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Psychophysics of Multiple-Channel Stimulation

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Abstract

Eight patients implanted with multiple-channel cochlear prostheses have displayed good discrimination of sound sensations elicited at different sites within the cochlea. All patients rank the sensations from "sharp" to "dull" in an order which corresponds with basal to apical position in the cochlea. Detailed psychophysical studies have been carried out on two patients. These showed that discrimination of rate of (pulsatile) stimulation is good for frequencies up to 300 Hz and falls off sharply for frequencies above this. Electrode transitions (changes in position along the cochlea) are well discriminated for fast changes (25 msec), whereas rate transitions are not well discriminated for changes faster than 100 msec. From these results a speech processing strategy was formulated where second formant information is mapped to position in the cochlea and fundamental frequency mapped to rate of stimulation. Vowel and consonant confusion studies show consistent results for all patients using this processing strategy. A study involving two electrode stimuli demonstrated the possibility of presenting first formant information in addition to the second formant and fundamental frequency.

Introduction

The purpose of this paper is to review the major psychophysical results obtained with multiple-channel cochlear implant patients at the University of Melbourne in studies carried out between 1978 and 1983. Until 1982, only two patients were available for testing, and therefore all of the extensive investigations reported here have been carried out on one or both of these patients. In 1982, six patients were implanted with the Nucleus Limited multiple-channel hearing prosthesis, and this has allowed additional psychophysical investigations which have mainly taken the form of verification studies of previous findings.

The implanted devices used at the University of Melbourne provide biphasic charge-balanced pulsatile stimulation to an electrode array comprising 22 electrode bands (10 for prototype device) spaced along a 16 mm length of cochlea in the scala tympani. The parameters that are variable with these devices are the stimulated electrode, the stimulus amplitude in terms of current, the width of the stimulus pulse (typically 200 usec per phase), and the timing between successive stimulus pulses and hence the pulse rate or frequency of stimulation. By varying these parameters in a controlled fashion, it is possible to build up complex stimuli in terms of temporal and positional structure. Our aim has been to quantify the information-carrying characteristics of the various stimulation parameters and to formulate how best to use these parameters to provide the patient with useful speech discrimination.

Discrimination of electrode position within the cochlea

Reports from the first two multiple-channel implant patients suggested that the sound sensations elicited by electrodes at different sites within the cochlea were different even for stimuli of equal loudness at the same pulse rate. This difference was described as a variation in "sharpness/dullness" of the sensation by both patients. This quality was investigated by asking the patients to identify which of a pair of stimuli on different electrodes was "sharper". These stimuli were presented at the same pulse rate and the loudness was balanced for each electrode. By presenting all of the possible pairs of electrodes from the array, a response matrix can be built up and the electrodes ranked in terms of the perceived "sharpness". Results for the first two patients showed that this "sharpness" quality corresponded closely with the position of the electrode within the cochlea, as stimuli on the most apical electrodes were ranked as the "dullest" sensations and the sensations became progressively "sharper" for electrodes closer to the round window. These results are reported in detail in Tong et al. (6). For the six patients implanted in 1982, initial studies using a similar experimental paradigm have shown results consistent with those for the first two patients. All patients rank stimuli on the different electrodes according to "sharpness" in an order corresponding with apical to basal position in the cochlea. Figure 1 shows a response matrix for an electrode ranking experiment on a recently implanted patient. The electrode numbers correspond to position in the cochlea with the highest associated with the most apical electrode and the lowest with the most basal. Each electrode pair was presented three times in a random fashion and the patient asked to specify whether the first or second stimulus was the "sharper" sound. Each cell of the matrix corresponds to the number of times the second electrode was specified as the "sharper" stimulus. The pattern of responses clearly shows that the quality perceived by the patient as "sharpness" is closely related to the site of electrical stimulation within the cochlea. Patients are able to discriminate adjacent electrodes of the 22-electrode array which have a separation of only 0.75 mm. The patients' reports and the consistent ranking and discrimination results for electrode position suggest that it should be possible to represent important spectral information from a speech signal by varying the site of electrical stimulation along a multiple-electrode array.

Discrimination of rate of stimulation

Studies on the first two patients using different pulse rates of electrical stimulation on the same electrode showed good discrimination for rates of 100 pps and 200 pps with difference limens down to 3% (7). However, difference limens increased as the pulse rate increased, and for rates above 300 pps discrimination was quite poor with little change in perceived "pitch" for rates between 300 pps and 1000 pps. Extensive investigations of rate discrimination for the more recently implanted patients have not been carried out as yet but initial studies have tended to confirm previous results. All patients report the perceptual changes associated with varying the pulse rate as changes in "pitch" and descriptions frequently refer to "the same sound playing a different note".

SECOND ELECTRODE

FIRST ELECTRODE	1	3	6	9	12	14	16	18	20
1	-	0	0	0	0	0	0	0	0
3	3	-	0	0	0	0	0	0	0
6	3	3	-	1	0	1	0	0	0
9	3	3	3	-	2	0	0	0	0
12	3	3	3	2	-	0	1	0	0
14	3	3	3	3	2	-	0	0	0
16	3	3	3	3	3	3	-	0	0
18	3	3	3	3	3	3	3	-	0
20	3	3	3	3	3	3	3	1	-

Figure 1: Sharpness ranking response matrix. Electrode ranking data matrix for a recently implanted multiple-channel cochlear prosthesis patient. Each cell in the matrix represents a certain electrode pair in a particular order. The number in each cell corresponds to the number of times the second of the pair was identified by the patient as being "sharper" than the first. Each electrode pair was presented three times and thus a matrix entry of 3 indicates that the second electrode was chosen as "sharper" every time. A zero entry indicates that the first electrode was chosen as "sharper" every time. The electrode numbers correspond to position in the cochlea numbering from the basal end.

Discrimination of transitions of electrode position

Studies with the first implant patients revealed good discrimination of different electrode transitions for a number of different transition configurations (6). Patients were able to identify two transitions as different even when the position of the initial electrode was changed by only 1.5 mm (the minimum separation of active electrodes in the prototype implant). Further investigations with one patient showed that there was no degradation in discrimination performance for electrode transitions when the duration of the transitions was reduced from 100 ms to 50 ms and then to 25 ms. This suggested that electrode position may be suitable for the representation of rapidly changing segmental information in speech signals.

Discrimination of transitions of pulse rate

Discrimination studies with one patient for pulse rate transitions showed that good discrimination was possible for transitions of pulse rates below 250 pps, but that, when the duration of the transition was reduced below 100 msec, the discrimination performance was degraded. This is in contrast to the result for electrode transition (6). This suggested that pulse rate of stimulation may be suitable for the representation of the suprasegmental information provided by voicing or fundamental frequency in speech signals.

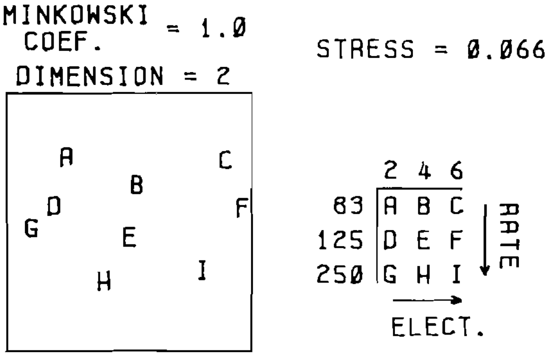

Figure 2: Multidimensional scaling solution for dissimilarity data obtained by a triadic comparison method for nine stimuli presented to a multiple-channel cochlear prosthesis patient varying in electrode position within the cochlea and pulse rate of electrical stimulation. (From Kruskal (3)

Independence of percepts associated with electrode position and pulse rate of stimulation

In order to use the parameters of electrode position and pulse rate to represent independent features of speech signals effectively, it is necessary that the interaction of the percepts associated with these two parameters is not significant. In other words, it is necessary that the patient is able to analyse information presented simultaneously via these parameters into its separate components. Two studies were undertaken to investigate the interaction of the percepts (6). One of these involved the discrimination of pulse rate transitions superimposed on simultaneous transitions across the electrode array. This showed that discrimination performance for the pulse rate transitions was not significantly affected by the electrode transitions presented in random order, indicating that the patient was able to separate the percepts related to these parameters. A second study investigated the perceptual dissimilarities of stimuli varying in electrode position and pulse rate using a multi-dimensional scaling technique (3). This technique attempts to fit a spatial configuration to the perceptual dissimilarity data of the stimuli used. A set of nine stimuli was used with three pulse rates on three different electrodes. A dissimilarity matrix for these stimuli was obtained by a triadic comparison method. The analysis of this data indicated that a "best fit" configuration was obtained for a two-dimensional solution (Figure 2), indicating the presence of two independent perceptual qualities in the stimuli. Furthermore, the stimuli was arranged regularly with electrode position along one axis and pulse rate along the other. This configuration is similar to that reported by Plomp (4) for nine acoustic stimuli generated by the excitation of three bandpass filters with three repetition rates.

Speech Processing Strategy

From the psychophysical results obtained with initial patients, a speech processing strategy was proposed in which the main spectral peak in

TABLE 1: Vowel Recognition results

Patient	Overall Correct (%)	Correct for /i/ (Highest F2) (%)	Correct for /ɔ/ (Lowest F2) (%)
1.	54	44	88
2.	58	94	81
3.	68	81	100
4.	54	94	94
MEAN	61	78	91

the mid-frequency range (usually the second formant for speech signals) was mapped onto position of electrical stimulation within the cochlea and the fundamental (or voicing) frequency mapped onto pulse rate of electrical stimulation. This strategy endeavours to maximize the speech information input whilst using the perceptual characteristics of electrical stimulation parameters appropriately. For instance, the discrimination of pulse rate, which is poor above 300 pps and is also affected by the rate of transition, suggests that it would be appropriate to associate pulse rate with fundamental frequency, which is typically below 300 Hz, and not with rapidly changing spectral peak (or formant) information. Similarly, it seems useful to associate the most important spectral peak for speech understanding with electrode position which is discriminated well for quite rapid transitions. The present cochlear prosthesis system does not preclude more complex processing strategies in which additional acoustic features of speech signals are represented. However, we feel it is important to have consistent and thorough psycophysical investigation of more complex schemes before incorporating them into the standard system.

Vowel and consonant recognition studies

Detailed vowel and consonant recognition studies have been carried out on four recently implanted patients using this speech processing strategy. The results of these studies are shown in Table 1 and Figure 3 (a) to (d). Vowel recognition was assessed by presenting randomized lists of 11 vowels (/i, I, ɛ, æ, ɒ, ʌ, u, U, ɔ, o, ɜ/) in /h/-vowel-/d/ context. Each list contained four occurrences of each vowel (44 items) and was presented under live voice conditions by a familiar speaker. The patient was required to choose his response from a list of the 11 vowels (in context). Table 1 shows the overall percent correct scores for each patient obtained for the presentation of four vowel lists over four test sessions using the cochlear prosthesis alone. The results are consistent for these four patients with scores ranging from 54% to 68%. The best recognition results were obtained for vowels with second formant values at the extremes of the range (i.e., /i/, /ɔ/), showing that the patients are able to use electrode position information effectively for steady state vowels. Consonant recognition was assessed using 12 consonants (/p, b, m, f, v, d, t, n, s, z, g, k/) in an /a/-consonant-/a/ context. Lists

PATIENT 1: RESPONSE

STIMULUS

	b	p	m	v	f	d	t	n	z	s	g	k
b		2	5	2	5	1		1				
p		5	1	1	2	1	2					4
m	1	1	8		1	2		3				
v		1	4	4	2	2		1	1		1	
f		2			4				5	5		
d		2	1	1		1		3	1		2	5
t	1	3			1	2	4		1		2	2
n		1	2	2	1			6			4	
z					3				9	4		
s				2					5	9		
g		2	1		1	1	1	1			6	3
k		1				2	6				3	4

PERCENT CORRECT: 31%

PATIENT 2: RESPONSE

STIMULUS

	b	p	m	v	f	d	t	n	z	s	g	k
b	3	1	4	3				2				3
p	2	2		1		4	6				1	
m		3	3	2	2			2			2	2
v	1		1	4	1	4	1	3			1	
f					2		5		8	1		
d			1	1		8	1	3			1	1
t						1	9	1	4	1		
n	1		1	4	1			4				5
z							3	1	11	1		
s									1	15		
g	2			4		5		3			1	1
k	1					4	8				1	2

PERCENT CORRECT: 33%

PATIENT 3: RESPONSE

STIMULUS

	b	p	m	v	f	d	t	n	z	s	g	k
b	6	3	4								2	1
p	6	7		1	1						1	
m			14	1				1				
v			4	12								
f				7	8	1						
d						4	2	1			6	3
t					1		15					
n	1		5	1				9				
z				2	2				8	4		
s					4				3	9		
g	1	4		1		5		1			2	2
k							11				4	1

PERCENT CORRECT: 49%

PATIENT 4: RESPONSE

STIMULUS

	b	p	m	v	f	d	t	n	z	s	g	k
b	8	1	3		2			1			1	
p	2	5	2								3	4
m	3		7		2			4				
v	3	2	1	5	2			1			1	1
f	1			8	4	2		1				
d	2					11		2				1
t						1	15					
n		1			1			12			2	
z									9	7		
s									6	10		
g		1						2			10	3
k		1	1					1			2	11

PERCENT CORRECT: 56%

Figure 3: Consonant confusion matrices, cochlear prosthesis alone. Consonant confusion matrices obtained for four multiple-channel cochlear prosthesis patients from the presentation of 12 consonants in an /a/-consonant-/a/ context. The consonants were presented via the cochlear prosthesis alone over four test sessions using randomized lists containing four occurrences of each consonant.

containing four of each consonant (48 items) were presented to the patients via the cochlear prosthesis without lipreading under live voice conditions by a familiar speaker. The confusion matrices obtained from the presentation of four lists at four separate test sessions for each patient are shown in Figure 3. Here we see differences in the performance of these four patients which were not evident in the vowel study. The overall scores range from 31% to 56% and these scores correlate well with performance on other speech tests. That is, the

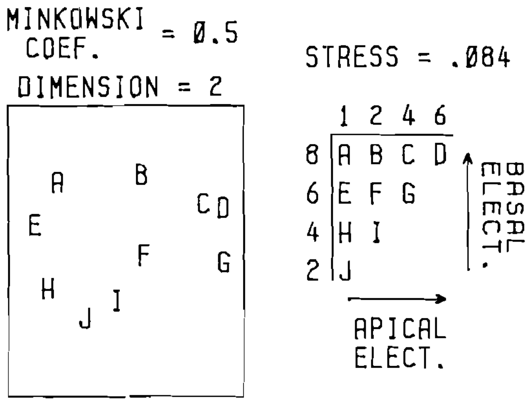

Figure 4: Multidimensional scaling solution for dissimilarity data obtained by a triadic comparison method for two-electrode stimuli presented to a multiple-channel cochlear implant patient. (From Kruskal (3)

patients who do well with consonant recognition tend to perform better on most other speech tests, a not unexpected result. Results for the two initial patients for consonant discrimination have been reported elsewhere (2, 1), and fall within the same range as the four patients reported here.

Two-electrode studies

Some initial studies have been carried out with simultaneous activation of two electrodes. The aim is to increase the information carrying capability of the speech processing system by representing more than one spectral peak via the intracochlear electrode array. The activation of the two electrodes is not truly simultaneous but consists of interleaved pulses on the two electrodes separated by a minimal delay time (0.5 msec) to avoid current interactions within the cochlea. This makes the control of perceived loudness much easier for this type of system.

A study involving one patient investigated the perceptual dissimilarities of a set of two-electrode stimuli using a multidimensional scaling technique (3) similar to that described above. The analysis (7) showed that a two-dimensional configuration was most appropriate for fitting the dissimilarity data, and that the two perceptual dimensions corresponded with (a) the more basal electrode of the electrode pair, and (b) the more apical electrode of the pair. The configuration obtained is shown in Figure 4. This result suggests that two spectral peaks (e.g., first and second formants) could be effectively mapped onto the electrode array using this type of two-electrode stimulation.

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References

1. Clark, G.M., Tong, Y.C. (1982) A multiple-channel cochlear implant: A summary of results for two patients. Arch. Otolaryngol. 108:214-217.

2. Dowell, R.C., Martin, L.F.A., Tong, Y.C., Clark, G.M., Seligman, P.M., and Patrick, J.F. (1982) A 12-consonant confusion study on a multiple-channel cochlear implant study. J. Sp. Hear. Res. 25:509-516.

3. Kruskal, J.B. (1964) Multidimensional scaling by optimizing goodness of fit to a non-metric hypothesis. Psychometer, 29:1-27.

4. Plomp, R. (1976) Chapter 6 In: Aspects of Tone Sensation. pp. 108-109. Academic, London

5. Tong, Y.C., Blamey, P.J., Dowell, R.C., and Clark, G.M. (1983) Psychophysical studies evaluating the feasibility of a speech processing strategy for a multiple-channel cochlear implant. J. Acoust. Soc. Am. (in press).

6. Tong, Y.C., Clark, G.M., Blamey, P.J., Busby, P.A., and Dowell, R.C. (1982) Psychophysical studies for two multiple-channel cochlear implant patients. J. Acoust. Soc. Am. 71:153-160.

7. Tong, Y.C., Dowell, R.C., Blamey, P.J., Clark, G.M. (1983) Two-component hearing sensations produced by two-electrode stimulation in the cochlea of a totally deaf patient. Science 219:993-994.

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