A Cochlear Nucleus Auditory Prosthesis
Based on Microstimulation

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Abstract and Summary

Surface-electrode auditory brainstem implants (ABIs) are in general clinical use but provide the patient with limited speech recognition compared to cochlear implants (CIs). One possible reason for this difference in performance is the difference in pitch selectivity of the electrodes. Acoustic-electric pitch matches were obtained for all electrodes in 3 ABI patients with residual hearing in the non-implanted ear, and pitch estimates were obtained from 5 additional ABI patients. Three new processor strategies were tested that differed in their assignment of speech spectral information to electrodes. None of the three experimental maps produced improved performance over the standard clinical map. Thus, efforts to improve surface-electrode ABI performance by matching speech spectral regions to electrodes with the appropriate pitch were not promising. It is possible that the improved pitch selectivity that might be obtained with a penetrating microelectrode ABI could result in improved speech recognition.

Introduction

There are presently more than 100 patients using an auditory brainstem implant (ABI) with a multichannel surface electrode array. The performance of these patients is poorer than that of cochlear implant patients with the same speech processing strategy and the same number of electrodes. The reason for this difference in performance is not clear, but could be due to the difference in the two device's link to the tonotopic array of neurons in the cochlea and cochlear nucleus.

In the cochlear implant the electrodes are arranged in a linear array along the length of the scala tympani. The primary auditory neurons are arrayed along this structure in a tonotopic fashion as well. Thus, each electrode is close to a section of nerve that normally carries a distinct range of pitch information. Different electrodes generally excite neurons with different characteristic pitch.

However, in the ABI, the electrode array is placed in the lateral recess of the IV ventricle, which is adjacent to the dorsal cochlear nucleus. The neurons targeted for stimulation by the ABI are tonotopically arrayed in the posteroventral cochlear nucleus (PVCN) but that tonotopic axis is not aligned with the electrode array. Thus, the electrical field from each electrode can excite neurons in the PVCN (and other CN subunits) that are not tonotopically related to the electrode location in the array. This could result in a poor match between electrode location and the pitch percept evoked by that electrode.

ABI Pitch Range

Results from multichannel ABI patients have shown a relatively weak relation between electrode location and pitch. In most patients pitch increases as the electrode location is changed from lateral towards the brain midline (medial). However, some ABI patients show the reverse ordering of pitch and a few have no change in pitch across their electrode array (Shannon et al., 1993). Cochlear implant patients on the other hand generally show a clear and orderly relation between electrode location and pitch.

All ABI patients are deafened by neurofibromatosis type 2 (NF2), which is a genetic defect on Chromosome 22. NF2 causes multiple tumors on primary cranial nerves and along the spinal cord. The defining symptom of NF2 is bilateral vestibular schwannomas, which eventually cause deafness and are life threatening so they must be removed. Several ABI patients have received the implant during the surgery to remove the first of the bilateral tumors. In some of these cases the patients temporarily have residual acoustic hearing on the second side. To further assess the range of pitch sensations provided by the present surface electrode ABI we had three patients with residual hearing match the pitch of the sensation produced by electrical stimulation with each of their ABI electrodes.

Each ABI electrode was pulsed at a moderate stimulation rate (250 Hz) at a comfortable level. Electrodes were pulsed in two stimulation modes: monopolar and bipolar (BP), which should change the shape of the electrical field. The patient then heard (in their non-implanted ear) an acoustic sinusoid presented in the sound field from a calibrated audiometer. The frequency of the acoustic tone was adjusted by the audiologist until the patient felt it best matched the pitch of the electrical stimulus. A bracketing procedure was used to define the range of pitch, and the bracket was narrowed until a pitch match was achieved. In some cases pitch matches were poorly defined due to the complex character of the electrically elicited percept. In one case electrical stimulation elicited multiple pitches, and the patient was able to match individual pitch components to acoustic tones. Figure 1 plots the frequency of the acoustic matching pitch as a function of electrode location for three ABI patients with residual acoustic hearing. Open and filled symbols for patient 44 represent his pitch matches to bipolar monopolar stimulation and bipolar stimulation with adjacent electrodes. Open and filled symbols for patient 70 represent matches to the low-pitch and high-pitch components of the sensation, respectively. Patient 54 received only monopolar stimulation. These results expand and confirm earlier measures of pitch ranking by ABI patients (Shannon et al., 1993) in that mostly low-frequency pitch sensations are evoked by the ABI. Occasionally a high pitch sensation is produced.

Importance of matching pitch to electrode location.

Fu and Shannon (1999a,b) have demonstrated the importance of matching the speech frequency range to the tonotopic location of the electrode in cochlear implant (CI) listeners and to the frequency of the carrier bands in normal-hearing (NH) listeners. Both CI and NH listeners were highly sensitive to mismatches between the frequency information in speech and the place in the cochlea to which that information was delivered. Speech recognition decreased markedly when the envelope information in speech was delivered to a cochlear location that was shifted more than 3 mm from it's normal tonotopic place.

Shannon et al. (1998) and Fu and Shannon (1999c) demonstrated the importance of matching the frequency bandwidth of stimulation to the cochlear extent excited by the electrode. They systematically changed the bandwidth and distribution of the frequency band assigned to each electrode and changed the spacing and stimulation mode of the electrodes. Speech recognition declined dramatically when the absolute frequency and the bandwidth of the frequency information was not matched to the cochlear location and to the number of nerve fibers activated. In some cases eliminating the information from a spectral region was better than presenting that information to the wrong pitch place. This result was similar in both normal-hearing listeners with a noise-band vocoder simulating a cochlear implant and in cochlear implant listeners. The results of these studies indicate that it is important to match both the absolute frequency and the bandwidth between the analysis filters and the place of stimulation.

In an ABI this matching is problematic because of the poor tonotopic selectivity of the present surface electrode device. There may not be a clear match in either tonotopic location or in tonotopic bandwidth between the surface electrodes and the neurons in the cochlear nucleus. Thus, one possible reason that the present surface electrode device provides relatively poor speech performance is that the speech information is not being delivered to the tonotopic dimension of the cochlear nucleus in a manner that preserves absolute frequency-place and bandwidth. The following experiments were performed to achieve a better match between speech frequency information and the tonotopic dimension of the cochlear nucleus.

Methods

Subjects.

Five patients with the multichannel ABI participated in the following experiments. These patients were selected because they had a relatively large pitch range across their electrodes.

Speech Test Materials.

Once an experimental processor was defined and adjusted the subject's recognition of consonants and vowels was assessed. Sixteen medial consonants and eight medial vowels from the Iowa Videodisc (Tyler et al., 1987) from a single male talker were used. The listener was presented with a randomly chosen consonant token (or vowel token) and asked to indicate its identity from the 16 item set (or 8 item set for vowels). Chance performance was 6.25% correct for consonants and 12.5% for vowels.

Pitch Estimation Procedure.

Patients were presented with a single stimulus (250 pps biphasic pulse train) on a randomly selected electrode. They were instructed to assign each stimulus a number from 0-100 representing its pitch. They were instructed that low numbers should be used to represent the lowest pitch they could remember and high numbers used to represent high pitches.

The pitch matching results in Figure 1 suggest that the pitch range produced by an ABI is relatively small. However, the five patients participating in this experiment all had a sizable range in pitch, as indicated in Table 1. One possibility for this discrepancy is that patients with some residual hearing (Figure 1) are actually using the full range of pitch because they continue to experience a full range of pitch sensations in their hearing ear. However, ABI patients with no residual hearing have only the auditory sensations produced by the ABI. If these sensations have a limited pitch range, this limited experience may, over time, change the patient's pitch scale.

Table 1

Patient #	Age	ABI Use	CUNY Score	Pitch Range (0-100)
35	30	full time	55	30-71
36	30	full time	19	41-77
53	41	full time	0	23-65
66	20	no use - hearing in other ear	4	15-72
71	46	full time	0	48-80

Experimental Speech Processing Strategies.

Three experimental speech processing strategies were compared to the strategy used in patient's clinical speech processor, in which the speech spectrum was divided into the same number of bands as there were available electrodes. Figures 2, 3, and 4 show schematic representations of the experimental processor strategies. The frequency spectrum of speech is partitioned into 10 analysis filters, and their outputs is to be distributed to four electrodes. The four electrodes in the hypothetical examples each stimulated a restricted portion of the tonotopic range in the cochlear nucleus. The two hypothetical lower-pitch electrodes excite a narrower segment of the tonotopic range than the two hypothetical higher-pitch electrodes. The experimental processors differ in the way the outputs of the analysis filters are assigned to electrodes.

The first experimental speech processing strategy, called the NEW processor (Figure 2) used a strategy similar to that used in the ABI patient's original clinical processor, but additional analysis filters were used. In general, ABI patients have only 6-8 usable electrode combinations. The standard SPEAK processing strategy used in cochlear implants employs as many as 20 analysis filters to process the speech. To accommodate this mismatch between the number of filters and number of electrodes, each electrode can be assigned the output of more than one filter band. In the NEW strategy the lowest pitch and highest pitch electrodes received the output from multiple filters, and the middle pitch electrodes usually received the output of a single analysis filter.

The second (MATCH) and third (EXPanded) experimental speech processing strategies differed in the way they divided the entire speech frequency range among the available electrodes - either matching (MATCH) or expanding (EXP) the pitch range of the electrodes. In the MATCH processor (Figure 3) the entire speech spectrum was divided into 10 bands. The ABI patients were asked to assign the pitch of each electrode a number from 0-100. It was assumed that their pitch estimates on this 0-100 scale were linearly related to log frequency, i.e., that an electrode that produced a pitch percept of 0-10 was equated with the lowest analysis band. This assumption is similar to a piano keyboard, in which the linear progression of keys is related to logarithmically spaced frequency. A speech analysis band was assigned to an electrode only if the pitch of the electrode matched the pitch of the center frequency of that speech analysis band. Thus, an electrode that was assigned a pitch estimate of 0-10 received the output of the lowest frequency speech analysis band. An electrode that was assigned a pitch estimate of 10-20 received the output of the next-lowest frequency speech analysis band. If no electrode was assigned a pitch between 30 and 40, then the information from that speech analysis band was simply omitted, i.e., it as not assigned to any electrode. This processor was intended to maximize the match between a frequency range in speech and the pitch produced by an electrode. Speech information was simply omitted from spectral bands for which there was no electrode matched in pitch. This manipulation will of course remove some critical speech information, but the intention was to test the relative importance of omitting speech information as opposed to assigning it to an electrode with the wrong pitch. In normal-hearing listeners it is sometimes the case that eliminating a band of speech information is better than presenting the information to the wrong tonotopic location.

In the EXP (expanded) processor (Figure 4) the 10 filter bands representing the 10 spectral frequency ranges were all assigned to electrodes. In this case the filters were assigned to the electrode which elicited the closest pitch match to that frequency band. The highest and lowest pitch electrodes received all speech information from the entire speech frequency region either higher or lower than the pitch of the electrodes, respectively. Thus, the entire pitch range of speech was compressed into the pitch range of the electrodes. Conversely, the electrodes were representing speech information from an expanded (EXP) spectral range.

Results

Figures 5 and 6 present the phoneme recognition performance by the 5 ABI patients, for consonants and vowels. Five panels in each figure give the individual subject data for each processing strategy, and the average results across subjects are presented in the lower right panel of each figure. No systematic trend was observed in performance for any of the experimental processing strategies. No experimental condition produced any improvement in performance over the patient's standard clinical processor.

Discussion

The present results are not encouraging for the surface electrode ABI. Several strategies to match the frequency region of speech with the pitch of each electrode were tried and none produced any improvement in performance over the patient's normal clinical processor. This result suggests that the limited pitch range and pitch selectivity of the surface electrode ABI may not allow a good level of speech recognition. Of course, performance may improve over time with additional experience with each processor. However, it is our experience that in cochlear implant patients, improvements in speech recognition due to improving the pitch-position match are immediate. Additional improvements in the performance of ABI users may occur over time, but the fact that no immediate improvement was observed is not encouraging.

These results suggest that high levels of speech recognition with an ABI may only be achievable with a penetrating electrode system in which a close coupling between electrodes and pitch-specific neurons can be achieved. If the cochlear nucleus contains intrinsic processing mechanisms and circuits that are bypassed in electrical stimulation, then even penetrating electrodes may not be able to provide high levels of speech performance.

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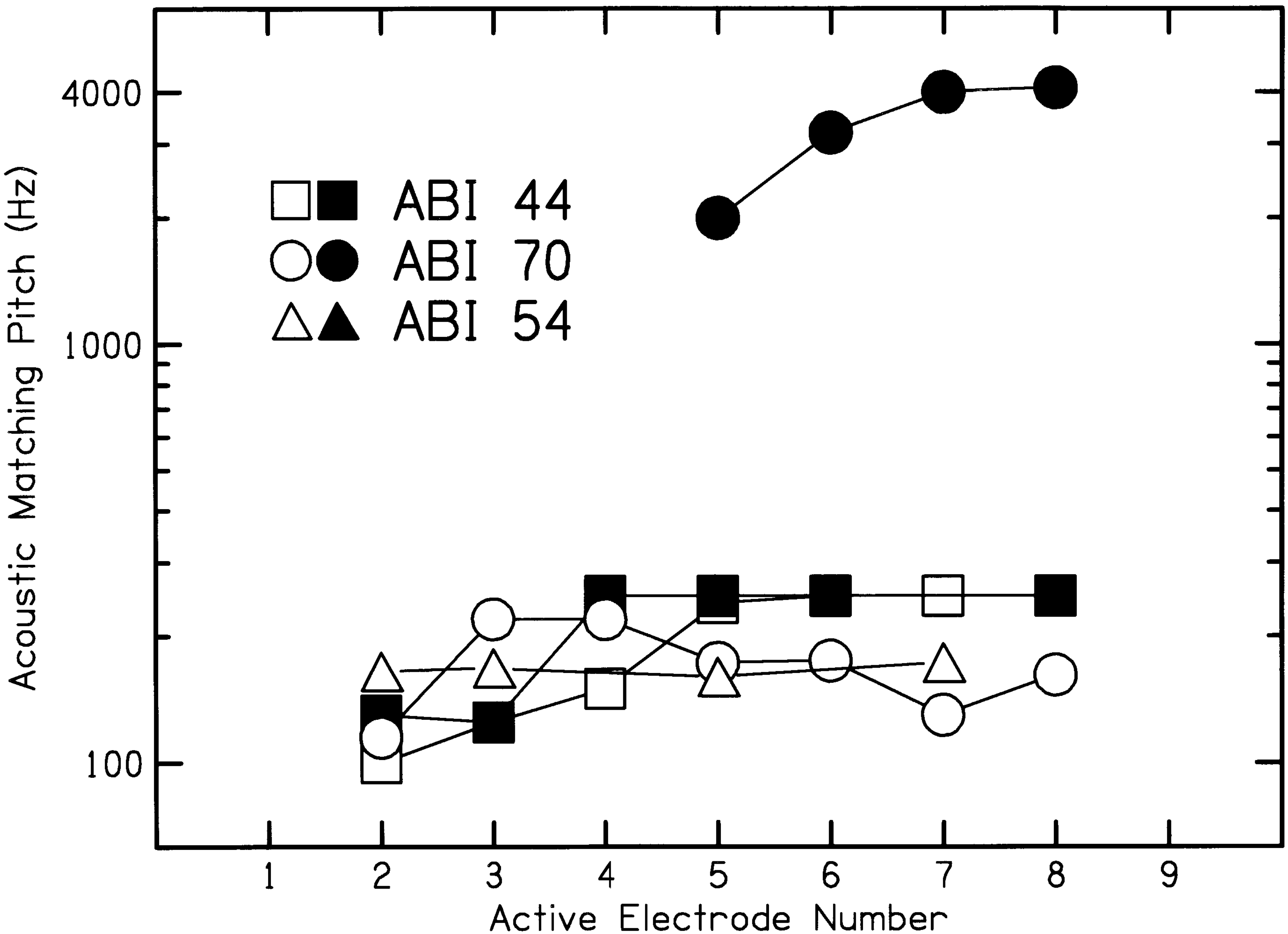


Acoustic Matching Pitch (Hz)
4000
1000
100
ABI 44
ABI 70
ABI 54
1
2
3
4
5
6
7
8
9
Active Electrode Number

FIGURE 1

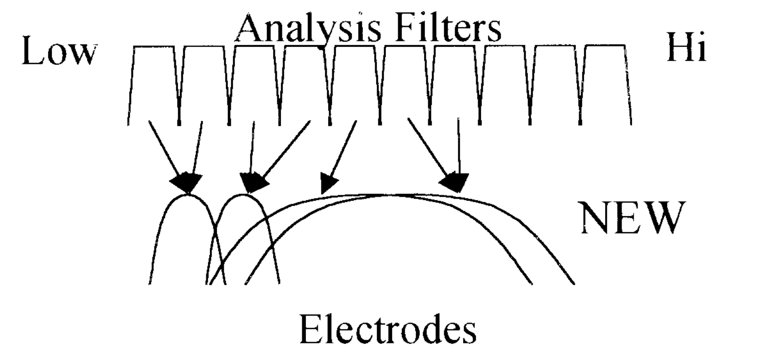


FIGURE 2

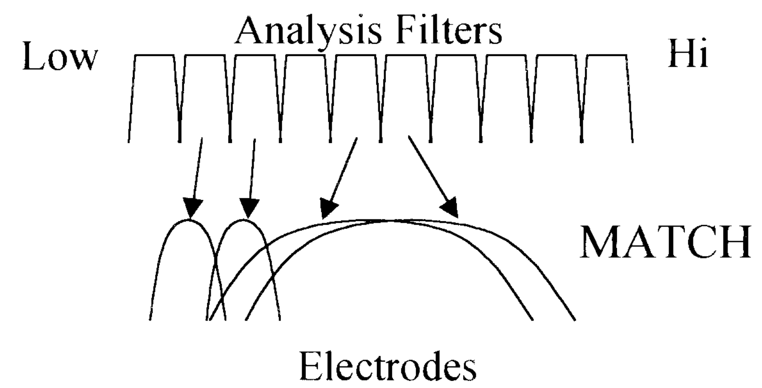


FIGURE 3

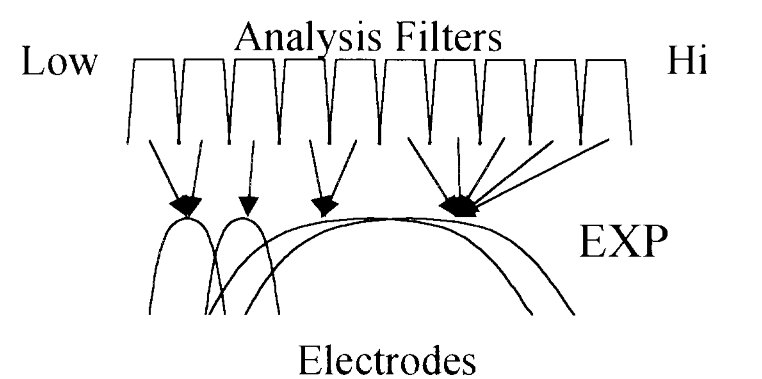


FIGURE 4

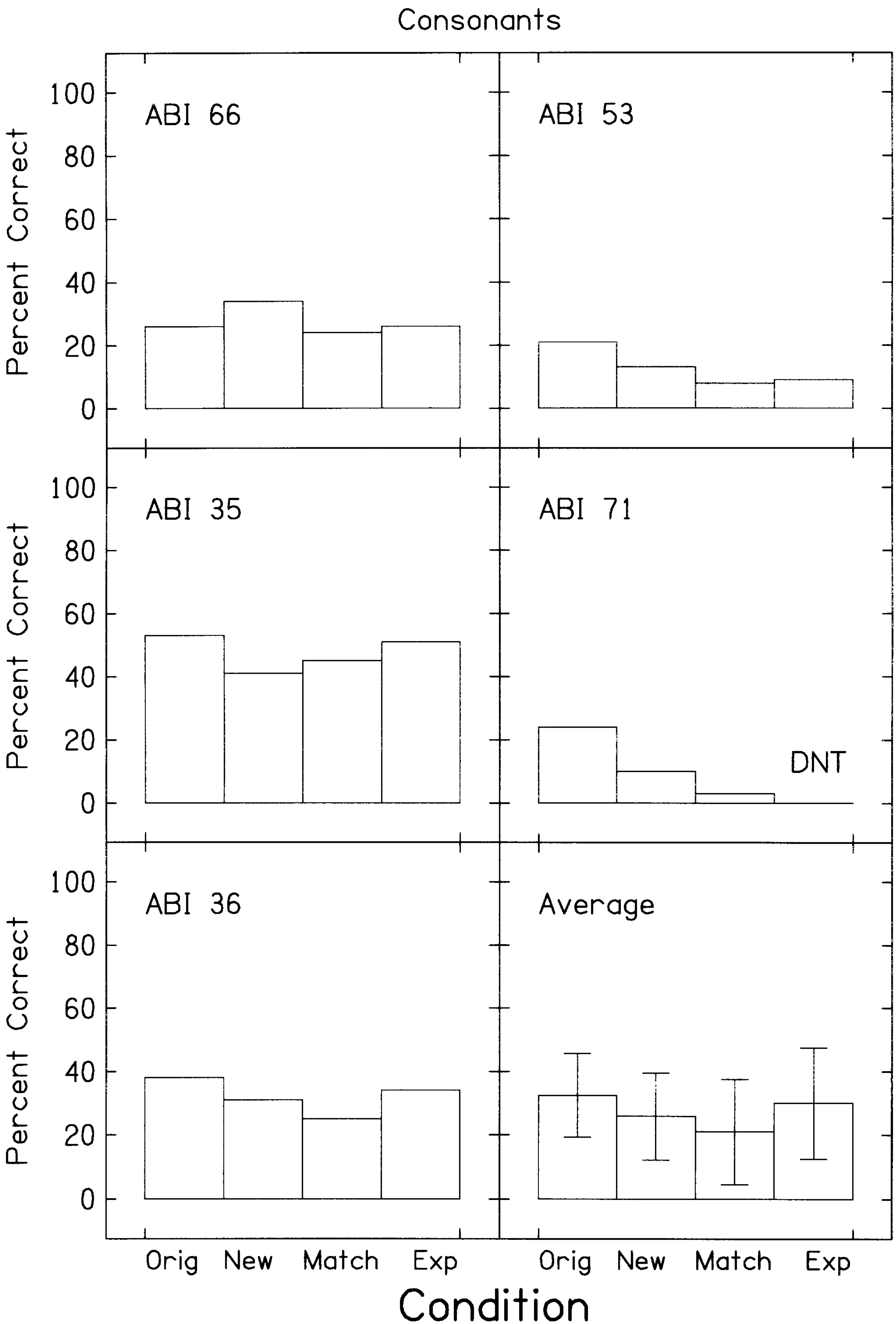
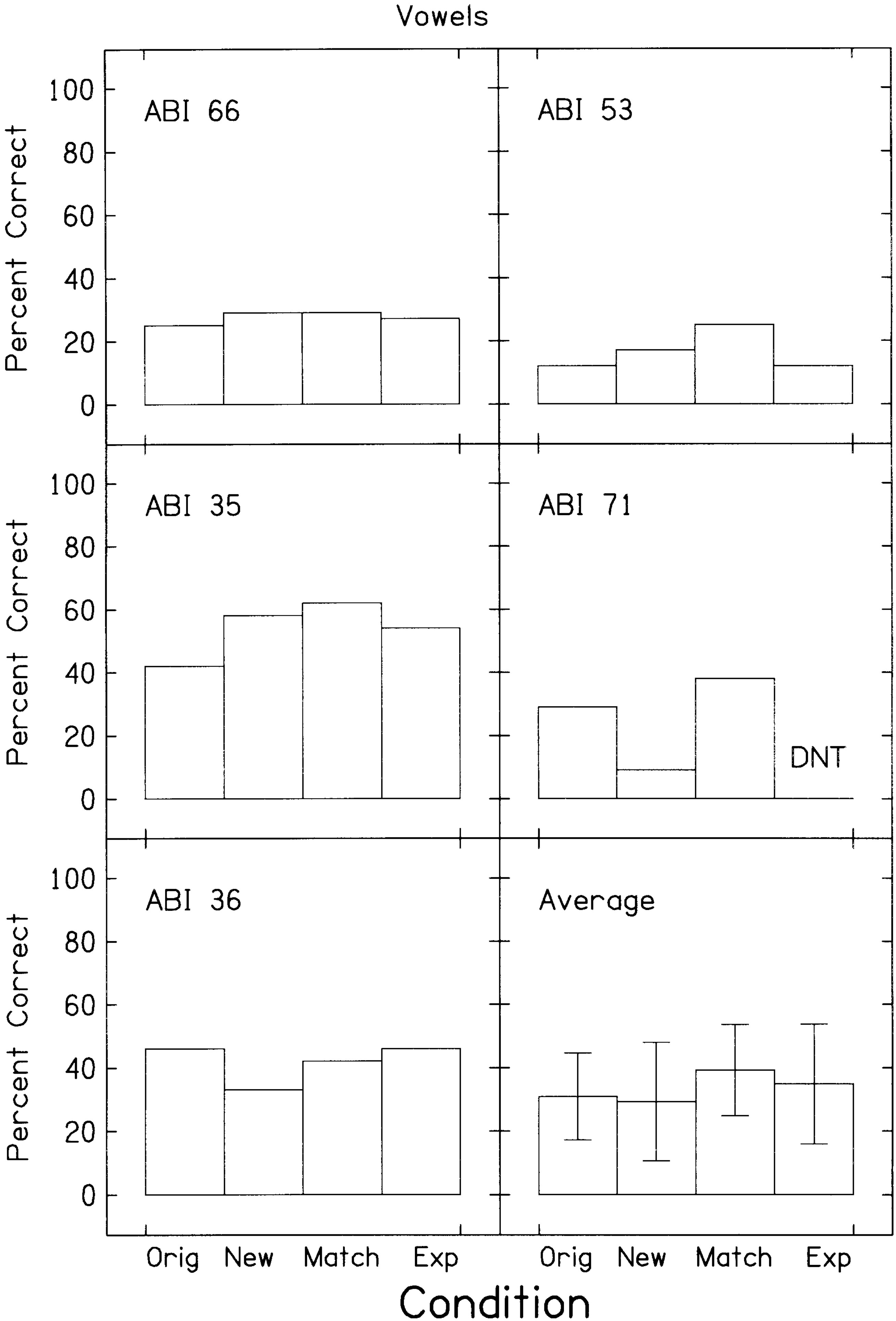

Consonants
ABI 66
ABI 53
ABI 35
ABI 71
DNT
ABI 36
Average
Percent Correct
100
80
60
40
20
0
Orig
New
Match
Exp
Condition

FIG 5



Vowels
Percent Correct
ABI 66
ABI 53
ABI 35
ABI 71
DNT
ABI 36
Average
100
80
60
40
20
0
Orig New Match Exp
Condition

FIG 6