Low-pass filtering in amplitude modulation detection associated with vowel and consonant identification in subjects with cochlear implants

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Temporal auditory analysis of acoustic events in various frequency channels is influenced by the ability to detect amplitude modulations which for normal hearing involves low-pass filtering with a cutoff frequency around 100 Hz and a rejection slope of about 10 dB per decade. These characteristics were established in previous studies measuring modulation transfer functions. For cochlear implant subjects, the delivery of detailed amplitude modulation information has been recently shown to result in very significant improvements in speech understanding. Several previous studies on cochlear implant subjects have reported capacities for temporal resolution rather equivalent to those of normally hearing subjects but with some notable individual differences. Recently two studies on some cochlear implant subjects indicated modulation transfer functions often quite similar to those of normal hearing but exhibiting marked individual differences in shape and absolute sensitivity. The present study compared amplitude modulation detection and phonetic recognition in a group of cochlear implant subjects to determine the extent to which the two tasks are correlated. Nine individuals who had been implanted with an Ineraid device and who demonstrated open speech understanding ranging from excellent to poor were chosen and tested in the present study. For each subject modulation transfer functions were measured at the most apical electrode and phonetic recognition of isolated vowels and intervocalic consonants was assessed. Results showed a strong correlation between the depth of high-frequency rejection in modulation transfer functions and success in vowel and consonant intelligibility. These results emphasize the importance of temporal speech features and offer perspectives for customizing signal processing in cochlear implants.

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INTRODUCTION

Improvements in signal processing done by cochlear implant devices in order to improve speech understanding by cochlear implant subjects is an important research domain. To this aim, considerations both of acoustic features used for speech perception and of individual psychophysical capacities of implanted patients need to be combined. For speech perception, as well as for all auditory sensations, the cochlea analyzes incoming acoustic signals in both the time and frequency domains resulting in spectro-temporal coding. The cochlea performs a tonotopic frequency analysis (see Wilson, 1992 for a review) which is tentatively reproduced in multichannel cochlear implants by attributing different frequency bands to different electrodes placed from the base towards the apex (Merzenich *et al.*, 1974; Parkins and Anderson, 1983; Clark *et al.*, 1984; Keidel and Finkenzeller, 1984). It has been established long ago (Helmoltz, 1868; Zwicker and Feldtkeller, 1967) that normal-hearing perception involves for each frequency band a low-pass filtering of amplitude modulations. The importance of delivering fine temporal variations of intensity within each channel of cochlear implant has received a remarkable demonstration in recent studies issued from the Ineraid device (Wilson *et al.*, 1989; Wilson *et al.*, 1991). In the continuation of our previous studies attempting to determine how different sensitivities from individual patients contribute to successful speech understanding (Cazals *et al.*, 1990, 1991), the present study examined capacities of several cochlear implant subjects to perceive amplitude modulation in relation to measures of their phonetic recognition.

The exploration of sinusoidal amplitude modulation perception with acoustic stimuli has been used as one measure of temporal resolution, and detection thresholds as a function of the frequency of amplitude modulation were taken to define temporal modulation transfer functions (Zwicker and Feldtkeller, 1967; Viemeister, 1977, 1979; Rodenburg, 1977; Forrest and Green, 1987; Formby and Muir, 1988). These functions for listeners with normal hearing show a low-pass filtering characteristic with a cutoff frequency around 100 Hz and a rejection slope of about 10 dB per decade. Listeners with limited hearing have been found to show functions of similar shape although sometimes with a reduced sensitivity (Bacon and Viemeister, 1985; Bacon and Gleitman, 1992). Two recent reports (Shannon, 1992; Busby *et al.*, 1993) measured amplitude modulation detection in cochlear implant subjects and indicated that their temporal modulation transfer

TABLE I. Clinical data for the nine patients of the study. Numbers in years.

Patient	Age	Etiology	Deafness duration	Duration of implant use
1	22	meningitis	6	4
2	53	otosclerosis	12	2
3	72	unknown	50	1
4	32	meningitis	9	2
5	75	sudden deafness	1	1
6	65	unknown	58	5
7	40	progr. deafness	25	4
8	58	sudden deafness	3.5	3
9	52	antibiotic	11	3

functions often had essentially the same low-pass characteristics but with large intersubject differences. Other previous measures of temporal resolution, using gap detection in cochlear implant subjects, have also reported performances in the same range as for normal hearing subjects with clear individual differences (Dobie and Dillier, 1985; Hochmair-Desoyer *et al.*, 1985; Moore and Glasberg, 1988; Tong *et al.*, 1993; Shannon, 1989; Tyler and Moore, 1989; Cazals *et al.*, 1991). Few of these studies related gap detection performance with speech perception scores. Shannon (1989) found no difference in gap detection between subjects with high or low speech scores. Tyler and Moore (1989) reported that cochlear implant subjects with normal gap thresholds showed a wide range of speech scores whereas subjects with the longest gap thresholds showed poor speech recognition. Recent data from our own studies (Cazals *et al.*, 1991) indicated a clear correlation between gap detection and phonetic identification.

Phonetic sounds are composed of amplitude variations occurring in different frequency bands (Koenig *et al.*, 1946; Miller *et al.*, 1991). The importance of these modulations in speech perception has been quantified (Steeneken and Houtgast, 1980), and analyses of phonetic perception were elaborated from temporal patterns of amplitude modulation (Miller and Nicely, 1955; Voiers, 1971; Wang and Bilger, 1973; Peckels and Rossi, 1973; van Tassel *et al.*, 1987, 1992; Freyman *et al.*, 1991). Considerable individual performance variability appears in many of these studies on speech perception, revealing large differences in using these features to identify phonetic sounds. Therefore, in cochlear implant subjects an explanation of individual differences in speech recognition could include both variations of basic psychophysical sensitivities to amplitude modulation and/or different cognitive use of amplitude modulation cues.

This study was designed to investigate vowel and consonant identification in a group of subjects with cochlear implants in order to better understand the importance of fine temporal coding in speech perception.

I. MATERIALS AND METHODS

Nine postlingually deaf subjects participated in these experiments. Clinical information about these patients is presented in Table I. They were all implanted with an Ineraid device (Smith & Nephew, Richards, Inc.). These subjects were selected from a group of 28 patients implanted at the Cantonal University Hospital of Geneva, on the basis of their scores on vowel and consonant intelligibility tests which ranged from poor to excellent scores. All subjects regularly use their device with four channels connected to the four most apical electrodes.

Amplitude modulation detection was measured for each patient at the most apical electrode. Electrical signals were delivered through an optically isolated current generator in monopolar configuration, the electrode in the temporal muscle being used as a reference. Test signals for modulation transfer functions were calculated in a small computer and generated through a 12-bit digital-to-analog converter (Data Translation DT2821) at a sampling rate of 20 kHz. All current levels were measured in microamperes peak to peak. A train of biphasic pulses at a rate of 1667 pulses per second was used as a carrier; the width of pulses was set at 50 μs for seven subjects. In order to cover loudness ranges of the other two subjects, the pulse width was increased to 100 μs for subject 5 and to 200 μs for subject 4. The carrier was chosen to be similar to that of Wilson *et al.* (1991) so that comparison could be made and practical implications could be inferred. Fixed sinusoidal modulation frequencies of 20, 50, 71, 100, 200, 400, and 800 Hz were used. Modulation of the electrical current followed the usual formula $s(t)=c(t)\{1+m\sin[\omega(t)]\}$, where $s(t)$ is the resulting signal, $c(t)$ the carrier, m the modulation index varying from 0 to 1, and ω the modulation pulsation.

Thresholds of amplitude modulation were measured using a three-alternative forced-choice procedure with a one-up two-down format and visual feedback. Each stimulus was 500 ms in duration and the interstimulus interval was 1 s; one stimulus only was modulated the other two were unmodulated. A starting level of 100% modulation depth ($m=1$ in the above formula) was used with a decreasing step of 4 dB for the first reversal; the step size was successively halved twice at the second and fourth reversals and remained fixed at 1 dB thereafter. For each test a total of 13 reversals was used and the average of the last four peaks and four valleys was computed for threshold determination. For each subject measures were repeated two to four times at selected modulation frequencies to check reproducibility and the average was taken as a final measure. Subjects reported clear perception of a modulation for the low modulation frequencies up to about 100 Hz, whereas at higher modulation frequencies perception of loudness modulation was less consistently reported but subjects were still able to reliably perform the detection task. Modulation thresholds were measured at three loudness levels (low, medium, and high) for the first five subjects, and only at medium loudness for the last four subjects. To determine these levels a simple loudness magnitude scaling on a ten-step scale, spanning from threshold of audibility to discomfort, was rapidly determined by scanning current levels upward and then downward delivering the unmodulated carrier. The low loudness level was chosen corresponding to subjective magnitude step 2, and medium and high levels corresponding to steps 7 and 9. Modulation threshold data originally in microamperes were computed in two ways. First, they were calibrated for each subject as a percentage of his range between threshold of audibility and

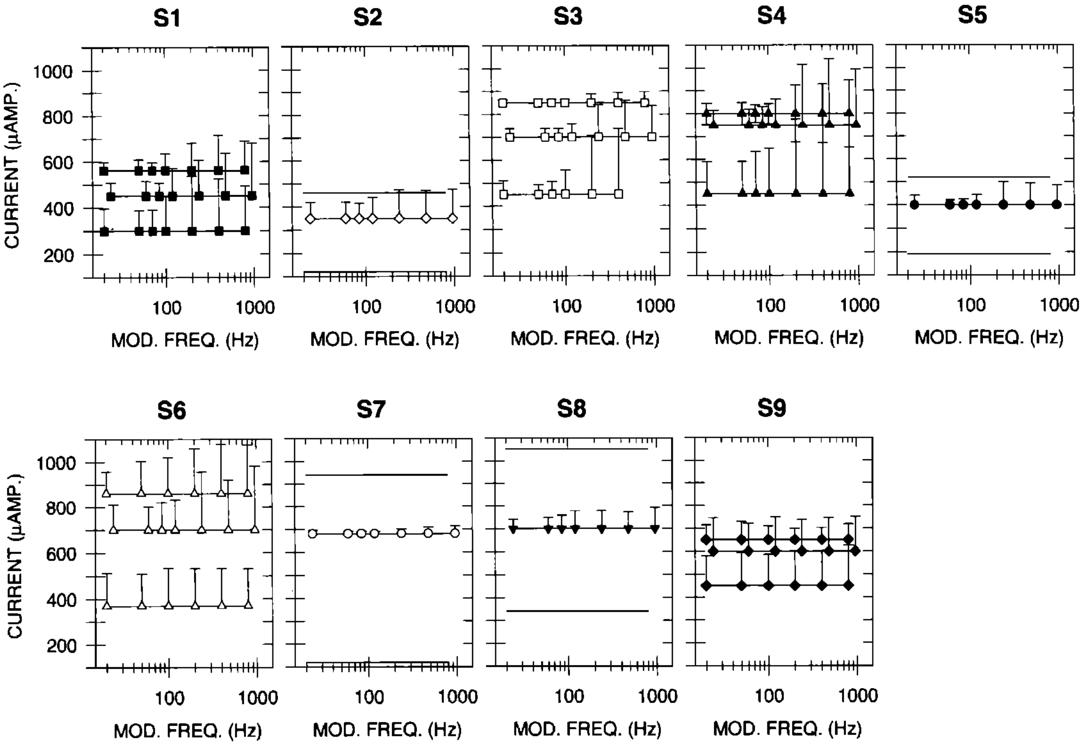

FIG. 1. Values of amplitude modulation thresholds (vertical bars) as a function of modulation frequency for the nine subjects of this study (S1 to S9). Subjects were ranked from best to worst intelligibility scores. The data for each subject are plotted using a separate symbol. Use of these symbols will be consistent in the following figures. For five subjects, data were obtained at three intensity levels (in microamperes) corresponding to low, middle, and high loudness. For the other four subjects data were taken at one level only, corresponding to medium loudness. Thresholds of sensitivity and discomfort are indicated for these subjects by horizontal lines.

threshold of discomfort thus using a subjective unit scale (Zheng and Shannon, 1992). Second, they were expressed in decibels using the usual logarithmic transform formula: 20 log(m), where m is the modulation depth.

Vowel and consonant perception tests were performed with subjects using their implant as usual. Recordings on videotape of eight utterances from a male speaker for seven vowels (i, y, u, e, o, a, ã) in isolation, and of four utterances for fourteen consonants (p, t, k, b, d, g, f, s, v, z, m, n, l, R) in an intervocalic /a/ context (aCa) were used. Stimuli were presented in free field at a level of approximately 70 dBA. Speech stimuli sounded to the cochlear implant subjects as comfortably loud having a level approximately equivalent to the medium loudness level used for amplitude modulation detection. Confusion matrices were obtained from each subject based on results from five test sessions performed at different days. For each subject all results were summed in one global vowel matrix for 40 presentations of each vowel and one global consonant matrix for 20 presentations of each consonant. Spectrograms of all utterances were obtained from which acoustic features used for confusion matrix analyses were checked as being obvious and consistent. For vowels, confusion matrices were analyzed in terms of total correct identification, first formant in three categories ($F1<400$ Hz, $400<F1<600$ Hz, $F1>600$ Hz) corresponding to closed, midopen, and open articulation features, and second formant in three categories ($F2<900$ Hz, $900<F2<1500$ Hz, $F2>1500$ Hz) corresponding to posterior, central, and anterior articulation features. In French overall duration is not a distinctive feature among vowels. For the specific tokens of Swiss French used in this study spectrograms confirmed that duration was similar for all vowels. For consonants the following features and categories were selected: voicing, mode of articulation in four categories (plosives, fricatives, nasals, and liquids), place of articulation in three categories (labial, alveolar, velar), interrupted or not, fricated or not, and finally, vocalic or not. Scores in percentage of information transmitted were computed for each phonetic feature and served for further correlation studies with results of amplitude modulation detection.

II. RESULTS

For each subject the estimate of loudness, above very low loudness levels, increased approximately linearly with increasing current level. The threshold values for audibility and discomfort varied between subjects and the associated individual dynamic ranges presented approximately two- to eightfold ratios. This is illustrated in Fig. 1 which shows amplitude modulation thresholds as a function of modulation frequency for each of the nine subjects.

Subjects' modulation thresholds show quite large values compared with the available intensity range, thus indicating poor intensity resolution compared with the performance of normal-hearing subjects. All subjects showed improvement of performance with increasing loudness level. In Fig. 1, subjects are ranked from one to nine as spanning from excellent to poor speech understanding. It can be noted that for

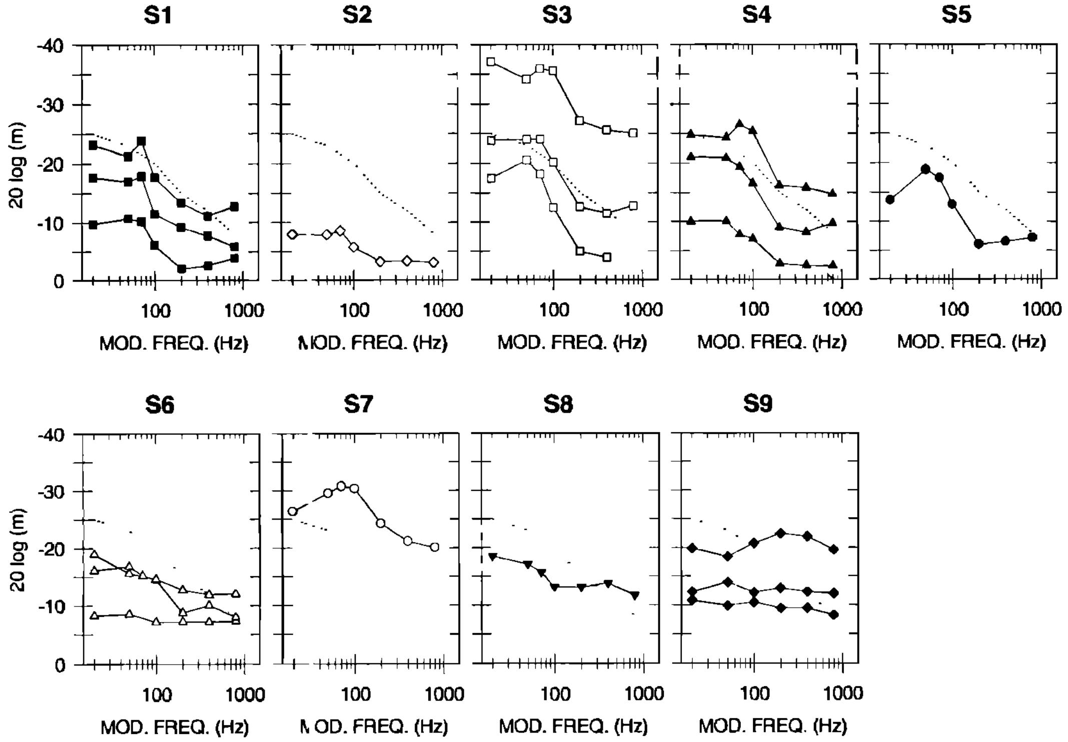

FIG. 2. Amplitude modulation transfer functions for the nine subjects, at the three stimulation levels, expressed in decibels using the usual formula for acoustic signals. The dotted line in each graph shows modulation transfer function measured in normal ears. Same symbols for the various subjects as for Fig. 1.

subjects with better speech understanding, modulation thresholds increase as modulation frequency increases above about 100 Hz.

Results of modulation thresholds as the logarithm of modulation depth are presented in Fig. 2. Values obtained for normal hearing (Viemeister, 1979) are plotted using a dotted line. Since loudness increase was an approximately linear function of current intensity, modulation thresholds expressed as a percentage of each subject's dynamic range are presented in Fig. 3. Modulation transfer functions obtained with the two modes of calculation present rather similar patterns. However, the presentation in subjective units indicates a low-pass filtering sometimes less marked as loudness level increases, whereas the usual logarithmic formula presents very similar shapes of modulation transfer functions at all three loudness levels. Thus modulation transfer functions display some clear low-pass filtering characteristics for subjects with better speech understanding, whereas they show little or no such characteristics for subjects having poorer speech intelligibility. For all subjects, the range of variability between repetitive measures of threshold at a given modulation frequency and loudness level was around 2–3 dB computed with the 20 log(m) formula.

Results of speech tests are given in Fig. 4. Between-subjects differences in scores are large whereas within-subject variations are much smaller. Distribution of subjects' performances also differ notably between vowel and consonant recognitions although in both cases subjects rank in almost exactly the same order. For vowels. six subjects have a score above 50% of information transmitted, whereas for consonants, six subjects have a score at or below this value.

Relation between low-pass filtering properties of modulation transfer functions and speech recognition was assessed with Pearson's correlation coefficient. To estimate the rejection strength of the low-pass characteristic of the modulation transfer function, the difference between modulation thresholds at 71 and 400 Hz for the curve at medium loudness level for each subject was computed using both subjective units and decibels. These rejection factors were found correlated with speech recognition performances. Results, presented in Fig. 5, indicate high correlations especially for the average information transfer for vowels and consonants as indicated in the two top diagrams. Somewhat lower correlations were observed separately for vowels and consonants. In all cases, correlation values obtained with subjective units were higher than those obtained with decibel units. With nine subjects (and only seven degrees of freedom), only correlation coefficient values above 0.798 can be considered significant at the 1% probability level. Subsequent computations of correlations between rejection strength and other acoustic features indicated strong correlations ($p<0.01$) with first and second formants for vowels, and for consonants strong correlations ($p<0.01$) with the voicing and interrupted features, moderate correlations ($p<0.05$) with other features, and no significant correlation with place of articulation.

Links between modulation thresholds and speech performances were further studied by examining correlation coefficients computed between all amplitude modulation data expressed in subjective units and all scores of information transmitted for the various phonetic features. Only two moderate correlations ($p<0.05$) were found linking higher threshold values at 400 and 800 Hz with the interrupted fea-

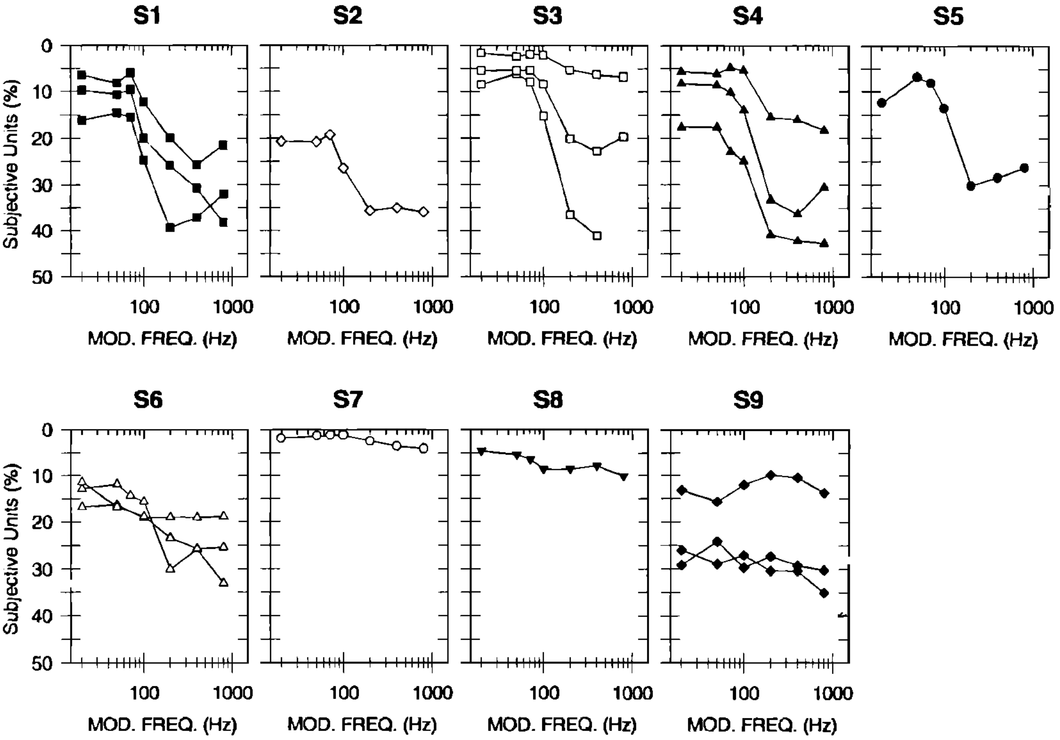

FIG. 3. Amplitude modulation transfer functions for the nine subjects expressed in subjective units (as a percentage of each subject's dynamic range). Same symbols for the different subjects as in Fig. 1.

ture for consonants. These moderate correlations must be mentioned but they do not seem to merit detailed comments without further confirmation as they can be obtained by chance when many correlations are computed.

After the recent studies of Udriot and Pelizzone (1992) and Moon *et al.* (1993) establishing a correlation between a better absolute sensitivity and speech recognition scores, we examined this relation in our limited set of data. Absolute sensitivity thresholds were not precisely measured in this study, but were estimated (using an ascending–descending method) for the unmodulated 1667-Hz pulse-wave carrier. They were not found significantly correlated with the rejection strength of low-pass filtering ($r=0.498$). These thresholds were, however, moderately correlated with the average performance for vowels and consonants ($r=0.68$, $p<0.05$); close values almost reaching significance at the 5% level were also found with vowels ($r=0.658$) and consonants ($r=0.647$) separately. For vowels correlations with first and second formant features almost reached significance, for consonants correlations with all features, but place of articulation and interruption were significant at the 5% level.

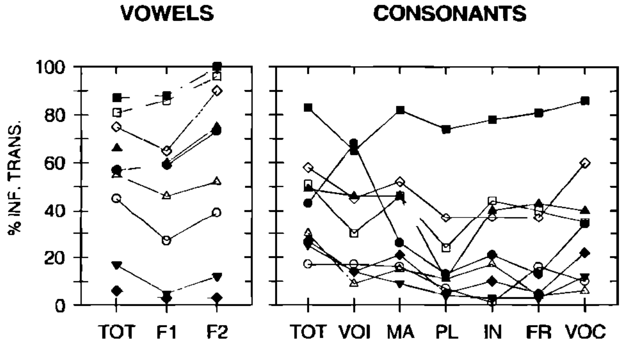

FIG. 4. Scores of percentage of information transmitted for the different subjects and the various acoustic and phonetic features considered in this study. For vowels: total score TOT, first formant F1, second formant F2. For consonants: total score TOT, voicing VOI, manner of articulation MA, place of articulation PL, interrupted IN, fricated FR, and vocalic VOC. Same symbols for the different subjects as in Fig. 1.

III. DISCUSSION

Results from these experiments on a group of nine subjects implanted with an Ineraid device indicate strong relations between low-pass filtering in amplitude modulation detection at the most apically implanted electrode and speech recognition scores for isolated vowels and intervocalic consonants. In this study, amplitude modulation detection was measured only at the low-frequency channel; however, measures at this channel are certainly of major significance as previous studies have shown that most speech information is conveyed by this low-frequency and a second high-frequency channel, the low-frequency channel always being necessary for best performance (Dorman *et al.*, 1989). Intelligibility of logatomes used in this study can be considered a good predictor of open speech perception as it was recently shown to be highly correlated with other measures of speech perception (Rabinowitz *et al.*, 1992).

Our finding of phonetic recognition associated with the existence of a low-pass filtering in amplitude modulation transfer functions is consistent with a similar low-pass filtering working in normal ears for acoustic stimuli (Zwicker and Feldtkeller, 1967; Viemeister, 1979; Bacon and Viemeister, 1985). A likely explanation of a link with phonetic recognition is that if high-frequency modulations above about 50–100 Hz are not rejected as in acoustical hearing they certainly would add disturbing noiselike interferences. This is in line with experiments on speech recognition for normal ears and modulation transfer functions which demonstrated and quantified predictively the effects of various distortions of signal envelope (Steeneken and Houtgast, 1980). It should also be noted that some slight broadening of TMTFs was found in hearing-impaired subjects (Bacon and Gleitman, 1992); unfortunately no relation to speech perception data was concomitantly available. Our findings are in agreement with limited observations of Wilson *et al.* (1992a,b) indicating that a decrease in pulse rate and/or pulse width could result in better speech intelligibility for cochlear implant patients with poor speech understanding.

Two recent publications (Shannon, 1992; Busby *et al.*, 1993) documented sensitivity to amplitude modulation in several cochlear implant subjects. Shannon (1992) studied patients implanted with three different devices, including the Ineraid device, and tested at their most apical electrode as in the present study. Results indicated modulation transfer functions being low pass for some subjects and rather bandpass around 100 Hz for other subjects, the low-pass functions being quite similar to those of the present study. Interestingly, subjects showed notable variations in their rejection slopes and are said to also differ considerably as to their speech understanding but data are not available to check a possible relation between both. Busby *et al.* (1993) studied seven patients implanted with a cochlear device and tested the ninth electrode situated about the middle of the array. Results indicated modulation transfer functions generally similar to those reported by Shannon (1992) but showing for one subject a continuous low-pass filtering with a cutoff frequency around 5 Hz and for another subject a flat curve up to the highest (250 Hz) modulation frequency tested. No correlation with phonetic recognition is available in the article of Busby *et al.* (1993) but the three prelingually deafened adults showed more variable and poorer results. Notably, however, the subject with flat modulation transfer function was postlingually deaf.

Several previous studies of amplitude modulation detection of acoustic stimuli by hearing-impaired subjects (Bacon and Viemeister, 1985; Formby and Muir, 1988; Bacon and Gleitman, 1992) reported variable results but the observed alterations consisted of decreased sensitivities and steeper rejection slopes of the modulation transfer functions but never in loss of low-pass filtering as observed in the present study. For cochlear implant subjects poorer speech perception associated with flat TMTFs indicate individual differences in temporal interferences between and/or within channels, which may reflect individual differences in nerve survival and/or electrical coupling between electrodes and neural elements.

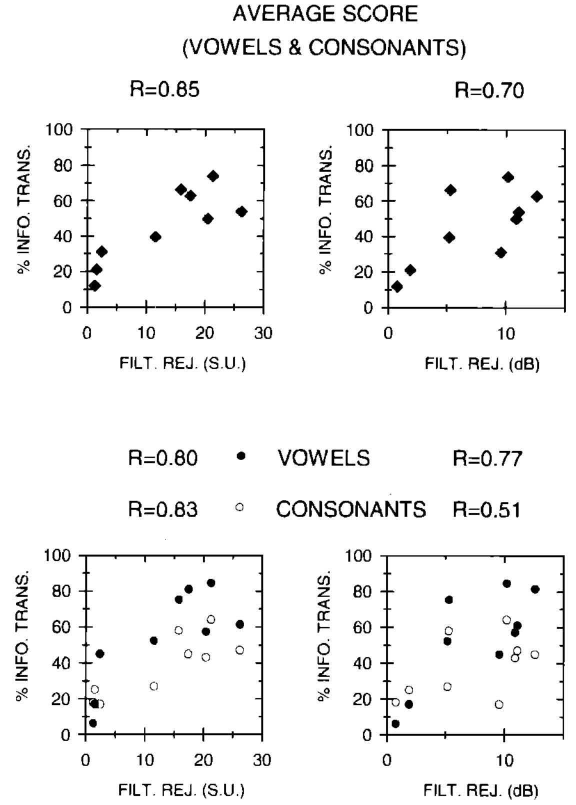

FIG. 5. Percentage of total information transmitted for the vowels and the consonants as a function of filter rejection value as defined in the text expressed in decibels or subjective units as in Figs. 2 and 3. Values of Pearson's correlation coefficients (*r*) are given at the top. With only seven degrees of freedom, only correlations higher than 0.798 are significant at the 1% level.

In the present study the phonetic features for consonant test stimuli, except nasality and place of articulation, were checked on spectrograms as having obvious corresponding acoustic amplitude modulations. For all speech stimuli the fundamental frequency varied from about 90 to 120 Hz. Thus for consonants, all features but nasality and place of articulation involved amplitude variations of about 10 ms or more, which fell within the bandpass of the modulation transfer functions at the most apical electrode. Acoustic cues for nasality and place of articulation were probably transmitted to more basal electrodes. For vowels, the six subjects with better recognition scores showed most errors on vowels with high second formants ([i,y,e]) and on the nasalized vowel ([ã]). The fact that speech tests were not performed with only channel one of the Ineraid device working and that precise excitation at the most apical electrode cannot be known for each subject make it hard to further speculate for each phoneme about detailed relations between specific amplitude modulations and perceptual identification beyond what was indicated above.

The absence of significant correlation between low-pass filtering strength and values of absolute sensitivity, for the limited group of subjects of this study, suggests that these two measures could represent two complementary aspects of individual psychophysical capacities involved in successful speech recognition by cochlear implant subjects.

Data from this study agree with previous investigations in showing that acoustic features of speech linked to temporal envelope variations provide a very substantial amount of information to cochlear implant subjects. In addition, they indicate that a low-pass filtering of amplitude modulations similar to that existing for acoustic hearing seems essential for successful phonetic identification. These findings are worth exploring further for other intracochlear electrodes and on a larger group of subjects; they could serve as guides for designing signal processing devices and eventually customizing them to individual sensitivities.

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Bacon, S. P., and Viemeister, N. F. (**1985**). "Temporal modulation transfer functions in normal-hearing and hearing-impaired listeners." Audiology **24**, 117–134.

Bacon, S. P., and Gleitman, R. M. (**1992**). "Modulation detection in subjects with relatively flat hearing loss," J. Speech Hear. Res. **35**, 642–653.

Busby, P. A., Tong, Y. C., and Clark, G. M. (**1993**). "The perception of temporal modulations by cochlear implant patients," J. Acoust. Soc. Am. **94**, 124–131.

Calliope, X. (**1989**). *La Parole et son Traitement Automatique* (Masson, Paris), 717 pp.

Cazals, Y., Pelizzone, M., Kasper, A., and Montandon, P. (**1990**). "Multichannel cochlear implant patients with different open speech understanding show some similar basic psychophysical performances," Acta Oto-Laryngol. suppl. **469**, 150–155.

Cazals, Y., Pelizzone, M., Kasper, A., and Montandon, M. (**1991**). "Indication of a relation between speech perception and temporal resolution for cochlear implantees," Ann. Otol. Rhinol. Laryngol. **100**, 893–895.

Clark, G. M., Pyman, B. C., Webb, R. L., Bailey, Q. E., and Sheperd, R. K. (**1984**). "Surgery for an improved multiple-channel cochlear implant," Ann. Otol. Rhinol. Laryngol. **93**, 204–207.

Dobie, R. A., and Dillier, N. (**1985**). "Some aspects of temporal coding for single channel electrical stimulation of the cochlea," Hear. Res. **18**, 41–55.

Dorman, M., Dankowski, K., McCandless, G., and Smith, L. (**1989**). "Consonant recognition as a function of the number of channels of stimulation by patients who use the Symbion cochlear implant," Ear Hear. **10**, 288–291.

Formby, C., and Muir, K. (**1988**). "Modulation and gap detection for broadband stimuli and filtered noise signals," J. Acoust. Soc. Am. **84**, 545–550.

Forrest, T. G., and Green, D. M. (**1987**). "Detection of partially filed gaps in noise and the temporal modulation transfer function," J. Acoust. Soc. Am. **82**, 1933–1943.

Freyman, R. L., Nerbonne, G. P., and Cote, H. A. (**1991**). "Effect of consonant-vowel ratio modification on amplitude envelope cues for consonant recognition," J. Speech Hear. Res. **34**, 415–426.

Helmoltz von, H. (**1868**). *Théorie Physiologique de la Musique Fondée sur l'étude des Sensations Auditives*, first ed., translated by G. Guéroult (Masson, Paris).

Hochmair-Desoyer, I. J., Hochmair, E. S., and Stiglbrunner, H. K. (**1985**). "Psychoacoustic temporal processing and speech understanding in cochlear implant patients," in *Cochlear Implants*, edited by R. A. Schindler and M. M. Merzenich (Raven, New York).

Keidel, W. D., and Finkenzeller, P. (**1984**). "Cochlear implants in clinical use," *Advances in Audiology* (Karger, Basel), Vol. 2.

Koenig, W., Dunn, H. K., and Lacy, L. Y. (**1946**). "The sound spectrograph," J. Acoust. Soc. Am. **18**, 21–32.

Merzenich, M. M., Schindler, R. A., and Sooy, F. A. (**1974**). *Electrical Stimulation of the Acoustic Nerve in Man* (Velobind, San Francisco).

Miller, G. A., and Nicely, P. E. (**1955**). "An analysis of perceptual confusions among some English consonants," J. Acoust. Soc. Am. **27**, 338–352.

Miller, J. L., Kent, R. D., and Atal, B. S. (**1991**). *Papers in Speech Communication: Speech Perception* (Acoustical Society of America, Woodbury, NY), p. 764.

Moon, A. K., Zwolan, T. A., and Pfingst, B. E. (**1993**). "Electrical of phase duration on detection of electrical stimulation of the human cochlea," Hear. Res. **67**, 166–178.

Moore, B. C. J., and Glasberg, B. R. (**1988**). "Gap detection with sinusoids and noise in normal, impaired and electrically stimulated ears," J. Acoust. Soc. Am. **83**, 1093–1101.

Parkins, C. W., and Anderson, S. S. (**1983**). "Cochlear prostheses," Ann. N. Y. Acad. Sci. **405**, pp. 532.

Peckels, J. P., and Rossi, M. (**1973**). "Le test de diagnostic par paires minimales," Rev. Acoust. **27**, 245–262.

Rabinowitz, W. M., Eddington, D. K., Delhorne, L. A., and Cuneo, P. A. (**1992**). "Relations among different measures of speech reception in subjects using a cochlear implant," J. Acoust. Soc. Am. **92**, 1869–1881.

Rodenburg, M. (**1977**). "Investigation of temporal effects with amplitude modulated signals," in *Psychophysics and Physiology of Hearing*, edited by E. F. Evans and J. P. Wilson (Academic, New York), pp. 429–439.

Shannon, R. V. (**1989**). "Detection of gaps in sinusoids and pulse trains by patients with cochlear implants," J. Acoust. Soc. Am. **85**, 2587–2592.

Shannon, R. V. (**1992**). "Temporal modulation transfer functions in patients with cochlear implants," J. Acoust. Soc. Am. **91**, 2156–2164.

Steeneken, H. J. M., and Houtgast, T. (**1980**). "A physical method for measuring speech transmission quality," J. Acoust. Soc. Am. **67**, 318–326.

Tassel, D. J. van, Soli, S. D., Kirby, V. M., and Widin, G. P. (**1987**). "Speech waveform envelope cues for consonant recognition," J. Acoust. Soc. Am. **82**, 1152–1161.

Tassel, D. J. van, Greenfield, D. G., Logemann, J. J., and Nelson, D. A. (**1992**). "Temporal cues for consonant recognition: Training, talker generalization and use in evaluation of cochlear implants," J. Acoust. Soc. Am. **92**, 1247–1257.

Tong, Y. C., Busby, P. A., and Clark, G. M. (**1988**). "Perceptual studies on cochlear implant patients with early onset of profound hearing impairment prior to normal development of auditory, speech and language skills," J. Acoust. Soc. Am. **84**, 951–962.

Tyler, R., and Moore, B. C. J. (**1989**). "Performance of some of the better cochlear-implant patients," J. Speech Hear. Res. **32**, 887–911.

Udriot, B., and Pelizzone, M. (**1992**). "Compréhension du langage chez le sourd implanté: Évaluation et facteurs pronostiques," Méd. Hyg. **50**, 2761–2769.

Viemeister, N. F. (**1977**). "Temporal factors in audition: A system analysis approach," in *Psychophysics and Physiology of Hearing*, edited by E. F. Evans and J. P. Wilson (Academic, New York), pp. 419–428.

Viemeister, N. F. (**1979**). "Temporal modulation transfer functions based upon modulation thresholds," J. Acoust. Soc. Am. **66**, 1364–1380.

Voiers, W. D. (**1971**). *Diagnostic Approach to the Evaluation of Speech Intelligibility* (Tracor, Austin, Texas).

Wang, M. D., and Bilger, R. C. (**1973**). "Consonant confusions in noise: A study of perceptual features," J. Acoust. Soc. Am. **54**, 1248–1266.

Wilson, B. S., Finley, C. C., and Lawson, D. T. (**1989**). "Speech processors for auditory prostheses," Second Quarterly Prog. Rep. Research Triangle Institute, Research Triangle Park, North Carolina.

Wilson, B. S., Finley, C. C., Lawson, D. T., Wolford, R. D., Eddington, D. K., and Rabinowitz, W. M. (**1991**). "Better speech recognition with cochlear implants," Nature **352**, 236–238.

Wilson, B. S., Lawson, D. T., Zerbi, M., and Finley, C. C. (**1992a**). "Speech processors for auditory prostheses," Eleventh Quarterly Prog. Rep. Research Triangle Institute, Research Triangle Park, North Carolina.

Wilson, B. S., Lawson, D. T., Zerbi, M., and Finley, C. C. (**1992b**). "Speech processors for auditory prostheses," Twelfth Quarterly Prog. Rep. Research Triangle Institute, Research Triangle Park, North Carolina.

Wilson, J. P. (**1992**). "Cochlear mechanics," in *Auditory Physiology and Perception*, edited by Y. Cazals, L. Demany, and K. Horner (Pergamon, New York), pp. 71–84, Advances in the Biosciences, Vol. 83.

Zheng, F. G., and Shannon, R. V. (**1992**). "Loudness balance between electric and acoustic stimulation," Hear. Res. **60**, 231–235.

Zwicker, E., and Feldtkeller, R. (**1967**). *Das ohr als Nachrichtenempfanger* (Hirzel, Stuttgart).