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What Should be Implemented in Future Cochlear Implants?

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Cochlear-implant performance can be improved by focusing on: 1) *psychophysical studies* to determine hearing limitations; 2) *speech perception* to suggest the most effective *speech-processing* strategies; 3) *aural rehabilitation* to effectively train patients to use the new electrical stimuli. Basic psychophysical studies have shown only weak correlations with speech perception. Perhaps more speech-like stimuli should be explored in psychophysical tasks. Studies on vowel and consonant recognition suggest enhancing all speech features, but particularly frication and place of articulation should help most patients. Probably the feature that would be the most beneficial to enhance is place of articulation, which is poorly coded even in the best patients. Empirical studies are needed to determine the ways in which these cues can be enhanced. Certain types of auditory training are likely to be beneficial, particularly when the signal is new, incomplete or distorted. However, much more research in aural rehabilitation is needed. *Key words: cochlear implants/signal processing.*

INTRODUCTION

One of the most remarkable aspects of cochlear-implant performance is the enormous intersubject variability. These differences are related primarily to: 1) residual hearing, 2) the type of cochlear implant, and 3) some 'information-processing ability'. The memory for speech sounds and the ability to guess and assign appropriate labels to distorted or fragmented percepts is part of the information-processing abaility. We review our recent research and suggest some avenues for improving performance.

METHODS

Understand Limitations and Enhance Psychophysical Abilities

We have examined the relationship between speech recognition and psychophysical performance for stimuli transformed by the signal processors of the cochlear implant. Fig. 1 shows the relationship between gap detection and phoneme recognition in words in a group of 53 of the better cochlear-implant patients (1). Patients with good gap detection skills can have both poor and good word-recognition skills. However, patients with poor gap detection abilities tend to have poor word recognition (see also 2, 3). The perception of second-formant frequency transitions could also be relevant to speech perception. However, the data in Fig. 2 suggest that there is no obvious relationship between formant-frequency difference limens and consonant recognition.

Because these tasks are typically measured in only one spectral region, and because there are many other underlying factors in speech perception, we should not expect close correlations with any single variable. Nevertheless, it may be that in order to gain insights into speech perception we must use stimuli that are more speechlike, if not speech itself. We need to understand the psychophysical limitations of each patient and to learn how to compensate for them.

Determine Important Speech Cues for Individuals

Speech recognition should be measured with sentence and phoneme tests. Sentence tests reflect the rapid rate of information conveyed in normal conversation (4). Phoneme tests

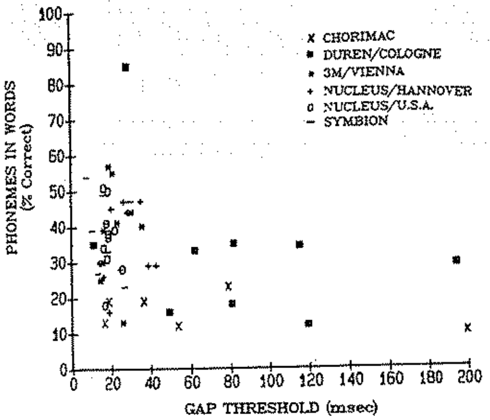

Fig. 1. The relationship between gap detection and phoneme recognition in words in 53 of the better cochlear-implant patients (1).

provide for a detailed analysis of the speech features. Phoneme tests have less face validity because we do not communicate in isolated utterances. This face-validity issue is superficial, however, because sentences are comprised of a series of syllables, and there is a significant correlation between consonant recognition and word recognition (Fig. 3).

The most important benefit for most cochlear-implant patients is speechreading enhancement. Although it is often argued that the speech features that are most difficult to hear are the ones that are the easiest to see, audiovisual performance rarely achieves 100% correct. Therefore an improvement in all features could be helpful. Fig. 4 shows the relationship between sound-alone performance and speechreading enhancement (sound-plus-vision minus vision) on consonant recognition. Patients who score higher on sound-alone tests generally get more enhancement on speechreading tasks. Also noteworthy is the observation that many patients obtain a greater enhancement score than their sound-alone score. Their enhancement is larger than a simple addition of their vision-alone and sound-alone scores. This is particularly true for patients who scored less than 40% correct

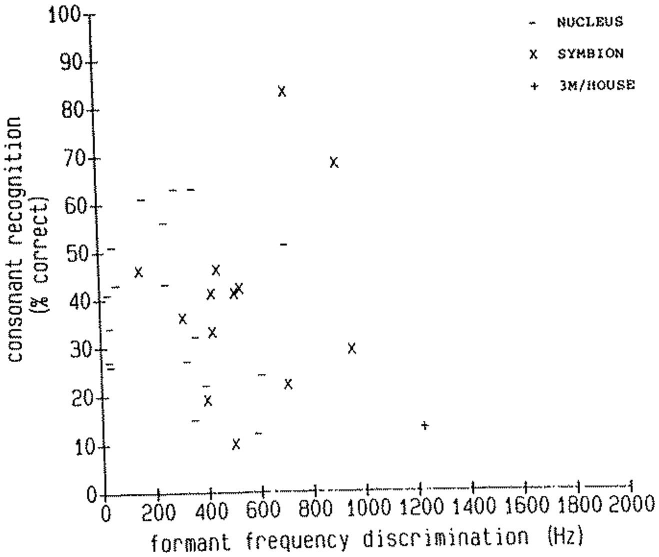

Fig. 2. The relationship between formant-frequency discrimination and consonant recognition for a group of cochlear-implant subjects tested in Iowa. The standard was a 50-ms single-formant transition at 2000 Hz. Increments in the starting frequency were measured to determine the difference limen. Testing was performed in soundfield, incorporating the effects of the particular signal-processing of each implant.

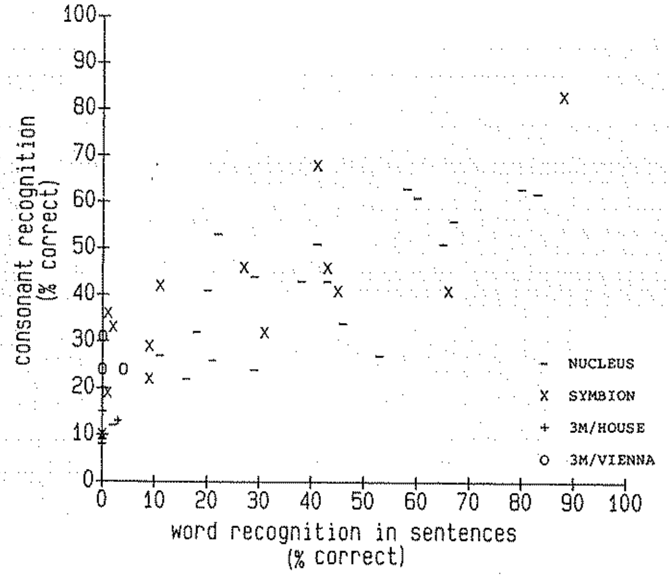

Fig. 3. The relationship between consonant recognition measured in isolated nonsense syllables and word recognition in cochlear-implant patients (r=0.83, p<0.001).

with sound alone. Although a more detailed description of the ways to improve cochlear implants should consider audiovisual and auditory-alone characteristics separately (5), we focus on sound-alone conditions here.

Spectral processing

Studies on vowel recognition can be used to examine spectral processing. In one experiment, patients were required to recognize two-formant synthetic vowels (6). Patients were provided with written vowel pairs from which to select one that was heard. In one set of stimuli, each pair had identical F2 values and differed only in F1. In the second set, each

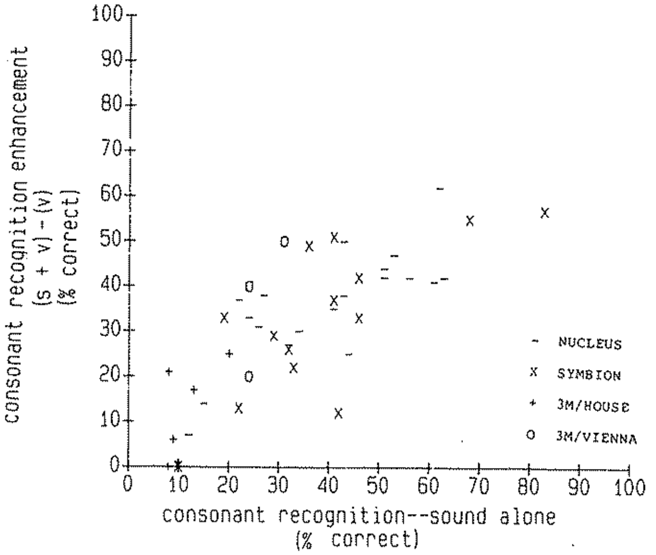

Fig. 4. The relationship between sound-alone performance and the difference between sound-plus-vision and vision-alone (speechreading enhancement) on a consonant recognition task ($r=0.78$, $p<0.001$).

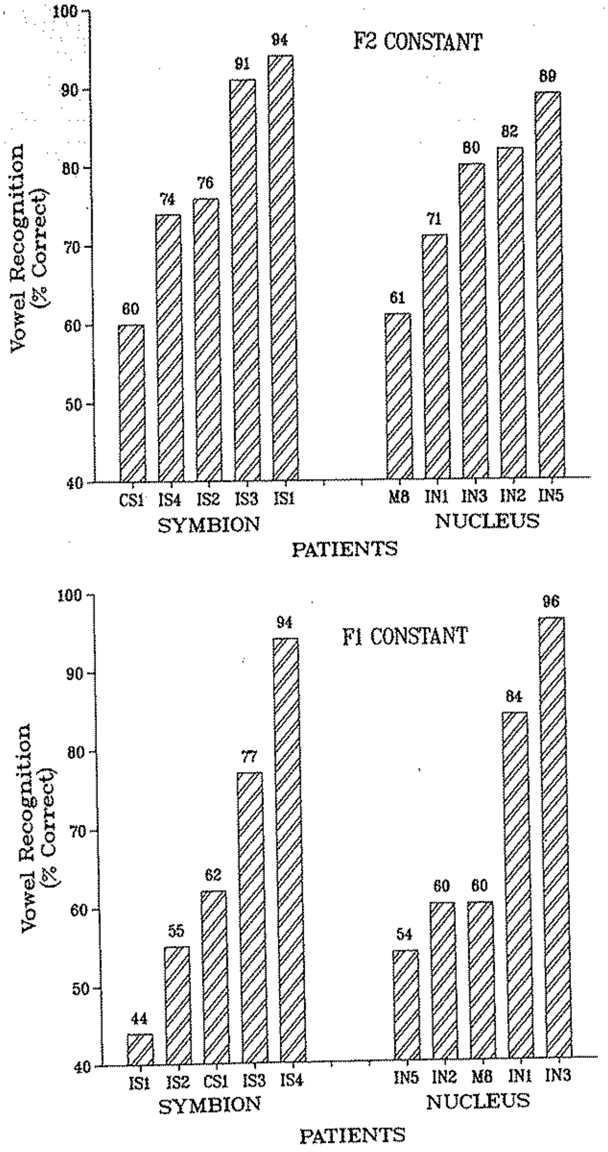

Fig. 5. The recognition of two-formant synthetic vowels. *Top:* Stimuli differed only in F1. The pairs included /æ, ɛ/, /ɑ, ʊ/, and /ɔ, u/. *Bottom:* Stimuli differed only in F2. The pairs included /ɜ, ɛ/, /ɪ, ʊ/, and /i, u/. The results are averaged across vowel pairs. Adapted from Tyler, Tye-Murray & Otto (6).

pair had identical F1 values, and differed only in F2. The results, shown in Fig. 5, indicated that 8 out of 10 patients scored above chance when F1 differed (F2 constant), but only 5 out of 10 patients scored above chance when F2 differed (F1 constant). There is an opportunity for improvement if spectral information, particularly in the higher frequencies, can be coded more effectively.

We must not overemphasize studies focusing on vowel perception. Vowels contain largely steady-state information which is quite different from the dynamic transitions in consonants. Consonants also 'carry' more information. For example, a sentence without consonants: 'e oy i e o i i.' is much more difficult to interpret than one without vowels: 'Th b lks t drnk mlk.' Certain implant processors may code steady-state sounds effectively, but have great difficulty coding formant transitions.

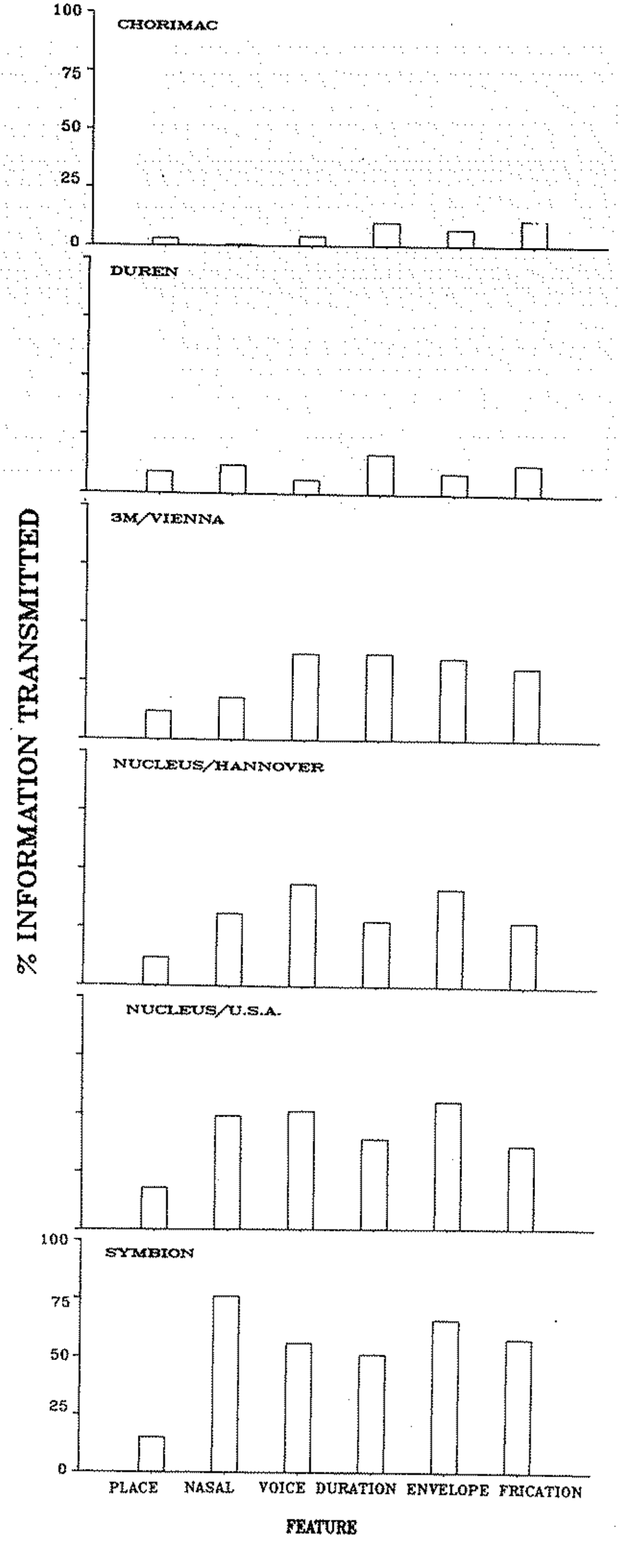

Fig. 6. Information-transfer analysis performed on six different cochlear-implant groups representing some of the better patients. Adapted from Tyler & Tye-Murray (13).

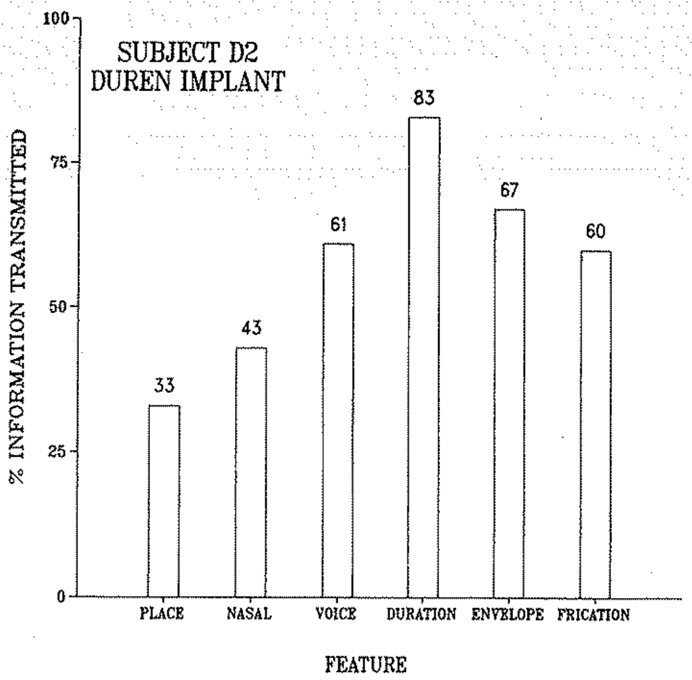

Fig. 7. Individual information-transfer analysis from patient D2 (single-channel, extracochlear) with the Duren/Cologne cochlear implant.

Consonant confusions

One important tool for understanding confusions is information-transfer analysis (7). Consonants are assigned feature categories and performance is analysed according to the feature perceived.

In one study we have examined the performance of some of the better cochlear-implant patients. The study included patients with the multichannel Chorimac (8), single-channel 3M/Vienna (9), multi- and single-channel Duren/Cologne (10), the multichannel Nucleus (11), and the multichannel Symbion (12) device. In Fig. 6 the information-transfer analysis indicates that the place feature is the most poorly perceived, and the features of nasality, frication, voicing and envelope are transmitted more effectively (13).

Examining some individual data may also be of interest. Fig. 7 shows the results from one of the best patients (56% consonant recognition). Although her 'place' score is higher than that of other subjects, it still represents the poorest transmitted feature for her.

Provide Intensive Modular Rehabilitation

One of the most unexplored areas of cochlear-implant work is the design of individual auditory rehabilitation programs. While all the attributes of the information-processing ability may not be trainable, some can be. While much useful rehabilitation is being accomplished, very little research to determine the most effective techniques has been done.

For those patients that are not receiving information about particular features, it may be more efficacious and less expensive to provide comprehensive rehabilitation. Such programs could be modular, focusing on individual features. They could also be computer based, reducing the cost and allowing for individually-paced and individually-designed programs (5, 14).

DISCUSSION

Improving feature perception

For most patients, improved speech perception will result if any of the features are enhanced. The features of frication and place provide useful and different kinds of information, high-frequency aperiodicity and frequency transitions, respectively. Sounds that are nasal or voiced share the characteristics of having a high-amplitude envelope compared with non-nasal and unvoiced sounds. Therefore, systematic efforts at improving the perception of place, frication, and the envelope are likely to be the most fruitful.

Although the place feature is important for speech perception, it is not perceived well by any of the patients. The acoustic cues thought to be relevant to the place feature in normal listeners are formant transitions and initial burst spectrum. Empirical studies are required to evaluate different enhancement schemes. However, because of the enormous individual differences in performance, the number of subjects involved in these trials should be relatively large, perhaps 20 or 30.

Adapting the device to the individual

Individual adaptations will need to be made to maximize performance. It may be necessary to adjust the frequency response both within and across channels. Adjusting channel bandwidths may also improve performance. Increasing the number of channels that respond to particular frequency transitions could aid perception of the place feature.

Feature-extraction devices may need to emphasize some features and de-emphasize others. For example, in subjects who perform poorly, the voicing feature might be emphasized (15) to improve speechreading performance, whereas other features could be given less emphasis. In subjects who perform well, the voicing feature might be de-emphasized, and all the coding capacity could be designed to enhance the 'place' cues.

Some patients may prefer analogue stimulation, whereas others may prefer pulsatile. New implants may need to be able to present either, and perhaps to utilize both simultaneously. For example, aperiodic pulsatile stimulation could code frication on a high-frequency channel, whereas analogue stimulation could code other features on remaining channels.

A variety of noise-reduction schemes should be available to the individual, so that different ones could be implemented depending on the environment. For example, diffuse low-frequency periodic background noise may require a different type of noise suppression than undesirable human voices coming from one direction.

Finally, with microprocessor-based systems, the coding strategies could change automatically. The 'optimal' coding scheme will depend upon many factors in the acoustic environment. Different algorithms could be automatically switched in and out; depending upon whether two or more talkers are present, whether the talker is an adult male, adult female or child (15), and whether the background noise is continuous, intermittent, periodic, aperiodic, diffuse, or focused.

Our experience with cochlear implants, including signal processing, assessment techniques, and patient performance, should help in the development of new generations or more sophisticated hearing aids.

ACKNOWLEDGEMENTS

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