Frequency discrimination and speech recognition by patients who use the Ineraid and continuous interleaved sampling cochlear-implant signal processors

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Patients who use the Ineraid cochlear implant were tested in four experiments with materials which assessed frequency discrimination and speech understanding. In each experiment both frequency discrimination and speech recognition varied among patients. Correlations between the two measures were significant and ranged from 0.60 to 0.83. Most generally, frequency discrimination was better in the frequency domain of $F1$ than in the domain of $F2$. In experiment 5, both the Ineraid signal processing strategy and a continuous interleaved sampling (CIS) strategy were implemented for a single patient. The CIS strategy improved frequency discrimination in the domain of $F2$ and improved speech understanding. *© 1996 Acoustical Society of America.*

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INTRODUCTION

This article describes the outcome of tests of frequency discrimination and speech understanding for a relatively large group of patients who use the Ineraid cochlear implant. The aim of the tests was to determine the relationship between frequency discrimination in the domains of the first and second formants of speech, on the one hand, and speech understanding, on the other. In all but one experiment signals were presented through the patients' four-channel analog signal processors. The experiments were prompted by the results of an earlier experiment in which performance on a pitch scaling task was found to be related to speech understanding for a small number of patients who use the Ineraid (Dorman *et al.*, 1990a). In that experiment, patients with relatively good speech understanding scaled pitch through their signal processors over a wider range (e.g., 100 Hz to 2 and 3 kHz) than patients with poor speech understanding (e.g., 100 Hz to 0.6–1.0 kHz). A reasonable inference from these data is that frequency discrimination and speech understanding are related.

Our interest in the relationship between frequency discrimination and speech understanding also led to tests of a patient fitted with a continuous interleaved sampling (CIS) processor (Wilson *et al.*, 1991). A CIS processor produces nonsimultaneous, pulsatile stimulation to six channels (for the patient in this experiment). In contrast, the Ineraid produces simultaneous, analog stimulation to four channels. Wilson *et al.* (1991) and Boex *et al.* (1994) have reported that patients perform significantly better on tests of speech recognition when fitted with a CIS processor than when fitted with the Ineraid processor. The aim of our tests was to determine whether a CIS processor also allows better frequency discrimination.

The data on frequency discrimination and speech understanding by Ineraid patients are summarized as the results of four experiments. In experiment 1, the stimuli in the frequency discrimination task spanned a wide range of speech frequencies—125–3300 Hz. In experiment 2, the stimuli spanned the frequency range of first formants in speech—350–850 Hz—and used smaller frequency increments (100 Hz) than used in experiment 1. In experiment 3, frequency discrimination over the range 350–850 Hz was compared for stimuli presented through the patients' signal processors and for stimuli presented directly to a single electrode. In experiment 4, psychometric functions for frequency discrimination were obtained at several fixed frequencies. In experiment 5, frequency discrimination and speech understanding was assessed for the Ineraid and CIS processors.

I. EXPERIMENT 1

In this experiment the relationship between performance on a task of frequency discrimination which spanned the range 0.125–3.3 kHz and performance on tasks of speech understanding was assessed. The stimuli in the frequency discrimination task were presented in ten stimulus triads (see Fig. 1) and patients were asked to indicate both the highest and lowest pitch in each triad.[1]

The step size among members of the triads was adjusted following pilot testing so that performance averaged over the entire range of frequencies would not be at a ceiling or floor.

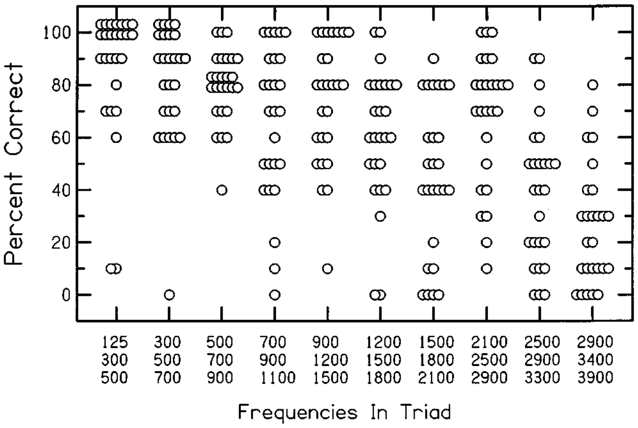

FIG. 1. Frequency discrimination score as a function of the frequency composition of the triad. Each data point indicates the score for a single patient. The data are from experiment 1.

In addition, the steps were chosen from the point of view of the frequency resolution necessary for speech understanding. For example, discrimination of 200-Hz differences centered at 300, 500, and 700 Hz would allow at least a rough quantification of vowel height. In similar fashion, discrimination of 300-Hz differences centered at 1200, 1500, and 1800 Hz would allow a rough quantification of vowel place.

A. Method

1. Subjects

The patients were 26 individuals fit with the Ineraid cochlear implant. All had used their implant for a minimum of 1 year before testing. All had participated in speech perception or psychophysical experiments previously. The patients ranged in age from 21 to 73 years.

2. Implant design

The Ineraid prosthesis consists of (i) six monopolar electrodes implanted in the scala tympani with remote reference, (ii) a percutaneous pedestal to which the electrode wires are attached, and (iii) a portable speech processing and electrode stimulation system (Eddington, 1980). The most apical electrode is located about 22 mm from the round window. The electrodes are spaced at 4-mm intervals. The four, most apical, electrodes are activated in most patients. Each of the four electrodes is driven by an analog signal derived from the input signal after the operation of an AGC circuit and bandpass filtering.

3. Pure-tone signals

To assess frequency discrimination the following sine frequencies were created using custom software: 125, 300, 500, 700, 900, 1100, 1200, 1500, 1800, 2100, 2500, 2900, 3300, 3400, and 3900 Hz. The signals were organized into the following stimulus triads:

(1) 125:300:500,
(2) 300:500:700,
(3) 500:700:900,
(4) 700:900:1100,
(5) 900:1200:1500,
(6) 1200:1500:1800,
(7) 1500:1800:2100,
(8) 2100:2500:2900,
(9) 2500:2900:3300, and
(10) 2900:3400:3900 Hz.

The stimuli were 1 s in duration and had a 16-ms rise time. The interstimulus interval among members of the triads was 250 ms.

Loudness balancing was accomplished in the following manner. A reference frequency was established, e.g., 1 kHz, and comfortable loudness was set. Comfortable loudness was defined as a 6–7 level on a 10 point loudness scale. The patient then heard the reference frequency and the middle frequency of a triad. The patient was asked to indicate whether the second stimulus was louder or softer than the reference stimulus. The experimenter adjusted the stimulus level until the patient indicated the two stimuli were equally loud. Then the middle frequency of the triad was used as the reference and one of the other two members of the triad was balanced for loudness. Finally, the third member of the triad was balanced against the middle member. This procedure was repeated for all triads. Thus the middle members of all triads were balanced against the reference level of loudness and all members of a triad were balanced by reference to the middle member. At the end of the procedure all stimuli were played and changes made in stimuli that were not correctly balanced.

After loudness had been balanced, the triads were randomized and presented in a discrimination format. Each triad was presented five times in the test sequence. The patients were told they would hear three tones in a sequence and, following the first presentation of the sequence, were instructed to indicate which of the three was the highest pitched tone. This response was then entered into a custom software program by the experimenter. The triad was presented again, in the same order, and the patient was instructed to indicate which of the three signals was the lowest pitch. The patients were allowed to hear each triad as many times as he/she wished before making a response. The task was self-paced.

4. Speech signals

Speech understanding was assessed with a 12 vowel test in "bVt" environment (Dorman *et al.*, 1989), a 16 consonant test in "aCa" environment (Dorman *et al.*, 1990b), and female-voice recordings of the Spondee Recognition Test, the CID Sentence Test, and the Monosyllable Recognition Test (NU-6) from the MAC Battery. The recordings of the tests from the MAC Battery were made in the fashion of "clear" speech (Picheny *et al.*, 1985). For the tests of vowel and consonant recognition, five tokens of each stimulus were created and presented in a randomized test sequence. Response collection was accomplished by custom software linked to a touch sensitive pad.

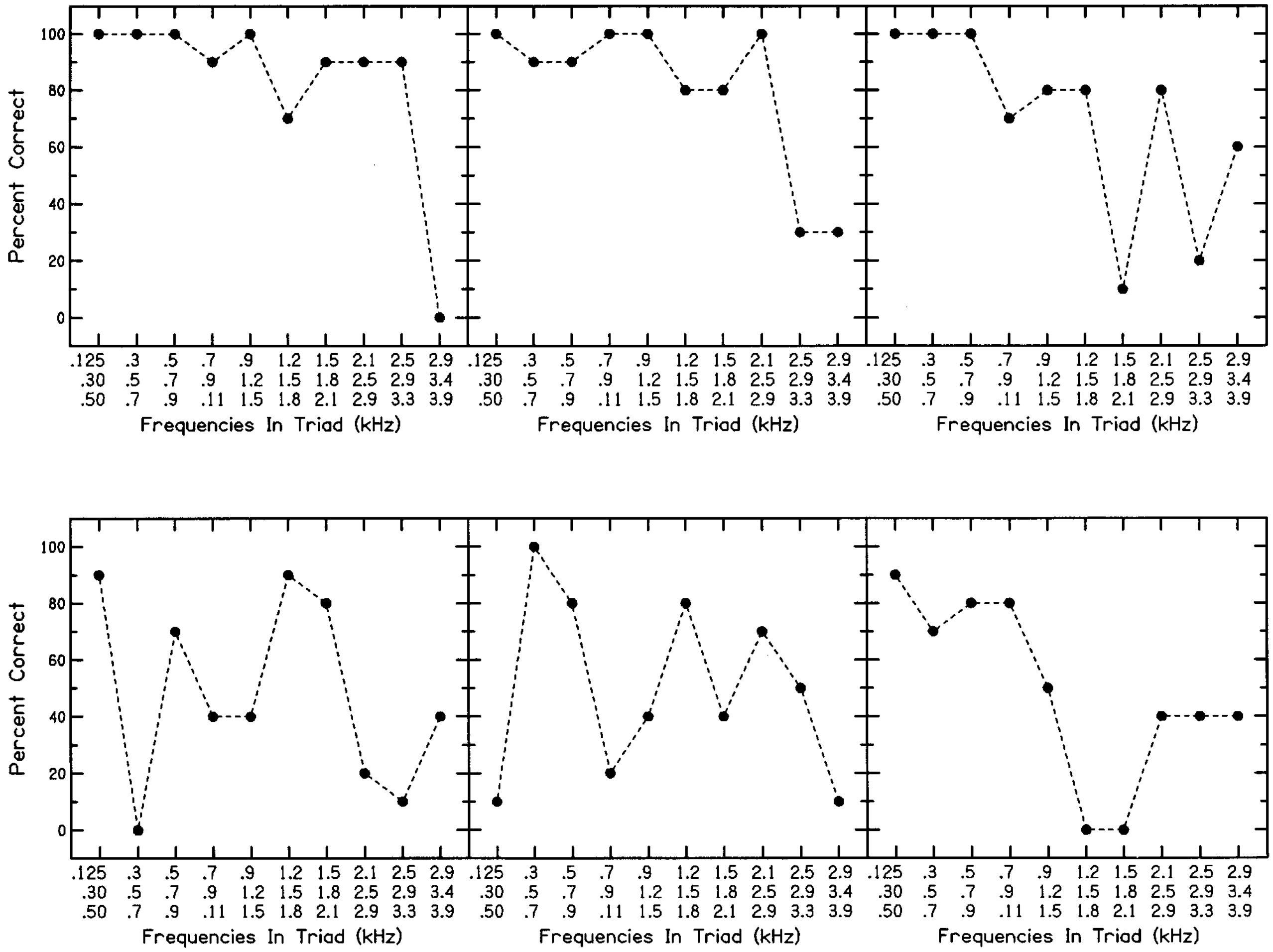

FIG. 2. Frequency discrimination score as a function of the frequency composition of the triad for six patients. The three individuals with the best overall performance are shown in the top plots. Three individuals with poor performance are shown in the bottom plots.

5. Apparatus

All test signals were routed out of the PC via a Data Translation 2801A D/A board to custom hardware with amplifiers, optical isolators, and current drivers. The signals were then directed to the auxiliary input jack of the Ineraid and presented to the patient following multichannel signal processing by the Ineraid.

B. Results and discussion

For each patient, for each stimulus triad, the percent correct "high" and percent correct "low" responses were averaged to provide a measure of discrimination accuracy.^{2} The results for all patients are shown in Fig. 1. In the domain of the first formant ($F1$) of speech, i.e., triads 1, 2, and 3, a large number of patients evidenced discrimination scores equal to or greater than 90% correct—19 patients for triad 1, 14 patients for triad 2, and 8 patients for triad 3 (this level of performance indicates that the discrimination task, *per se,* was not too difficult). Fewer patients evidenced discrimination scores above 90% correct in the domain of $F2$, i.e., triads 5, 6, 7, and 8 (9, 3, 1, and 6 patients, respectively). Only two patients evidenced scores at or equal to 90% correct for the highest frequency triads centered at 2900 and 3400 Hz. Overall, the data suggest that a relatively large number of patients have frequency discrimination sufficient for at least modest resolution of frequency in the domain of $F1$. A much smaller number of patients have frequency discrimination sufficient for even modest resolution in the domain of $F2$.

The data presented in Fig. 1 give an indication of group performance but do not indicate the range of frequencies over which an individual patient evidenced good or poor discrimination. The extremes of individual performance are shown in Fig. 2. The results for three patients with the best overall performance are shown at the top of the figure while the results for three patients with poor overall performance are shown at the bottom of the figure.

It is clear that the best patients can resolve 200-Hz differences over the range of $F1$'s in speech. Resolution of 300-Hz differences in the domain of $F2$ is also possible, but no patient consistently scored 90% correct or better over the entire range of second formants in speech. Thus even 300-Hz differences in the domain of $F2$ were not always easy to discriminate even for the best performing patients.

The results of a pilot experiment provide additional information about the discriminability of frequency differences in the domain of $F2$. For one triad the stimuli were at 1.0, 2.0, and 3.4 kHz. Eleven of the 13 patients scored at the 90%

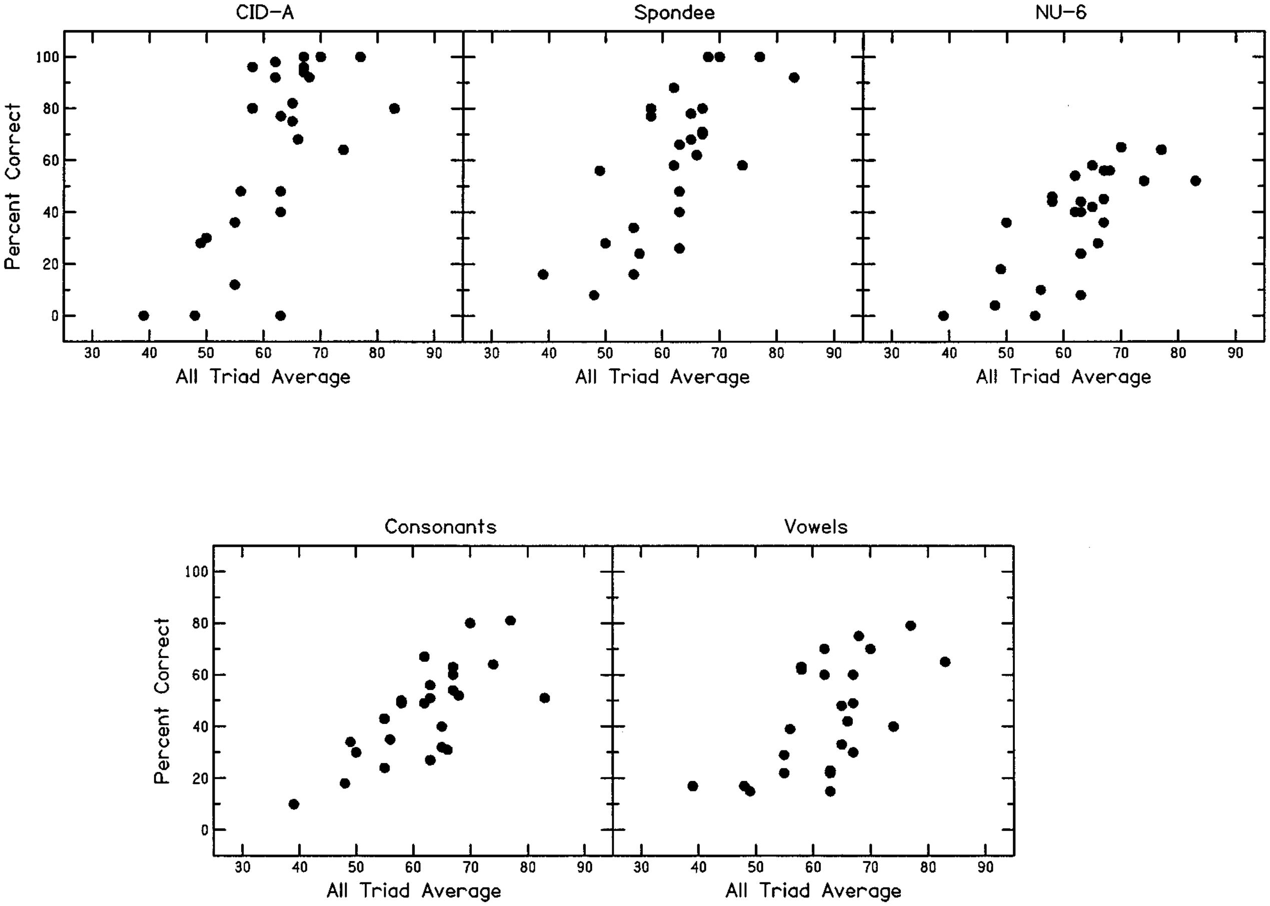

FIG. 3. Scatter plots of percent correct speech recognition as a function of the frequency discrimination score averaged over all triads in experiment 1.

or 100% correct level. Data were also collected for a triad with 700-Hz differences among stimuli, i.e., for stimuli at 0.9, 1.6, and 2.3 kHz. Ten of 13 patients achieved scores of 90% correct or better. This performance can be contrasted with performance, shown in Fig. 1, for the triad centered at 1.5 kHz which used 300-Hz differences. Only 3 of 26 patients achieved 90% correct or better.

Since $F2$ onset frequency is a major cue to consonant place of articulation, the poor quantization of frequency described above suggests that identification of consonant place of articulation should be difficult for the better, as well as the poorer, Ineraid patients. This is the case (e.g., Dorman, 1993; Tyler and Moore, 1992).

The plots for patients with the poorest discrimination scores, shown at the bottom of Fig. 2, illustrate two patterns of performance. The easiest to rationalize is the pattern shown in the third plot. Here it might be assumed that signals presented to electrode 1 (with filter center frequency of 500 Hz) and to electrode 2 (with filter center frequency of 1 kHz) produce slightly different pitches, but that signals presented to electrodes 2, 3, and 4 produce very similar pitches. Pitch scaling data from this patient indicates that this is the case (see Dorman *et al.*, 1990a; Fig. 9, patient 7). The patient reports that pitches above 1 kHz differ mostly in ''penetrativeness.'' Biographical data indicate that this patient has had a high-frequency hearing loss since early childhood.

The pattern of performance shown in the first two plots at the bottom of Fig. 2 is quite different from that shown in the third plot. Here performance is best described as not uniform. In additional informal tests, patients of this type indicate that pitch does not steadily increase when frequency is swept from low to high. Rather, as suggested by the data in Fig. 2 bottom, pitch might grow over a short range, and then not grow for several steps of frequency and then resume growth.

C. Correlations: Frequency discrimination and speech understanding

To obtain an overall measure of frequency discrimination for each patient, percent correct scores were averaged across the ten triads. This average score was then used in correlational analyses with the five measures of speech understanding, i.e., CID sentences, Spondee words, monosyllabic words, consonants, and vowels. In Fig. 3 the data are shown as scatter plots. The correlation coefficients for CID-A, spondee words, NU-6, consonants, and vowels were, respectively, 0.678, 0.721, 0.727, 0.70, and 0.597. All of the correlations were modest, but were significant at the 0.01 level. Thus differences in the ability to understand speech are related to differences in the ability to discriminate among pure-tone signals which differ in frequency.

The five scatter plots have a common form—patients with the poorest frequency discrimination score evidenced

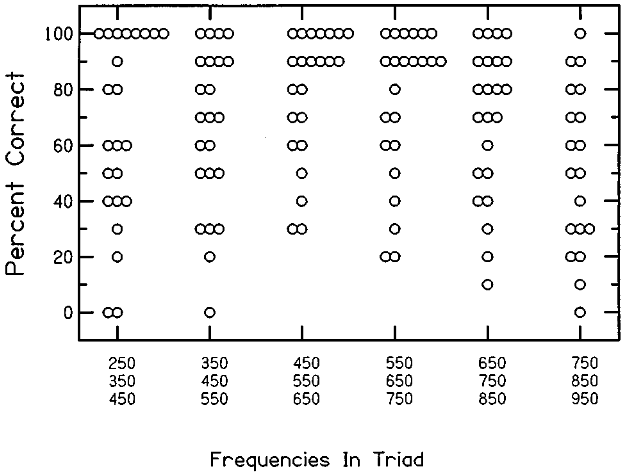

FIG. 4. Frequency discrimination score as a function of the frequency composition of the triad. Each data point indicates the score for a single patient. The data are from experiment 2.

very poor speech recognition scores while patients with the best frequency discrimination scores evidenced the best speech recognition scores. Patients with discrimination scores in the middle of the distribution, e.g., with average scores of 65%, evidenced the entire range of speech understanding.

The relationship between frequency discrimination and speech understanding, described above, is different than that found between temporal discrimination and speech understanding. Hochmair-Desoyer *et al.* (1985) and Tyler *et al.* (1989) have reported that patients with poor temporal resolution evidence poor speech understanding and that patients with good temporal resolution can evidence either good or poor speech understanding. In contrast, in the present experiment none of the patients with the best frequency resolution evidenced poor speech understanding.

II. EXPERIMENT 2

In experiment 1 many patients could resolve 200-Hz differences between signals in the region between 300 and 900 Hz. In experiment 2 the frequency difference between members of the triads was reduced to 100 Hz and discrimination performance was assessed.

A. Method

1. Subjects

Twenty-three patients participated in this experiment.

2. Pure-tone stimuli

The following triads were created under software control: 250:350:450, 350:450:550, 550:650:750, 650:750:850, and 750:850:950 Hz. The last triad (750:850:950) was added to the experiment after the first four patients had been tested. Thus in Fig. 4 there are only 19 data points for the final triad. All other aspects of stimulus presentation were identical to those in experiment 1. Loudness balancing was carried out in the manner of experiment 1. The reference signal for loudness balance was 500 Hz.

B. Results and discussion

As shown in Fig. 4, a large number of patients scored at the 90% correct or better level for triads centered at 350–750 Hz. Nine patients evidenced this level of performance at 350 Hz, 8 at 450 Hz, 13 at 550 and 650 Hz, and 8 at 750 Hz. Only three patients were able to score at the 90% level or better at 850 Hz.

The performance across triads for the three best patients is shown in Fig. 5 (top). These patients were able to consistently discriminate 100-Hz differences at the 350- to 650-Hz center frequencies. All patients showed some diminution of performance at 850 Hz. As a group these patients would be expected to make relatively good use of first formant information in the speech signal.

The data described above for pure-tone discrimination fit well with vowel identification by the better Ineraid patients—even though the data are for pure-tone discrimination and not for formant frequency discrimination. Discrimination of between 300- and 700-Hz differences in the domain of $F2$ combined with discrimination of 100-Hz differences in the domain of $F1$ predicts accurate sorting of vowels into the categories of high, mid-, and low and predicts errors to be among the vowels in the three categories. The vowel confusion data reported by Dorman *et al.* (1989) are consistent with this prediction.

The patients with the poorest overall scores (Fig. 5, bottom), as expected from the results of experiment 1, were unable to consistently resolve 100-Hz differences for any of the triads. As a group, patients with this level of discrimination ability should make little use of differences in the frequency of the first formant in speech.

C. Correlations: Frequency discrimination and speech understanding

To obtain an overall measure of frequency discrimination for each patient, percent correct scores were averaged across the six triads. The averaged score was then used in correlational analyses with the measures of speech understanding. The data are shown as scatter plots in Fig. 6. The correlation coefficients for CID-A, Spondee words, NU-6 words, consonants, and vowels were, respectively, 0.755, 0.786, 0.825, 0.828 and 0.755. All were significant at the 0.001 level. Thus as was the case in experiment 1, differences in speech understanding are related to differences in the ability to discriminate differences in the frequency of pure-tone signals.

One of the two largest r values, 0.828, was for low-frequency discrimination and consonant recognition. The magnitude of the correlation suggests that frequencies in the domain of $F1$ play a significant role in consonant recognition by Ineraid patients. This inference does not fit well with the established view that information about consonant place of articulation resides principally in the frequency domain of $F2$. The correlation may exist because patients use the frequency region in which they have the best discrimination for consonant recognition.

It is possible that low-frequency discrimination is related to another variable, perhaps the overall ‘‘health’’ of the pe-

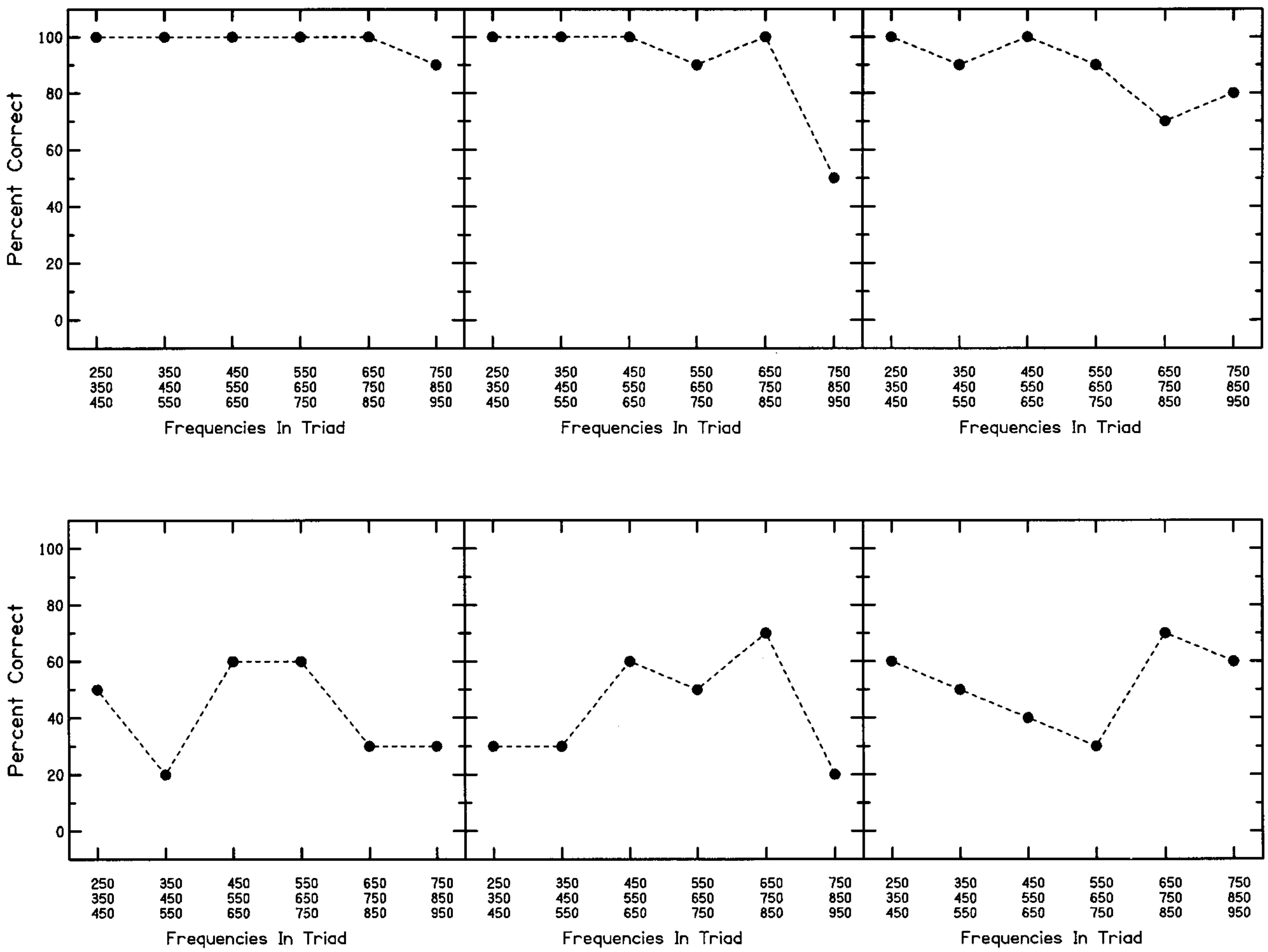

FIG. 5. Frequency discrimination score as a function of the frequency composition of the triad for six patients. The three individuals with the best overall performance are shown in the top plots. Three individuals with poor performance are shown in the bottom plots.

ripheral auditory system, and that this factor underlies all of the significant correlations in experiment 2. Lacking an independent measure of "health," this possibility cannot be evaluated.

III. EXPERIMENT 3

In experiment 2, many patients were able to resolve 100-Hz differences over the range 350–650 Hz. In this frequency range, the Ineraid processor provides patients with two cues—one temporal and one spatial—to signal frequency.

One cue is the rate, or periodicity, pitch of the signals. Previous research indicates that patients are able to use this temporal cue only over a restricted frequency range. Shannon (1993) suggests a 300- to 500-Hz maximum. Others have reported changes in rate pitch to 1250 Hz (or pulses per second) (Hochmair-Desoyer *et al.*, 1983; Townshend *et al.*, 1987). If changes in rate pitch are detectable to 1250 Hz, then the patients could have used rate pitch to discriminate among the stimuli in experiment 2.

The other cue to frequency is the distribution of energy at adjacent electrode sites. Due to the shallow slope of the filters for each channel in the Ineraid processor, a given signal will appear in several filter bands simultaneously. For example, low-frequency signals will produce energy in both channels 1 and 2 (and to a much lesser extent, channel 3). As frequency is increased from, for example, 250 to 950 Hz, the balance of energy shifts from predominately channel 1 to predominately channel 2. This change in the spatial distribution of energy is a potential cue to signal frequency.

The aim of experiment 3 was to determine the range of frequencies over which patients use rate pitch cues for frequency discrimination. To find out, the signal processor was bypassed and the triads from experiment 2 were presented to a single electrode (the most apical electrode). If patients relied on rate pitch in experiment 2 for frequency discrimination, then stimulation of a single electrode should allow the same level of discrimination as found in experiment 2.[3]

A. Method

1. Subjects

Sixteen patients participated in this experiment.

2. Stimuli

The stimuli were identical to those used in experiment 2.

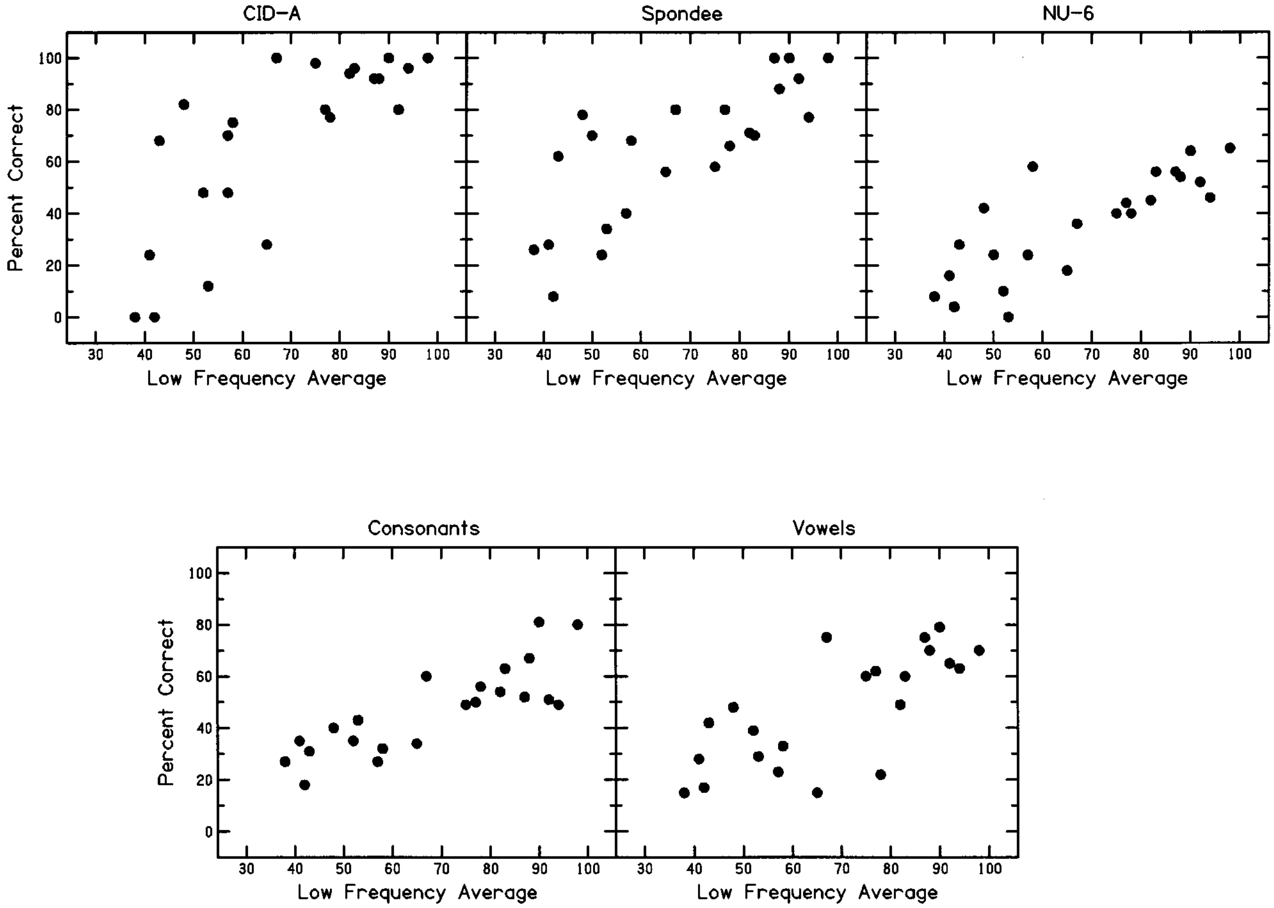

FIG. 6. Scatter plots of percent correct speech recognition as a function of the frequency discrimination score averaged over all triads in experiment 2.

3. Apparatus

Signals were routed from the D/A board to custom hardware which enabled signals to be directed, following optical isolation, to a current driver and then to the patient's most apical electrode in the array. Loudness was balanced among stimuli in the manner of experiment 1. The reference signal for loudness balance was 500 Hz.

B. Results and discussion

The results for direct stimulation are shown in Fig. 7 on the right. For comparison, the results for the same subjects when the signals were presented through the signal processor are shown on the left. A repeated measures analysis of variance revealed a significant main effect for stimulation type (direct versus processor) $[F(1,140)=9.38,\ p<0.0048]$ and for triad center frequency $[F(5,140)=5.38,\ p<0.0001]$. The interaction was significant $[F(5,140)=2.51,\ p<0.032)$.

The nature of the interaction is shown in the group-averaged data plotted in Fig. 7. For signals presented through the signal processor, percent correct scores changed little over the 350- to 750-Hz center frequencies. In contrast, for direct stimulation percent correct scores decreased systematically over the range 350–650 Hz and then remained at a low level.

At the 350-Hz center frequency performance for stimulation through the processor was not higher than performance with direct stimulation of a single electrode. Rate pitch is the most likely mechanism for discrimination of these stimuli. However, at higher frequencies discrimination of signals presented through the signal processor was better than discrimination of signals presented to a single electrode. Thus the relatively good discrimination of the 100-Hz differences found in experiment 2 was due, most likely, to patients using the spatial distribution of energy across electrodes to cue the relative frequency of the signals. If this is the case, then differences among patients in discrimination ability are due to differences in the availability of spatial cues to frequency.[4]

Inspection of the data for direct stimulation indicates that only 2 or 3 patients of the 16 in the sample could make use of rate pitch to discriminate 100-Hz differences over the range 350–750 Hz. If these data are viewed in terms of implications for signal processing strategies, then only a small number of patients might benefit from explicitly coding signals in the domain of $F1$ by rate pitch.

IV. EXPERIMENT 4

In experiment 4 psychometric functions for frequency discrimination were collected from three patients who evi-

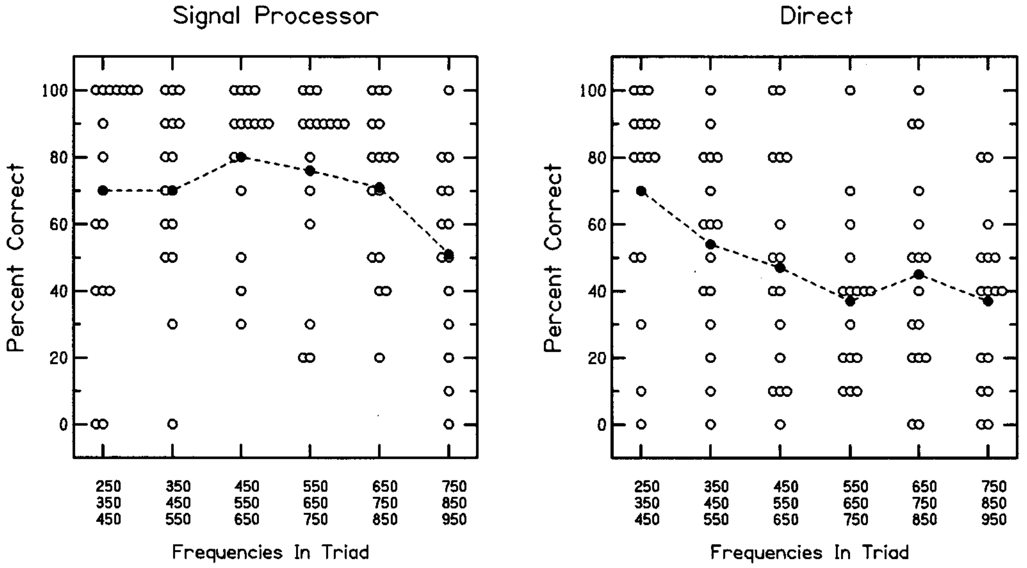

FIG. 7. Frequency discrimination score as a function of the frequency composition of the triad. Each data point indicates the score for a single patient. The right-hand plot shows performance when signals were directed to a single electrode (bypassing the signal processor). The left-hand plot shows performance through the signal processor. Group mean performance is indicated by filled circles.

denced high levels of discrimination in experiments 1 and 2 and who evidenced high levels of word intelligibility. Because the patients were not overpracticed and because the task involved a significant memory component, the outcome of this experiment does not indicate the limits of auditory discrimination by the patients. Rather, the outcome provides a more quantitative description of frequency discrimination than that found in experiments 1 and 2.

A. Method

1. Stimuli

The three-tone discrimination task used in experiments 1 and 2 was used in experiment 4. Center frequencies of 400, 600, 800, 1000, 1500, and 2000 Hz were employed. Frequency differences among members of the triads varied over the range 5–200 Hz. The frequency differences varied slightly among patients. Loudness matching was accomplished in the manner of experiments 1 and 2.

B. Results and discussion

The results for the three patients are shown in Fig. 8. The patients evidenced a similar pattern of results for the 400-, 600-, and 800-Hz center frequencies. At 400 Hz, 90% identification accuracy was reached by patients 1, 2, and 3 with 20-, 25-, and 25-Hz differences, respectively, among members of the triad. At 600 Hz the frequency differences were 22, 25, and 37 Hz. At 800 Hz the differences were systematically larger—between 87 and 175 Hz.

The results at the 1000-, 1500-, and 2000-Hz center frequencies were not as consistent across subjects as the results at the lower center frequencies. Patients 1 and 2 behaved in similar fashion. Both showed poor discrimination at 1000 and 2000 Hz but showed excellent discrimination at 1500 Hz. At 1500 Hz, 90% accuracy was reached with 100 Hz or less differences among members of the triads. In contrast to the first two patients, the third patient showed excellent discrimination at 1000 Hz (90% accuracy reached at 25 Hz) but poor discrimination at 1500 Hz. He evidenced relatively poor discrimination at 2000 Hz (as did the other two patients). Thus, as the results of experiment 1 suggested, discrimination across the frequency domain of $F2$ in speech is not uniform, even for the best patients.

V. EXPERIMENT 5

The results of experiments 1–4 indicated that there is a relationship between high levels of speech identification and the discrimination of small differences in frequency. Given this outcome, if Ineraid patients were fitted with a signal processor which improved speech understanding, then frequency discrimination should improve, also. This hypothesis was tested in experiment 5 by fitting an Ineraid patient with a continuous interleaved sampling, or CIS, processor and testing speech understanding and frequency discrimination.

A. Method

1. Subject

The subject was patient 3 from experiment 4. He had participated in many psychophysical experiments before participating in the present experiment.

2. Signal processor design

The signal processor was a six-channel CIS design (the six channels were of equal width on a logarithmic scale) with 12th-order bandpass filters, 400-Hz first-order smoother, full-wave rectification, 33-μs/phase pulse duration, 2525-Hz pulse rate, and staggered channel update order. Input signals were deemphasized at 6 dB/oct below 1.2 kHz prior to signal processing.

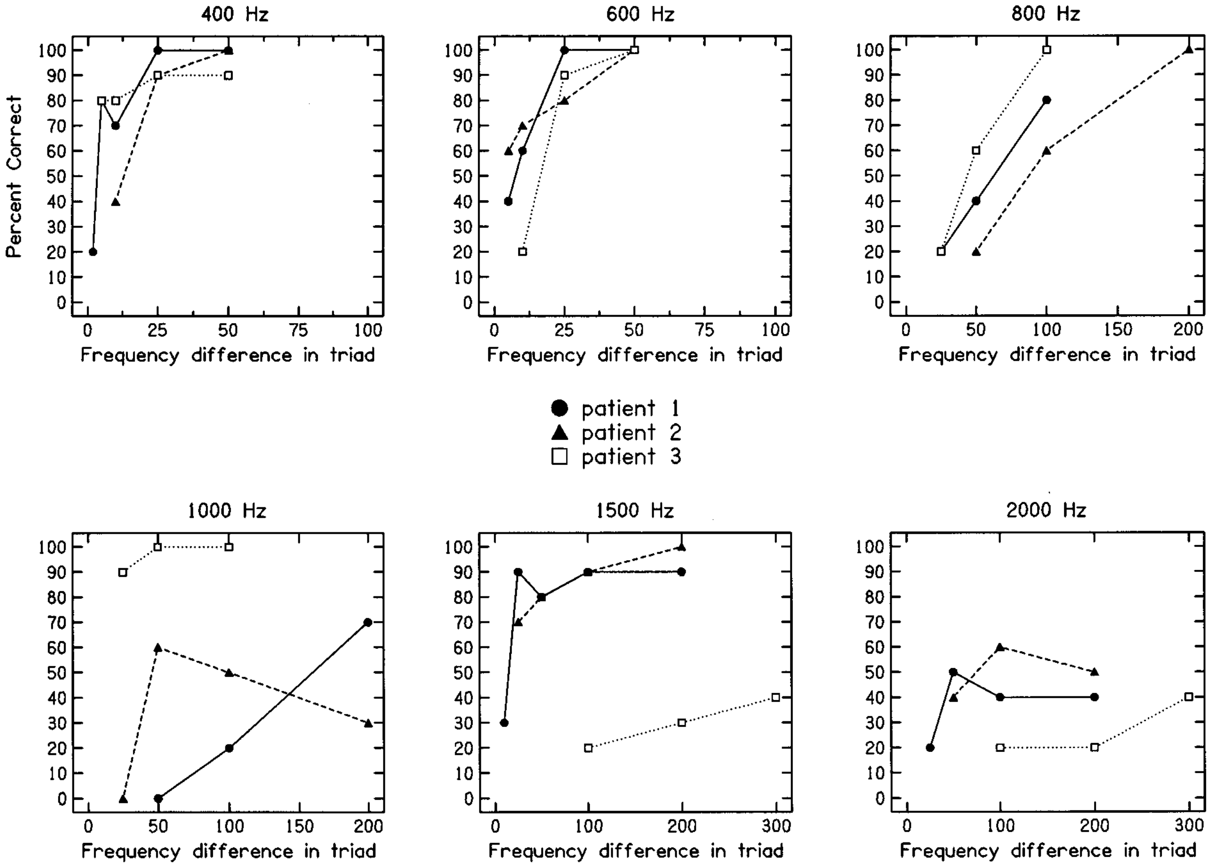

FIG. 8. Frequency discrimination score as a function of triad center frequency and of the frequency differences within the triad. The data from three patients are shown.

3. Stimuli

The stimuli were those used in experiment 4. Loudness was balanced in the manner of experiment 1.

4. Speech testing

With the Ineraid processor the patient achieved scores of 80% correct for consonants, 70% correct for vowels, and 65% correct for the NU-6 words. With the CIS processor the patient achieved scores of 98% correct for consonants, 72% correct for vowels, and 90% correct for the NU-6 words.

B. Results and discussion

The results of the frequency discrimination tests are shown in Fig. 9 (results via the Ineraid processor are replotted from Fig. 8). For signals processed through the CIS processor the point of 90% correct at 2 kHz was 75 Hz; at 1500 Hz it was 37 Hz; at 800 Hz it was 17 Hz (the average of the two 90% points); at 600 Hz it was 37 Hz. At 1300 and 1700 Hz (tested in the context of another experiment) 90% correct was reached at 30 and 35 Hz, respectively. At 1 kHz the function did not reach 90% but its shape was similar to those at other frequencies. Performance at 400 Hz was very poor and is discussed below. Thus, over the domain of much of the speech signal, the CIS processor allowed uniformly good, and, for some frequencies, greatly improved, discrimination. The high level of discrimination performance is consistent with the hypothesis that there is a relationship between discrimination of small differences in frequency and high levels of speech identification.

C. Low-frequency discrimination

At 400 Hz, discrimination with the Ineraid was excellent but discrimination with the CIS processor was poor. Several factors could contribute to this level of performance. One is frequency doubling as a consequence of full-wave rectification in the CIS processor. This would defeat the use of rate pitch, or temporal, cues to frequency. In addition, the skirts of the first and second filters in the CIS processor overlap minimally near 400 Hz (see Fig. 10). Thus there are minimal channel-balance cues in this frequency region.

To test whether the absence of channel balance cues was responsible for the poor discrimination at 400 Hz, a CIS processor with a seventh "virtual" channel (Wilson *et al.*, 1994b) was implemented.[5] The critical aspect of this processor was that (the new) channel 1 and channel 2 had filter skirts which overlapped in the region of 400 Hz (see Fig. 10). As shown in Fig. 9, with the seven-channel processor 90% identification of the signals centered at 400 Hz was reached at 25 Hz—a value consistent with the values obtained at higher frequencies with the six-channel CIS processor. Thus poor discrimination at 400 Hz can be attributed to

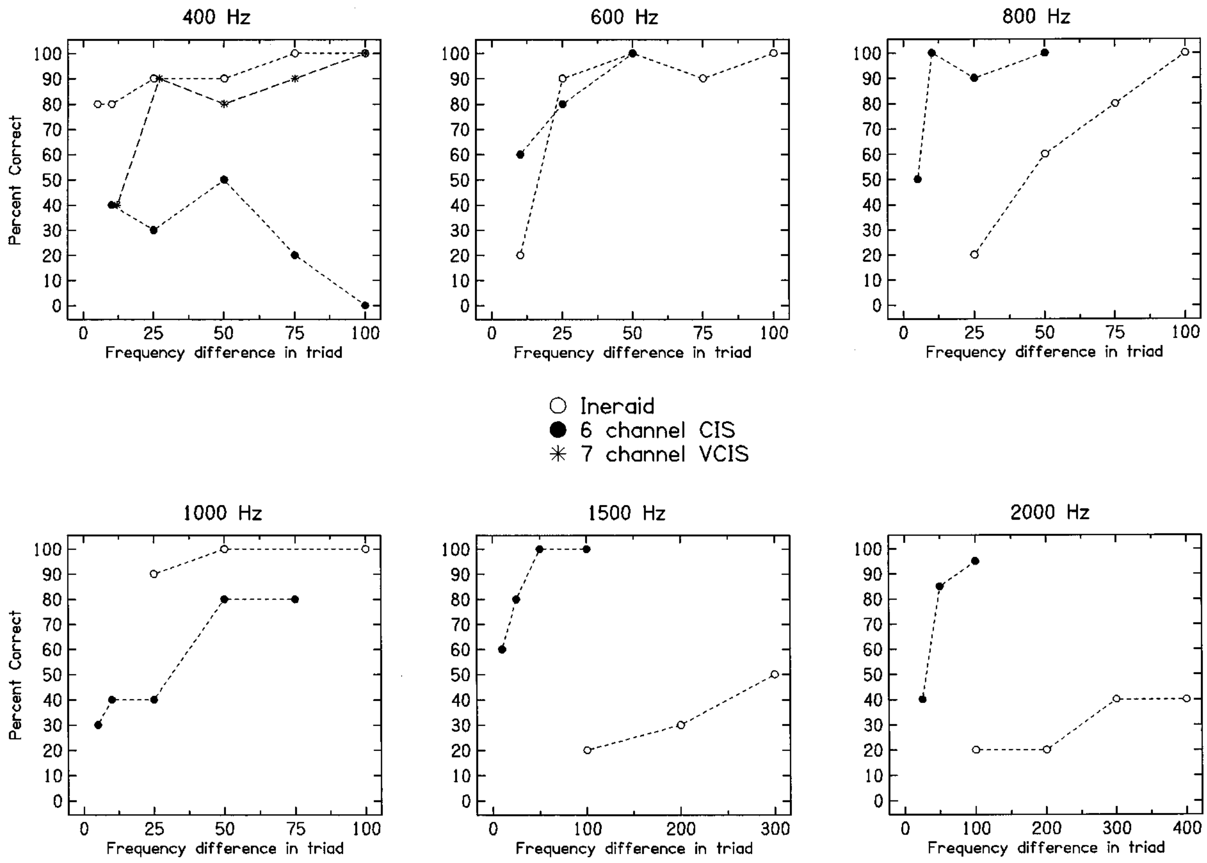

FIG. 9. Frequency discrimination score as a function of triad center frequency and of the frequency differences within the triad. The data are from one patient tested through the Ineraid signal processor and through a CIS processor. Performance through a virtual channel processor is shown at 400 Hz.

the absence of channel balance, or spatial, cues to frequency.[6]

VI. CONCLUSION

For patients who use the simultaneous, analog signal-processing scheme of the Ineraid, the ability to achieve high scores on tests of speech understanding is related to the ability to discriminate small differences in frequency. Differences in frequency discrimination ability among patients are related, in turn, to the ability to use small differences in the spatial distribution of energy along the cochlea as a cue to frequency. The spatial distribution of energy will be resolved best, we suppose, by patients for whom electrode, or current, interactions are minimal.

CIS processors should reduce current interactions and, as a consequence, should provide better resolution of the spatial distribution of energy along the cochlea. Thus CIS processors should provide better frequency discrimination and better speech understanding than the Ineraid. Our data from a single patient fitted with a CIS processor are consistent with these predictions.

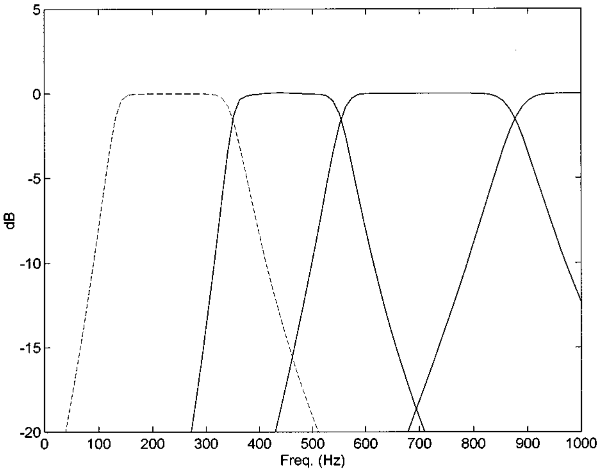

FIG. 10. Solid lines indicate I/O functions for the first three channels of a six-channel CIS processor. The dotted function indicates the first channel of a seven-channel CIS processor.

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[1] This format was chosen for our experimental task in order to increase the probability that patients were responding to differences in pitch rather than to differences in loudness and to minimize patient time in the laboratory. At issue was the finding for implant patients that differences in signal level can be heard as differences in pitch (e.g., Townshend *et al.*, 1987). Moreover, as Shannon (1993) has noted, the ability to detect differences in loudness may be better than the ability to balance loudness among stimuli. For this reason tests of frequency discrimination are often conducted with a roving loudness procedure. However, this procedure is extremely time consuming. For this reason we chose a three stimulus task and thought that by balancing loudness among three stimuli, instead of two, the possibility that loudness differences would be systematically related to pitch differences would be minimized.

The three stimulus task assumes, tacitly, that the perceptual distance between the first and middle stimulus is the same as that between the middle and last stimulus. To the extent that this is not the case, our data will underestimate the ability of the patient to discriminate. Thus the results described in experiments 1–5 are a conservative estimate of the frequency discrimination abilities of our patients.

The term frequency discrimination is used to describe our experimental task. Alternatively, the term pitch ranking could be used, since that is the nature of the task in perceptual terms. However, the term pitch ranking (or scaling) is used frequently to describe a task in which a large number of pure tones are presented in isolation and subjects are asked to assign a number or rank to the stimulus. To avoid confusion with this task, the term frequency discrimination is used in this manuscript.

[2] We chose a 90% correct level when contrasting differences in performance at different center frequencies because 90% correct indicates five out of five correct for one response, e.g., ‘‘high,’’ and four of five correct for the other response. This is a reasonable criterion for mastery of the discrimination.

[3] We tested only the most apical electrode. It is possible that tests on another electrode would have produced different results.

[4] The availability of spatial cues will vary among patients as a function of the distribution of excitable neural elements relative to the location of the electrodes in the cochlea, and as a function of the patterns of current interaction. As a result, discrimination accuracy cannot be related in a simple manner to the frequencies of the test signals relative to the implant filters’ center or edge frequencies.

[5] A virtual channel is constructed by simultaneously sending pulses to two electrodes. Generally, the perceived pitch is between that of the signals in isolation. However, in our experiment, the amplitudes of pulses to channels 1 and 2 were biased in such a manner that the perceived pitch was *lower* than that of channel 1. This was accomplished by simultaneously stimulating channel 1 with a positive-leading biphasic pulse and by stimulating channel 2 with a smaller negative-leading biphasic pulse. Modeling studies indicate that in this circumstance the amplitude of the basal-most portion of the excitation field for electrode 1 is reduced. The consequence is a field whose centroid is more apical than that of the field produced by a single pulse to channel 1.

[6] The improvement in frequency resolution had an unexpected effect on vowel recognition. Vowel identification rose to from 75% correct with the six-channel processor to 94% correct with the seven-channel processor. With the six-channel processor errors in vowel identification were limited principally to four vowels. ‘‘Bait’’ ($F1=480$–330 Hz) was confused with other front vowels, ‘‘bout’’ ($F1=684$-420) was confused with ‘‘boat’’ ($F1=530$-440), ‘‘boat’’ was confused with ‘‘boot’’ ($F1=350$ Hz), and ‘‘but’’ ($F1=625$ Hz) was confused with ‘‘bought’’ ($F1=625$-650). For two of the vowels (bait and boat) improvement in recognition can be reasonably attributed to improvement in resolution of the track of the first formant with the addition of a low-frequency first channel.

This result can also be viewed as an example of the benefits derived from extending the length of the electrode array by the addition of a ‘‘supra-apical’’ virtual channel. Wilson (1994a) have reported that virtual channels improve consonant recognition when the overall cochlear distance spanned by the electrode array is increased. Our result is consistent with this report.

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