PERCEPTION OF TWO-FORMANT VOWELS BY NORMAL LISTENERS AND PEOPLE USING A HEARING AID AND A COCHLEAR IMPLANT IN OPPOSITE EARS.

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ABSTRACT - 64 two-formant vowels were synthesised in an /h-vowel-d/ context using first formant frequencies (F1) from 300 to 900 Hz in 100 Hz steps and second formant frequencies (F2) from 600 to 2400 Hz in 200 Hz steps. Listeners classified the stimuli according to the nearest word from the list "hid, head, had, hud, hod, hood, heed, heard, hard, who'd, hoard". Analysis of the centre frequencies for each response category showed significant differences between the Australian and American response patterns, but not between the response patterns for male and female listeners with normal hearing. The cultural differences in the response patterns corresponded closely to differences that have been documented for vowel production. The implanted ear patterns were closer than the aided ear patterns to the normal listeners' patterns (from the same country). Binaural response patterns for the hearing-impaired listeners showed influences from both monaural patterns, but tended to be closer to the implanted ear pattern than the aided ear pattern. The response patterns for normal listeners showed greater consistency than for implanted ears which showed greater consistency than the severely-to-profoundly hearing-impaired hearing aid ears. The results show that hearing impairment and hearing aid use can change perceived vowel quality as well as affecting frequency resolution.

INTRODUCTION

One of the enduring questions of cochlear implant research is "What does electrical stimulation of the cochlea sound like?" The question was originally motivated by the aim of providing an electrical signal that was recognisable as speech by adults who had become deaf after learning spoken language through normal hearing (Tong et al, 1979). This objective has now been achieved sufficiently well for the majority of postlinguistically deafened implant patients to understand about 80% of sentences without lipreading within a few months of first switching on their new hearing device (Whitford et al, 1995). The question is still relevant in investigating individual differences between implant users, and group differences between implant users, hearing aid users, and normally-hearing listeners. In particular, there are some people who use a cochlear implant in one ear and a hearing aid in the non-implanted ear. For these people, it is of interest to know whether the two ears provide similar sounds, and whether the phonetic information derived from the two ears is redundant, complementary, or contradictory.

In order to study this question in a controlled manner, a set of synthetic vowel sounds which cover a broad range of first and second formant frequencies was developed. Listeners were asked to choose the word (from a set of eleven alternatives) that was closest to the sound heard. Normally-hearing listeners produced consistent patterns of responses to the stimuli. The task provides information on the perception of sounds that lie close to phonemic boundaries as well as sounds that normal listeners always identify with a definite vowel. Similar tasks have been used by Ainsworth (1975) and Nearey (1989) to assess the effects of fundamental frequency, third formant frequency, duration and other influences on the perception of vowels. The present study focussed on the differences between individuals and groups of listeners with different levels and types of hearing. By comparing the response patterns for individual implant and hearing aid users with those for normally-hearing listeners, a deeper understanding of how electrical stimulation and impaired hearing can affect the perception of vowel sounds is formed. The specific questions addressed in the study were:

a) Are there perceptual differences between male and female listeners with normal hearing?
b) Are there perceptual differences between Australian and American listeners with normal hearing?
c) How does perception of vowels differ between normal ears, implanted ears, and impaired ears?

METHOD

Subjects

In the first part of the study, sixteen subjects with normal hearing were tested. There were eight Australians, and eight Americans, four males and four females of each nationality. All listeners were native to their country and spoke English as their first language. In the second part of the study, responses were collected for hearing impaired individuals using cochlear implants and hearing aids in opposite ears. There were seven American subjects and three Australians in the group with impaired hearing. Their hearing losses were all profound (pre-operative audiological thresholds in excess of 95 dB HL) in the implanted ear, and severe-to-profound in the non-implanted ear (thresholds greater than 75 dB HL).

Stimuli

The stimuli were synthesised using the parallel branch of a cascade/parallel formant speech synthesiser (Klatt, 1980), using two formant frequencies for each stimulus. The duration, amplitude envelope, pitch contour, bandwidths, and loci of the formant transitions were fixed for all stimuli to produce a percept similar to a natural vowel in /h-vowel-d/ context. The amplitudes of the two formants were equal, and the stimuli were adjusted to have the same overall intensity. The first formant (F1) frequencies ranged from 300 to 900 Hz in 100 Hz steps. The second formant (F2) frequencies ranged from 600 to 2400 Hz in 200 Hz steps. Combinations where F2 was less than or equal to F1 were omitted, resulting in 64 stimuli altogether.

Procedure

The stimuli were presented one at a time in randomised blocks containing two instances of each stimulus. After each stimulus, the listener was asked to choose the response that was closest to the sound heard. The set of responses consisted of the eleven alternatives "hid, head, had, hud, hod, hood, heed, hard, heard, hoard, who'd". For American listeners, the response "hawed" was used instead of "hoard". Five blocks of stimuli were collected for every listener in each condition, making a total of ten presentations of every stimulus. Normally-hearing listeners were tested binaurally in a free-field. Hearing impaired listeners were tested in three conditions: hearing aid alone, implant alone, and binaural (implant plus hearing aid).

RESULTS

	2400	2200	2000	1800	1600	1400	1200	1000	800	600
300	ɪ		u	u	u	u	u	u	ʊ	ʊ
400	ɛ	ɛ		ɜ	ɜ		ʊ	ʊ	ʊ	ɔ
500	ɛ	ɛ	ɛ	ɜ	ɜ	ɜ				ɒ
600	ɛ	ɛ	æ	ɜ	ɜ	ɜ	ɒ	ɒ	ɒ	
700	æ	æ	æ	æ				ɒ	ɒ	
800	æ	æ	æ	æ	ʌ	ʌ		ɒ		
900	æ	æ	æ	æ	ʌ	a	a			

Figure 1. Vowel response pattern obtained for eight Australians with normal hearing.

The response patterns obtained consist of a three dimensional array of numbers, corresponding to the dimensions F1 x F2 x Response. Each entry in the array represents the number of times the particular response occurred for the stimulus with given F1 and F2 frequencies. Figure 1 shows a summary of the response pattern obtained for eight Australian listeners with normal hearing. The response shown for each stimulus occurred at least forty times out of a total of eighty trials. There are eleven blank stimuli where none of the responses occurred more than forty times. For each response, it is also possible to calculate a "centre of gravity" or "vowel centre" which is the average of the F1 and F2 frequencies for all stimuli weighted by the number of times the response occurred.

Figure 2 shows the mean vowel centres obtained for the Australian and American normally-hearing listeners. Some differences are apparent, such as the F2 centres for "who'd" and "hood" and the F1 centre for "hud". In a similar way, the vowel centres were compared for male and female listeners, keeping the two nationalities separate. The gender differences were much smaller than the differences between the nationalities. An analysis of variance was carried out using the vowel centres for F1 and F2 as dependent variables, with response vowel, nationality and gender as the independent factors. The ANOVA indicated a significant difference between Australian and American listeners ($p<0.001$ for the interaction of vowel response and nationality) and no effect of gender ($p>0.05$ for all terms involving gender). This result shows that the vowel patterns are reasonably consistent between normally-hearing individuals, but are sensitive to real differences between groups.

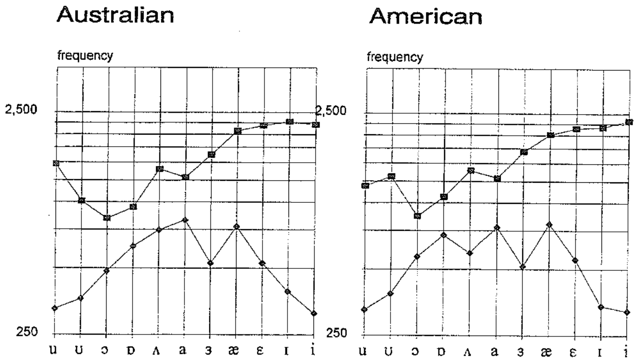

Figure 2. Comparison of F1 and F2 centre frequency values for each vowel obtained by Australian and American subject groups for male and female subjects combined.

	2400	2200	2000	1800	1600	1400	1200	1000	800	600
300	u	u	u	u	u			ʊ	ʊ	ʊ
400	u		u				ʊ	ʊ	ʊ	ʊ
500	ɛ	ɛ	ɜ		ɜ					
600	ɛ	ɛ	ɛ				ɒ	ɒ	ɒ	
700		æ	æ		æ			ɒ	ɒ	
800	æ	æ	æ	ʌ		ʌ	ʌ			
900	æ		æ	æ		ʌ	ʌ			

Figure 3. Vowel response pattern obtained for the implanted ear of a person with impaired hearing.

Figure 3 shows the vowel response pattern obtained for one implant user. Compared to the normal pattern, there are more empty cells (24 cf 11). The shapes and positions of the response regions have also changed. This will affect the vowel centres calculated from the responses. Figure 4 shows the vowel response pattern in the other ear of the same person. A hearing aid was used to amplify the sounds presented to this ear which has a very profound hearing loss. There are 52 empty cells and only 12 stimuli with responses that occurred five or more times out of ten. Only two vowel responses were used consistently, and their centres are very different from normal. This listener seems to depend much more on F1 than F2 in the hearing aided ear because there is little variation in the horizontal (F2) direction. In this particular case, the hearing-impaired listener obtains more consistent vowel information from the implant than from the hearing aid, and the pattern of responses for the implant is closer to the pattern of responses for normal listeners shown in Figure 1. Comparing Figures 1 and 3, there are 27 responses that are the same, and 9 that are contradictory. Comparing

Figures 1 and 4, there are only 2 responses that are the same, and 9 that are contradictory. The vowel response pattern shown in Figure 4 is an extreme case, but the finding that the implanted ear produced a more normal pattern than the aided ear applied to most of the hearing-impaired listeners in the study.

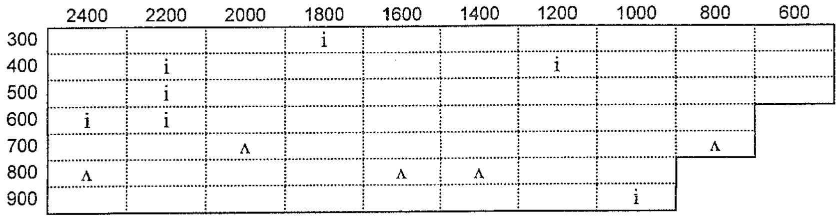

Figure 4. Vowel response pattern obtained for the aided profoundly hearing-impaired ear of the same person whose implanted ear data is shown in Figure 3.

Binaural, implant, and hearing aid vowel response patterns were obtained from ten people who used a cochlear implant in one ear and a hearing aid in the other. Figure 5 shows the proportion of stimuli for which one response accounted for more than the cut-off percentage. It shows that the response patterns for the normally hearing listeners were most consistent, followed in order of decreasing consistency by the binaural, implant, and hearing aid patterns. All of the experimental response patterns were significantly more consistent than a purely random response distribution.

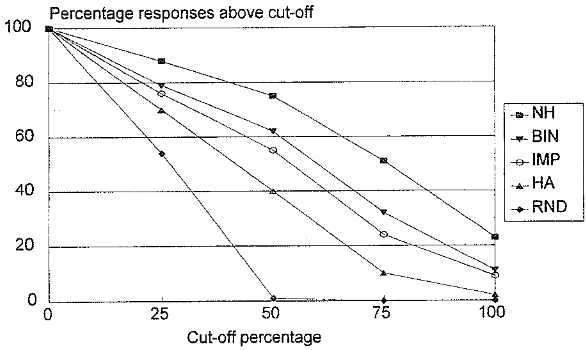

Figure 5. Percentage of stimuli for which one response accounted for more than a given proportion (the cut-off percentage) of trials of that stimulus, as a function of the cut-off percentage and the mode of presentation (normal, binaural, implant, or hearing aid). The lowest data line shows the percentages that would be obtained from purely random response distributions.

Figures 6 and 7 show the mean vowel centres obtained for the binaural, implant, and hearing aid ears compared with the ranges obtained for normally hearing listeners of the same nationality. The graphs show that the vowel centres were different in the two ears of the implant and hearing aid users. In some cases, the mean vowel centres for the hearing impaired subjects fell within the ranges observed for normally-hearing listeners, but there were also many cases which did not satisfy this criterion of "normality". The vowel centres for monaural hearing aid use tended to be further from the normal range than either the monaural implant centres or the binaural centres. This is in accord with direct observations based on vowel response patterns like those shown in Figures 1, 3 and 4. Analysis of variance indicated significant differences ($p<0.01$) between the vowel centres for normal hearing, implant, and hearing aid conditions, but no significant difference between the centres for implant and binaural (implant plus hearing aid) conditions.

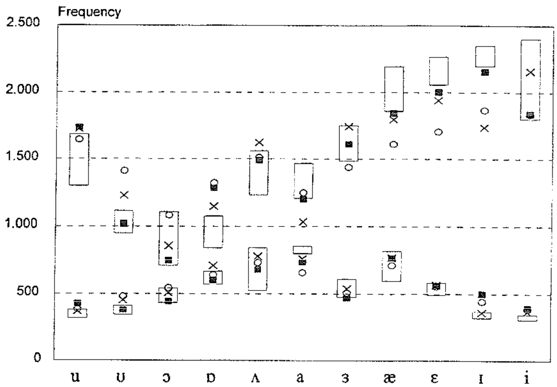

Figure 6. Mean vowel response centres for 3 Australian hearing impaired listeners compared with the range of vowel centres for the normally hearing Australian listeners. X indicates a binaural centre. Implant centres are represented by filled rectangles, and hearing aid centres by circles.

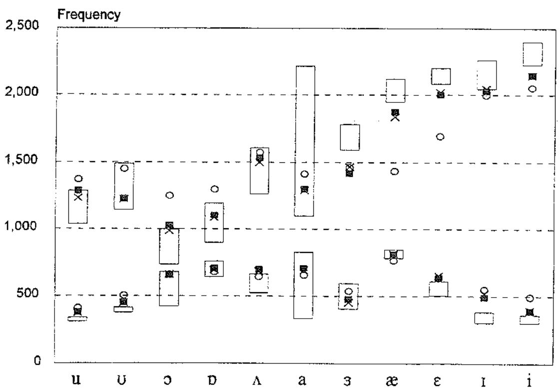

Figure 7. Mean vowel response centres for 7 American hearing impaired listeners compared with the range of vowel centres for the American normally hearing listeners. X indicates a binaural centre. Implant centres are represented by filled rectangles, and hearing aid centres by circles.

DISCUSSION

It is surprising that the response patterns for implanted ears are closer to normal than those for aided ears. Firstly, the mechanism of electrically stimulating auditory nerves with an electronically processed signal is very different from the normal mechanical transduction method that is applied to acoustic signals in normal and aided, impaired ears. Secondly, the electrodes in the cochlear implant are placed up to 25 mm into the basal end of the cochlea, region that corresponds to frequencies greater than about 600 Hz in normally-hearing people. Thus it might be expected that speech sounds both unnatural, and lacking in low frequencies compared to sounds heard through normal or impaired hearing. This does not seem to be the case, however. The results of this vowel study are in accord with direct pitch-matching results for the same subjects listening to pure tones in one ear and electrical pulse trains in the other ear (Blamey et al, in press). The pitch matching study showed that electrical stimuli presented at the apical end of the electrode array (about 20 to 25 mm into the cochlea) produced pitch sensations that were considerably lower than the pitch sensations produced by pure tones at a corresponding position in normal cochleae. The relatively small differences between the implant vowel centres and the normal centres are also in accord with the very good results for speech recognition obtained by postlinguistically deafened patients within a short time of implantation. This is important because it implies that very little perceptual adjustment or learning is required after implantation.

Possible mechanisms explaining the differences between normal and aided vowel patterns include the loss of frequency resolution that occurs with severe-to-profound hearing losses, and changes in the perceived relative amplitudes of F1 and F2. The latter effect includes the extreme case where one formant (usually F2) becomes completely inaudible.

CONCLUSIONS

The method of assessing vowel perception was sensitive to small differences between listeners, such as those between Australians and Americans. There were no significant differences between male and female listeners of the same nationality. The data indicate variations in the perception of vowels among and between groups of listeners with normally hearing ears, implanted ears, and severely-to-profoundly hearing-impaired ears using hearing aids. The differences between the normal ears and the impaired ears arose from two effects: poorer resolution of the vowel formants, resulting in less consistent patterns, and shifts in the vowel centres for some of the vowels. Shifts were apparent for both F1 and F2 frequencies of the centres, but the F2 shifts were of greater magnitude. Surprisingly, the implanted ears were closer to the normal ears than the aided ears in terms of their vowel perception patterns.

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