 electrodes are numbered from 1 at the basal end to 22 at the apical end of the array, with electrodes spaced 0.75 mm apart. The electrodes are normally stimulated as a bipolar pair, with the most basal member of the pair termed the "active" electrode. The normal Nucleus-22 SPEAK processing strategy divides speech into 20 contiguous frequency bands and assigns the output of each band to one electrode pair (McDermott et al, 1992). A selection of nine different frequency tables is available for a 20-electrode processor, increasing in frequency range from 75 to 5411 Hz (table 1) to 150 to 10,823 Hz (table 9) (Cochlear Corporation, 1989). The same frequency band division was used across all conditions (either frequency table 7 or 9, whichever was normally used by that patient). Experimental conditions were created with four activated electrodes (instead of the normal 20) by changing the number of analysis bands assigned to each electrode (Fishman et al, 1997).

For example, the output of analysis bands 1, 2, 3, 4, and 5 would normally be assigned to electrodes 1, 2, 3, 4, and 5, respectively. In one experimental processor, the outputs of all five bands were assigned to electrode 5 only (Fig. 1). In this case, electrodes 1, 2, 3, and 4 received no stimulation. When this assignment pattern was repeated along the entire electrode array, the outputs of the 20 analysis filters were presented to only 4 electrodes. For all conditions in experiment 1, the spacing between adjacent electrode pairs was held constant at 3.75 mm, whereas the location of the most apical pair was changed from electrode 20 to 16 (see Fig. 1). The sequence of testing for the five experimental processor conditions was randomized across subjects.

In the normal SPEAK processing strategy, between 6 and 10 frequency bands with the highest energy are selected for stimulation approximately every 4 msec (McDermott et al, 1992), and the electrodes assigned to those bands receive pulses. The average pulse rate per electrode was higher in the experimental processors because the activated electrodes received the output of more than one analysis filter band. For example, since the target electrode was assigned to receive the output of five contiguous analysis bands, that electrode received a stimulation pulse if any of the five filter bands was selected for stimulation. If all five filter bands were selected for stimulation, the electrode would receive five pulses in that stimulus frame. "Stimulus level" coding was used, which changes the electrical stimulation level by changing both pulse amplitude and pulse duration (for details, see *Audiologist Handbook,* Cochlear Corporation, 1989). At high loudness levels, the pulse duration is longer, resulting in a lower overall pulse rate.

For each experimental condition, electrical thresholds (T) and maximum comfortable loudness levels (C) were obtained using the Nucleus diagnostic and programming system with a personal computer and a dual processor interface with Cochlear Corporation 6.100 software. A stimulus pulse train of 250 Hz and 500-msec duration was used to obtain T and C levels. T levels were estimated by a standard clinical bracketing procedure. One to five pulse bursts were presented, and the listener was instructed to count the number heard. The T level used in the processor was the level at which the listener counted the pulses correctly 100 percent of the time. To obtain C levels, the experimenter increased the electrical level until the listener felt the loudness was the highest level that was still comfortable. These initial C levels were adjusted to balance loudness across adjacent electrodes.

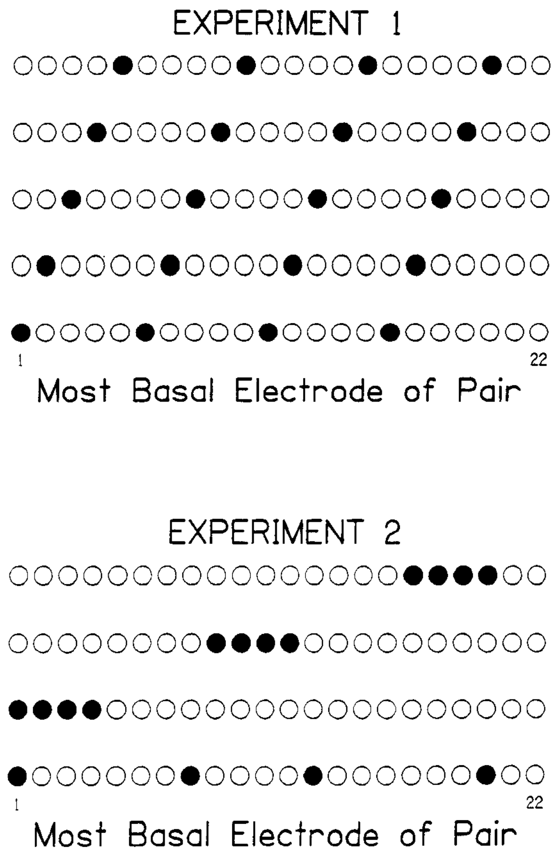

Figure 1 Schematic representation of experimental speech processor conditions. For experiment 1, the five conditions directed the output of 20 analysis filters to four evenly spaced electrodes. Darkened circles represent the activated electrodes. Electrodes were systematically shifted from apex to base of electrode array, keeping spacing constant. For experiment 2, there were three processors with four closely spaced electrodes at apical (4A), middle (4M), or basal (4B) locations. One processor used four widely spaced electrodes (4WS).

All listeners were programmed in the bipolar-plus-one mode electrode pairing (BP+1) for both their normal processors and for all experimental conditions. The same frequency allocation table was used for all conditions.

Procedure

During all testing, the listener was seated in front of a calibrated loudspeaker (Grason-Stadler) in a sound-treated room (IAC) with the microphone of the headset positioned 1 meter from the speaker. Throughout the testing, the listeners' speech processor sensitivity remained at the setting that was most comfortable in their everyday environments with the function switch set to normal. The presentation level was 70 dB on an A-weighted scale. All speech materials were recorded. A Panasonic laser videodisk player, a Yamaha cassette deck (Model KX-530), and a GSI audiometer (Model 16) were used to present the test items.

For all testing, listeners were instructed as to the type of material in the test (words, sentences, etc.) and the type of response required. Listeners were encouraged to guess on all items. No repeat presentations or feedback was provided.

Baseline testing was done using the listener's normal processor prior to the experimental conditions. The five experimental conditions were presented to each listener in random order. For each experimental processor, the battery of speech tests was administered to listeners after they had worn the experimental processor for 2 days to give them time to adjust to the processor. Because some of the experimental processors made everyday life difficult for the listeners, the adaptation period was limited to 2 days. The listener's normal settings were restored to the speech processor after the testing session until the listener returned for the next experimental condition, typically 1 week later. The period of 2 days for the adjustment period was selected in order to allow for some adaptation to the processor without the addition of undue hardship on the life of the patients because everyday listening with some of the processors was difficult.

Results

CUNY Sentences

Recognition of sentences was significantly affected by electrode location ($F = 3.99$, $df = 4$, $p < .01$) (Fig. 2A). Pairs of means were compared for significant differences using Bonferroni adjustments. Significantly higher scores were observed when the electrode locations were shifted so that electrodes 19 and 20 were the most basal active electrodes in the set. Performance was best when the electrodes were more apically located and decreased as the electrodes were shifted basally. The best mean performance with a 4-electrode experimental processor (with only 48 hours of experience) was only slightly poorer than the performance with the 10- or 20-electrode everyday processor.

Vowels

Vowel recognition did not change significantly as a function of the electrode location ($F = 1.29$, $df = 4$, $p > .05$) (Fig. 2B). Overall mean performance with the experimental 4-electrode processors was significantly poorer than performance with the 20-electrode everyday processor ($F = 8.46$, $df = 5$, $p < .01$, with statistically significant Bonferroni adjustments comparing all 4-electrode experimental processors to the 20-electrode everyday processor). Figure 2B also shows average performance of three implant listeners in similar conditions from a study by Fu and Shannon (1999c). In their study, implant listeners were not given any experience with the new experimental processor, and a significant drop in vowel recognition was observed as the electrodes were shifted basally.

Consonants

Consonant recognition also did not change significantly as a function of the electrode location ($F = 0.19$, $df = 4$, $p > .05$) (Fig. 2C). No significant difference in consonant recognition was observed across any of the five experimental processors. Performance with the experimental 4-electrode processors was not significantly poorer than the average score for the 20-electrode everyday processors, which was 74 percent correct. The present results are similar to previous results from a similar condition in a study by Fu and Shannon (1999c), also shown in Figure 2C, which were obtained with no practice period.

NU-6 Words and Phonemes

NU-6 words were scored for both words correct and for phonemes correct. Neither the word ($F = 1.76$, $df = 4$, $p > .05$) nor the phoneme scores ($F = 1.86$, $df = 4$, $p > .05$) were significantly affected by the electrode location (Fig. 2D, 2E). Both word ($F = 12.65$, $df = 5$, $p < .01$) and phoneme scores ($F = 10.17$, $df = 5$, $p < .01$) were significantly poorer than the performance levels with their 20-electrode everyday processor.

Questionnaire

After the 2-day trial with each experimental processor, listeners completed a 20-item questionnaire on perceived quality and benefit. Mean ratings for all five experimental processors were significantly poorer than the score for the original processor ($F = 10.48$, $df = 5$, $p < .01$), but mean ratings for all five experimental conditions were not significantly different from each other ($F = 1.11$, $df = 4$, $p > .05$). Subjectively, all listeners were distressed with the poor quality of all five experimental processors and strongly preferred their original processor.

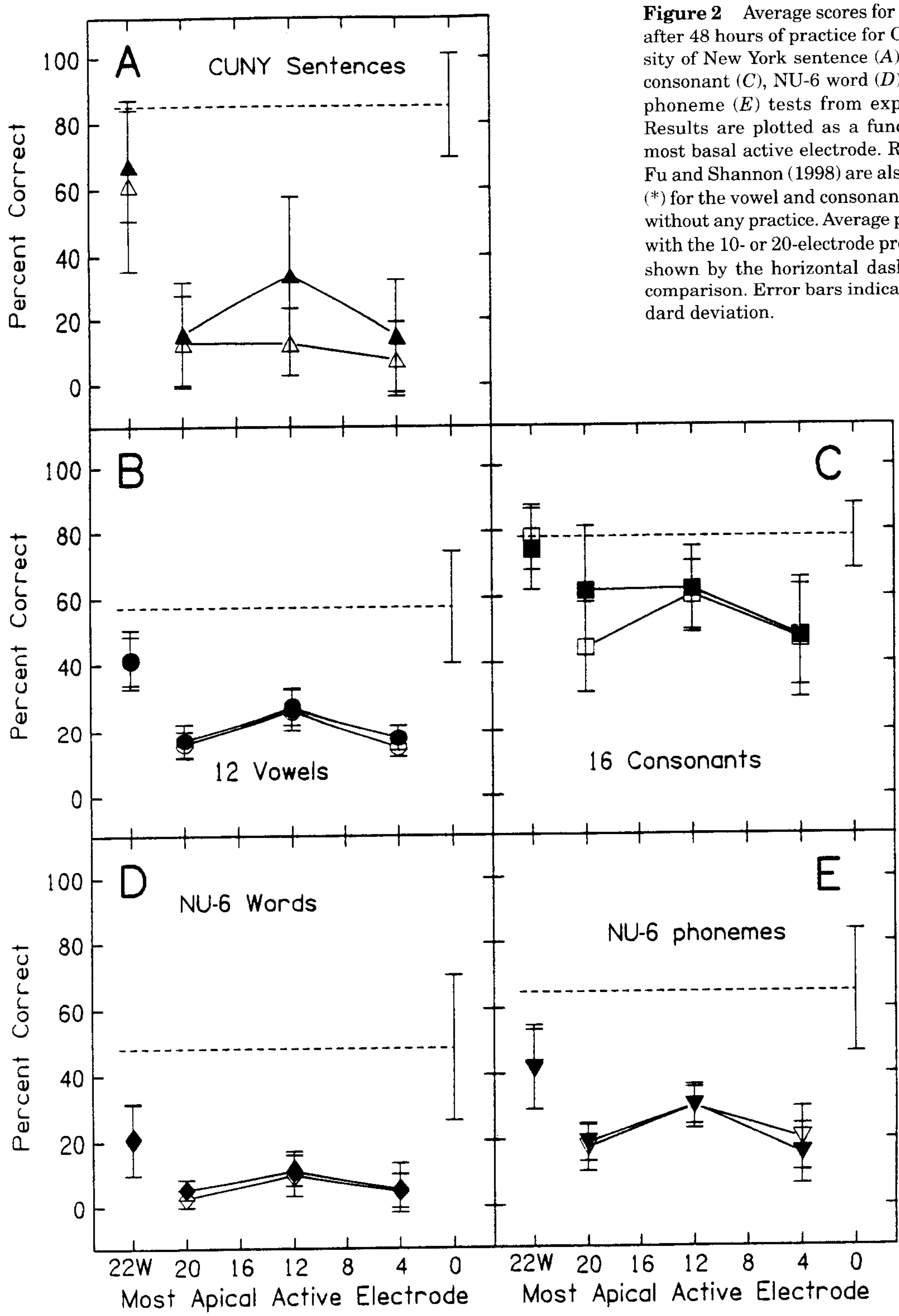

Figure 2 Average scores for 10 listeners after 48 hours of practice for City University of New York sentence (*A*), vowel (*B*), consonant (*C*), NU-6 word (*D*), and NU-6 phoneme (*E*) tests from experiment 1. Results are plotted as a function of the most basal active electrode. Results from Fu and Shannon (1998) are also presented (*) for the vowel and consonant conditions without any practice. Average performance with the 10- or 20-electrode processors are shown by the horizontal dashed line for comparison. Error bars indicate one standard deviation.

Learning Effects

Scores on the vowel and consonant tests were remeasured with each listener's normal processor following administration of all experimental conditions as a check on learning effects over the course of the experiment. The results show no significant differences (paired t-test, df = 9, p = .76 for vowels, p = .302 for consonants) from the initial administration, indicating that scores obtained reflect effects of experimental conditions rather than learning.

EXPERIMENT 2

Method

Listeners

Only six of the subjects who participated in experiment 1 took part in experiment 2 (N3, N4, N5, N6, N7, and N17; see Table 1).

Speech Materials

Vowel, consonant, word, and sentence identification testing were performed. These speech materials were identical to those used in experiment 1.

Experimental Speech Processor Conditions

Each listener was tested with his/her normal speech processor and four experimental speech processors. Testing was performed immediately after the listeners received each experimental processor and again after wearing it for 2 days. The processors in all experimental conditions were created with four activated electrode pairs. The 20 analysis filters were presented to four electrode pairs by assigning the output of 5 analysis filters to each electrode pair. For three of the experimental processors, four adjacent electrode pairs were stimulated at the basal-most end (4B), the apical-most end (4A), or in the middle of the electrode array (4M) (see Fig. 1). In these three conditions, the most basal active electrodes were 20, 12, and 4, respectively. In an additional condition ("widely spaced" — 4WS), both the apical and basal end electrodes were stimulated, as well as two more central electrodes.

Results

No significant difference was observed between the scores of tests administered before and after the subject wore the processors for 48 hours (Fig. 3) for vowels, words, and phonemes (see statistic results in Table 2). For CUNY sentence and consonant scores, there was a significant difference. However, after analyzing with paired t-tests, CUNY scores for the closely spaced central electrode map (4M) were the only scores that differed significantly before and after the subject wore the processor for 48 hours (paired t-test, $df = 5$, $p < .05$). Post hoc paired comparisons of consonant scores showed no significant differences (paired t-test, $df = 5$, $p > .05$). On closer inspection, only one of the subjects' scores improved over the 48-hour period for the closely spaced apical processor condition. All test scores obtained with the experimental processors with closely spaced electrodes were significantly poorer than those obtained with the subjects' everyday processors. Scores with the experimental processors with widely spaced electrodes were significantly higher than scores for processors with closely spaced electrodes but were significantly lower than scores with subjects' everyday processors for all test materials. The pattern observed with the mean scores for all of the tests was similar to that found for individual scores. In general, scores were lowest for the processors with apical and basal electrode locations (processors 4A and 4B) and were higher for the processors with the medially located electrodes and with widely spaced electrodes (processors 4M and 4WS).

Subjects showed a significant improvement in consonant recognition (3C) with processor 4A after wearing this processor for 48 hours. This is the only test and the only processor for which this improvement was significant. It is interesting to note that the consonant scores achieved with the processor with widely spaced electrodes (processor 4WS) were similar to subjects' everyday processor scores (74% and 78%, respectively).

Results of the questionnaire revealed that processor 4A received the poorest score regarding overall sound quality (see Table 2). In general, the subjective quality ratings were correlated with the listeners' actual test scores, except for a few subjects whose performance with processor 4B was poor, whereas their questionnaire response was moderate. Subjectively, all listeners were distressed with the poor quality of the four electrode conditions, except for processor 4WS, which several of the subjects commented on as sounding "pretty good."

To evaluate any potential effect of electrode insertion depth on the present results, the subjects' scores were divided into three groups depending on the number of rings inserted into the scala tympani, as visualized by the physician at the time of surgery. There were only two subjects per group with the three groups consisting of 0, 3 to 4, and 6 to 10 rings out. The same pattern of results was noted for insertion depth as for the other tests, with processor 4WS scores being the highest. The group having 3 to 4 rings out generally performed the best. However, with only two patients in each group, it is not possible to attribute this difference to electrode insertion depth per se.

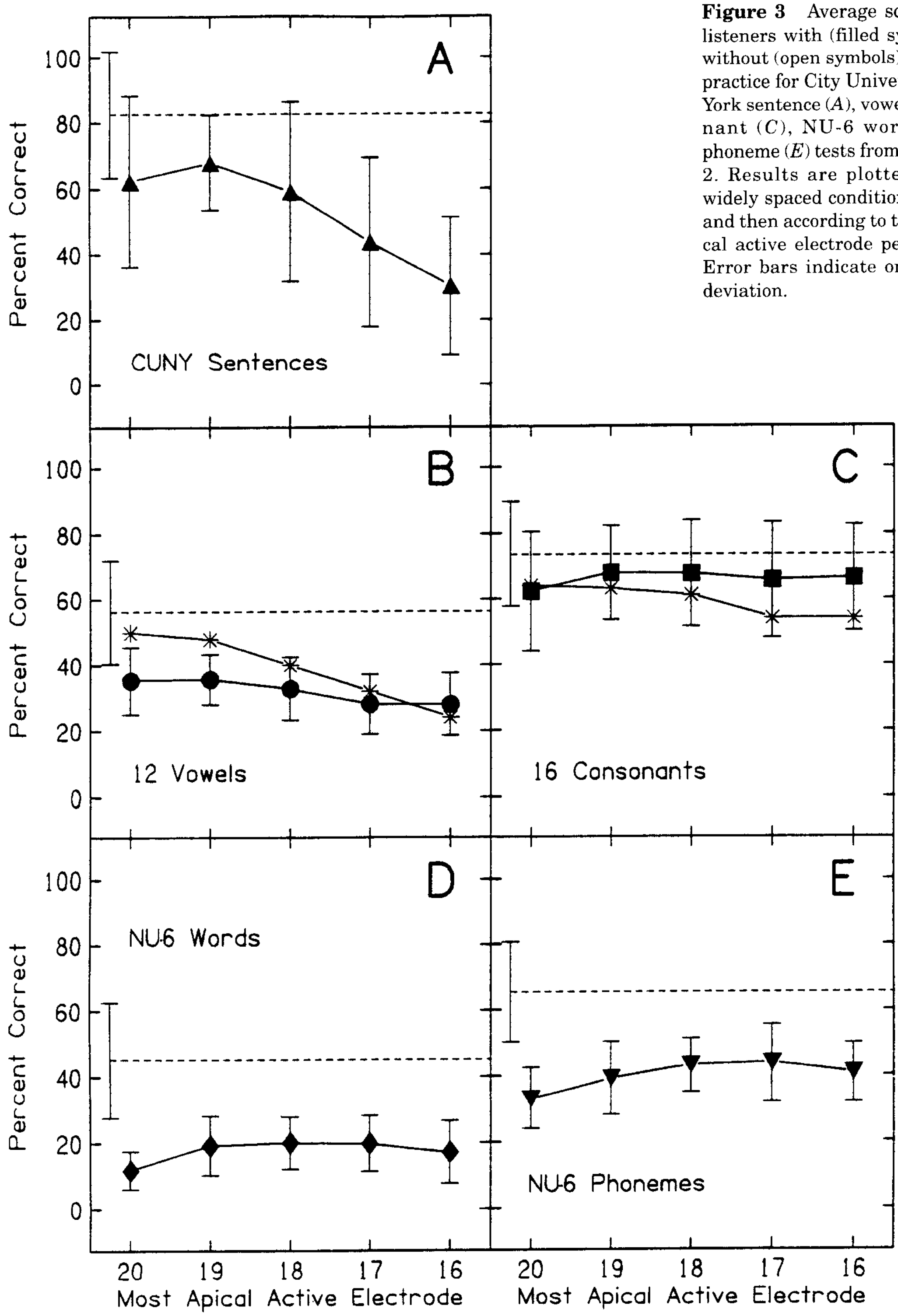

Figure 3 Average scores for six listeners with (filled symbols) and without (open symbols) 48 hours of practice for City University of New York sentence (*A*), vowel (*B*), consonant (*C*), NU-6 word (*D*), and phoneme (*E*) tests from experiment 2. Results are plotted with the widely spaced condition on the left and then according to the most apical active electrode per condition. Error bars indicate one standard deviation.

Discussion

Four-Channel Performance versus Everyday MAP

The clearest result is that for most of the various speech perception tests, maximum performance was observed with the patient's everyday processor, which used 10 or 20 electrodes as opposed to the experimental processors, which used only 4 electrodes. These results are not surprising since other researchers have observed that performance improves as the number of electrodes is increased. In general, speech recognition performance improves with the number

Table 2 Statistical Information for Experiment 2

Condition	Df Value	Vowel F Value	Vowel p Value	Consonant F Value	Consonant p Value	Word F Value	Word p Value	Phoneme F Value	Phoneme p Value	Sentence F Value	Sentence p Value
Immediate vs 48-hour testing	1	4.78	.08	8.25	.035	0.97	.37	0.55	.49	23.65	.01
Closely spaced electrodes vs everyday processor	6	72.35	.00	8.95	.000	31.25	.00	29.37	.00	30.48	.00
Widely vs closely spaced electrodes	7	44.11	.00	7.77	.000	11.89	.00	11.24	.00	20.77	.00
Widely spaced electrodes vs everyday processor	2	33.55	.00	4.48	.041	14.98	.00	14.23	.00	5.76	.02

of channels of spectral information. For simple speech materials, no improvement was observed for more than four channels (Shannon et al, 1995; Fishman et al, 1997). For more difficult speech materials, such as multitalker vowels and monosyllabic words, six to eight channels were needed to reach asymptotic performance (Dorman and Loizou, 1997; Fishman et al, 1997). For speech recognition in noise, even more spectral channels are necessary to achieve optimal performance (Fu et al, 1998).

Electrode Location

In some cases, speech recognition changed with electrode location. This effect was especially evident with CUNY sentences, where scores decreased as electrodes were shifted basally. In this experiment, it is not clear if the better performance at more apical locations was due to the cochlear location per se or to the better match between electrode tonotopic location and the frequency allocation table. From a series of experiments conducted by Fu and Shannon (1999a, b, c), it is clear that a tonotopic match between electrode and cochlear frequency is critical for good speech recognition. They noted that performance decreased dramatically as the tonotopic location of either carrier bands or analysis bands was shifted relative to each other by more than 3 mm. In patients who had several years of cochlear implant experience, the best match between frequency and electrode location appeared to be determined by their experience (i.e., the best experimental mapping was the one that was most similar to their clinical processor, regardless of the electrode insertion depth). The results of the present experiment do not show as clearly a relation between electrode location and performance, but that may be because the total shift possible with the clinical system was only 3 mm.

Electrode Spacing

Spacing between electrode pairs also had an important effect on speech recognition. Widely spaced electrodes produced better results than closely spaced electrodes. One explanation for this result is that electrode interactions were limiting performance in the closely spaced condition. In addition, the tonotopic pattern of stimulation with widely spaced electrodes was more similar to the listener's original 20-electrode processor. Among the closely spaced electrode conditions, best performance was obtained in the middle cochlear location, possibly due to a better positional match with their original 22-electrode processor.

The best performance with 4-electrode processors was obtained with the widest spacing. We offer two possible explanations: (1) the widest spacing minimizes any perceptual or neural interaction between adjacent electrodes and (2) the wide spacing provided a better match to the spacing of the frequency analysis filters, thus minimizing the distortion in the frequency-to-place pattern of activation. These alternatives are not mutually exclusive and may both have contributed to the resulting good performance.

Speech Recognition With and Without Context

Even though only CUNY sentence recognition showed a statistically significant change as a function of electrode location, the same pattern of results was also present to a lesser degree in the vowel, NU-6 word and phoneme scores, and consonant scores. This result may be explained in part by a mathematical model proposed by Boothroyd and Nittrouer (1988). They suggested that the probability of speech recognition in context (p_c) is related to the probability of recognition without context (p_i) by the equation $p_c = 1 - (1 - p_i)^k$, where k is a constant. The k factor is derived from measurements of recognition for speech presented with and without context and is basically a measurement of context effect. It is the amount by which the channels of independent information are multiplied when contextual information is added. In the Boothroyd and Nittrouer study (1988), sentence meaning had the most contextual constraint (k factor was the largest for recognition of words in sentences). This equation may help predict how a small effect seen with the vowels and consonants, phonemes, and words can have a magnified effect in sentence recognition. Thus, the small but not significant trend observed in the vowel scores may have been magnified by the sentence context effects to produce a significant improvement in sentence scores.

Effects of Learning

Relatively little learning was observed in experiment 2 after 48 hours of experience with the experimental 4-electrode processors. Implant patients may have been able to eventually achieve higher performance with the experimental processors with more experience, but 48 hours were not enough time to produce a significant improvement.

SUMMARY

The effects on speech recognition performance by the mismatch between the frequency band of the electrode and the frequency place in the cochlea were examined by systematically shifting the activated electrodes in the apical-basal direction. Average recognition of CUNY sentences decreased as activated electrodes were shifted into a more basal location.

The effects of electrode spacing on speech recognition performance were examined by shifting the location of the adjacent activated electrodes to the apical-most position, the basal-most position, and the medial position. Having the four electrodes widely spaced was also examined. Best performance was observed with the widely spaced electrode condition.

In both experiments, subjects performed better with their original processor, which had either 10 or 20 activated electrodes, than with any of the 4-electrode experimental processors.

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REFERENCES

Boothroyd A, Hanin L, Hnath T. (1985). *CUNY Laser Videodisk of Everyday Sentences.* New York: Speech and Hearing Sciences Research Center, City University of New York.

Boothroyd A, Nittrouer S. (1988). Mathematical treatment of context effects in phoneme and word recognition. *J Acoust Soc Am* 84:101–114.

Cochlear Corporation. (1989). *Audiologist Handbook.* Englewood, CO: Cochlear Corporation.

Cox R, Gilmore C. (1990). Development of the Profile of Hearing Aid Performance (PHAP). *J Speech Hear Res* 33:343–357.

Dorman MF, Loizou PC, Rainey D. (1997). Simulating the effect of cochlear-implant electrode insertion-depth on speech understanding. *J Acoust Soc Am* 102:2993–2996.

Fishman KE, Shannon RV, Slattery WH. (1997). Speech recognition as a function of the number of electrodes used in the SPEAK cochlear implant speech processor. *J Speech Hear Res* 40:1201–1215.

Fu Q-J, Shannon RV. (1999a). Recognition of spectrally degraded and frequency-shifted vowels in acoustic and electric hearing. *J Acoust Soc Am* 105:1889–1900.

Fu Q-J, Shannon RV. (1999b). Effects of electrode configuration and frequency allocation on vowel recognition with the Nucleus-22 cochlear implant. *Ear Hear* 20:332–344.

Fu Q-J, Shannon RV. (1999c). Effects of electrode location and spacing on speech recognition with the Nucleus-22 cochlear implant. *Ear Hear* 20:321–331.

Fu Q-J, Shannon RV, Wang X. (1998). Effects of noise and number of channels on vowel and consonant recognition: acoustic and electric hearing. *J Acoust Soc Am* 104:3586–3596.

Hillenbrand J, Getty L, Clark M, Wheeler K. (1995). Acoustic characteristics of American English vowels. *J Acoust Soc Am* 97:3099–3111.

McDermott HJ, McKay CM, Vandali AE. (1992). A new portable sound processor for the University of Melbourne/Nucleus Limited Multichannel cochlear implant. *J Acoust Soc Am* 91:3367–3371.

Robert ME. (1998). *CONDOR: Documentation for Identification Test Program.* Los Angeles: House Ear Institute.

Shannon RV, Zeng FG, Kamath V, Wygonski J, Ekelid M. (1995). Speech recognition with primarily temporal cues. *Science* 27:303–304.

Shannon RV, Zeng FG, Wygonski J. (1998). Speech recognition with altered spectral distribution of envelope cues. *J Acoust Soc Am* 104:2467–2476.

Tillman TW, Carhart R. (1966). *An Expanded Test for Speech Discrimination Utilizing CNC Monosyllabic Words.* Northwestern University Auditory Test No. 6, Technical Report No. SAM-TR-66-55. Brooks Air Force Base, TX: USAF School of Aerospace Medicine.

Tyler RS, Preece JP, Lowder MW. (1987). *The Iowa Audiovisual Speech Perception Laser Videodisc.* Laser Videodisc and Laboratory Report. Iowa City, IA: Department of Otolaryngology, Head and Neck Surgery, University of Iowa Hospital and Clinics.