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Abstract

It has been claimed that speech recognition with a cochlear implant is strongly dependent on the frequency alignment of analysis bands in the speech processor with characteristic frequencies (CFs) at electrode locations. However implanted electrode arrays often have the most apical electrode at positions with CFs of 1 kHz or more. The use of filters aligned in frequency with arrays in relatively basal locations inevitably leads to the loss of lower frequency speech information. This study simulates the effects on speech recognition of array insertion depth for a frequency-aligned speech processor in order to assess the significance of this information loss. Noise-excited vocoders were used to simulate a Continuous Interleaved Sampling (CIS) processor driving eight electrodes 2mm apart. Analysis filters always had centre frequencies matching the CFs of the simulated stimulation sites. The simulated position of the most apical stimulation site relative to the cochlear base was varied in 2mm steps between 24.9 mm (CF = 502 Hz) and 16.9 mm (CF = 1851 Hz). Identification of consonants, vowels and key words in sentences was measured in each condition. Each measure showed a significant decline in performance between each of the three more basal simulated electrode configurations. The results suggest that if implant processors were to use analysis filters frequency-aligned to electrode CFs, patients whose most apical electrode is 19 mm or less from the cochlear base are likely to suffer a significant loss of speech information.

1. Introduction

It has been claimed that speech recognition with a cochlear implant is significantly affect by a frequency mis-match of the analysis bands in the speech processor with the characteristic frequencies (CFs) at the implanted electrode locations when this mismatch is equivalent to basalward basilar membrane shifts of 3 mm or more (Shannon, Zeng, & Wygonski, 1998; Dorman, Loizou, & Rainey, 1997; Fu & Shannon, 1999). The primary support for this claim comes from simulations of cochlear implant speech processing in normally hearing listeners using vocoder-based processing. Here, speech is presented as a series of band-limited carriers, each modulated by an amplitude envelope extracted from one of a series of band-pass analysis filters. When the band-limited carriers are shifted upwards in frequency relative to the analysis band that determines the carrier's amplitude envelope, performance in speech intelligibility tasks is substantially poorer than in an unshifted control condition. The centre frequencies of the carrier bands may be assumed to simulate the positions of the electrodes of an array, with upward shifted carrier bands representing less apical sets of electrode positions. One practical implication of the effect of upward spectral shifting is that the speech receptive performance of cochlear implant users may be improved by the matching of speech processor analysis filters to the characteristic frequencies at the implant electrode locations.

One caution in accepting this implication is that these data are from acute studies. When normally-hearing listeners are given a few hours of training with spectrally shifted speech, performance is very substantially increased (Rosen, Faulkner, & Wilkinson, 1999). Since implant users necessarily use the clinical mapping of speech processor filters to their electrode locations for extended periods of time, it is very likely that they too adapt to the frequency mapping provided by their implant. That such adaptation does occur in patients is supported by a study in which the processor filter to electrode mapping was varied (Fu et al., 1999). Here, the participating subjects performed better with a mapping similar to that they were used to that with alternative mappings to which they were acutely exposed. This experience appeared to outweigh any effects due to an improved frequency match between the experimental processor and the CFs at electrode locations.

A second reason for caution in accepting the implication that speech processor filters should match electrode locations comes from a consideration of the range of electrode locations that are observed in implanted patients. In a study of 19 patients implanted with the Nucleus 22 channel electrode, spiral CT data showed that the most apical electrode position varied between 24 and 13.7 mm from the base of the cochlear, with a median distance of 20.3 mm (Ketten et al., 1998). All these electrode arrays were reported at surgery as fully inserted. From the cochlear position to frequency map due to Greenwood (1990), the range of characteristic frequencies at the most apical electrode in this patient group can be estimated as 590 to 2970 Hz, with a median of 1090 Hz [1]. The use of a speech processor whose lowest frequency band is centred on the CF of a most apical electrode at a position 20 mm or less from the cochlear base must entail the loss of speech information at frequencies below 1 kHz. This is likely to reduce speech intelligibility (e.g., French & Steinberg, 1947).

The present study simulates the effect of electrode insertion depth on the intelligibility of speech processed through an eight-band cochlear implant speech processor whose analysis filters are matched to the CFs of the simulated stimulation sites. Vowel identification data that address this issue for insertion depths that extend from CFs of 290 to 960 Hz at the most apical electrode location have been described by Fu & Shannon (1999). Over this range, simulated insertion depth had little effect. However, shallower insertions than these appear common, and it may be expected that as the lowest frequency band presented rises above 1 kHz, greater effects on intelligibility will occur.

2. Method

2.1 Speech processing and equipment

Speech processing used an eight-band noise-excited vocoder similar to that introduced by Shannon (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). The channel filter centre frequencies and –3 dB cut-off frequencies are shown in Table I. This series of

[1] The accuracy of these stimulation site to cochlear position estimates may be limited for sites in the apical turn if the electrode elements are directly stimulating the spiral ganglion cells rather than the associated dendrites. In the apical turn of the human cochlea the ganglion cells are not tonotopically located, but lie in bundles. The ganglion cells (and their dendrites) in the outer two turns are, however, tonotopically positioned, so these frequency mapping estimates should be reliable above about 1 kHz irrespective of the neural elements that are stimulated.

centre frequencies represents cochlear locations separated by a distance of 2 mm. Cross-over and centre frequencies for both the analysis and output filters were calculated using an equation (and its inverse) relating position on the basilar membrane to its characteristic frequency, assuming basilar membrane length of 35 mm (Greenwood, 1990):

$$frequency = 165.4\left(10^{0.06x} - 1\right)$$

$$x = \frac{1}{0.06}\log\left(\frac{frequency}{165.4} + 1\right)$$

Distance from base (mm)	Centre frequency (Hz)	Cut-off (Hz)	Condition				
			1	2	3	4	5
			Band	Band	Band	Band	Band
25.9		416					
24.9	502		1				
23.9		601					
22.9	715		2	1			
21.9		845					
20.9	995		3	2	1		
19.9		1167					
18.9	1364		4	3	2	1	
17.9		1591					
16.9	1851		5	4	3	2	1
15.9		2150					
14.9	2492		6	5	4	3	2
13.9		2886					
12.9	3338		7	6	5	4	3
11.9		3857					
10.9	4453		8	7	6	5	4
9.9		5138					
8.9	5923			8	7	6	5
7.9		6826					
6.9	7861				8	7	6
5.9		9050					
4.9	10416					8	7
3.9		11983					
2.9	13783						8
1.9		15850					

Table 1: *Simulated position of electrodes and filter centre and cut-off frequencies for the eight bands in each of the five conditions.*

The stages of processing in each band comprised an analysis filter, half-wave rectification, envelope smoothing with a 400 Hz low-pass filter, multiplication of the envelope against a white noise, and an output filter that always matched the analysis filter. Finally, the outputs of each band were summed. Each channel of the processor received speech as input, without pre-emphasis.

Two implementations of this processing were employed. Testing made use of off-line processing implemented in MATLAB. Training made use of real-time processing.

Off-line processing was executed at a 44.1 kHz sample rate. Analysis filters in the off-line processing were 6th-order Butterworth IIR designs (with 3 orders per upper and lower side) having responses that crossed 3 dB down from the pass-band peak. Envelope smoothing used 2nd-order low-pass Butterworth filters (400 Hz cut-off). A final low-pass filter was applied to the summed waveform from each of the eight bands at the upper cut-off frequency of the highest frequency channel (15.8 kHz) to limit the signal spectrum. This used a 6th-order low-pass elliptical filter forwards and backwards to obtain the equivalent of a 12th-order elliptical filter with zero phase characteristic.

Real-time processing ran at a 16 kHz sample rate on a Loughborough Sound Images DSP card (TMSC31), and was implemented using the Aladdin Interactive DSP Workbench (Hitech Development AB). To reduce the required computation, elliptical filter designs were used, with the same –3dB crossover frequencies as those used for off-line processing, Because of the limited 8 kHz bandwidth, the uppermost three bands of the total set used could not be implemented. Hence, in training, condition 5 used only 5 bands, condition 4 used 6, and condition 3 used 7 bands. Analysis and output filters were 4th-order band-pass designs, while the envelope smoothing filters were 3rd-order low-pass.

2.2 Stimuli

Speech materials for segmental-level testing comprised a set of 20 intervocalic consonants in /i/, /ɑ/ and /u/ vowel contexts, and a set of 17 vowels in bVd words. The consonant and vowel tokens were anechoic digital recordings from one adult male and one adult female, both with standard Southern British English accents. The recordings included 7 to 10 tokens of each utterance from each talker. In each test run of 120 consonants or 68 bVd words, stimuli were sampled randomly without replacement from the full set of tokens. For connected speech testing, the primary materials were the BKB sentences (Bamford & Wilson, 1979). The BKB sentences were digital recordings from different adult male and female talkers, again with the same accent. Sixteen sentences from the ASL sentence set (MacLeod & Summerfield, 1990) produced by the same male talker as for the BKB sentences were also used in an initial familiarisation session. Although the off-line processing used a 44.1 kHz sample rate, all the recorded speech materials were band-limited to 11.05 kHz before processing.

2.3 Subjects

Eight adult native speakers of English took part. They were screened for normal hearing at 0.5, 1, 2 and 4 kHz, and were paid for their services.

2.4 Procedure

Since we have found considerable training effects with some forms of simulated cochlear implant processing (Rosen et al., 1999), testing in each processor condition was preceded on each occasion by a 15 minute training period. In addition, where this was possible, feedback was provided during testing.

All testing and training took place in a sound-isolated room. The subject received diotic presentation of the processed speech stimuli over headphones (Sennheiser HD475 headphones for testing, AKG K240DF for training). Presentation levels were approximately 70 dBA. Since the processing conditions using higher frequency filters led to lower level processed output, a level correction was applied to ensure that all conditions were presented at a similar SPL. Interactive training was performed with the talker and subject in adjacent sound-isolated rooms, without visual communication.

The processing condition was held constant throughout each session of approximately one hour. Each session commenced with 15 minutes of Connected Discourse training (DeFilippo & Scott, 1978) with processed speech. The talker (author DS) was not visible to the subjects. In the testing that followed, the subject was presented with a sentence list (16 sentences with 50 scored key words) from each of the male and female talkers, followed by the consonant stimuli (120 items) and finally the vowel stimuli (136 items). Testing was controlled by a PC. During the consonant and vowel tests, but not the sentence test, subjects received visual feedback giving the identity of the stimulus after each response. The first session was treated as practice, and employed the intermediate set of filters from the total of five sets of simulated electrode positions. In each of ten subsequent test sessions, the same sequence of training and testing was again administered. The processing condition used in each session was randomly ordered for each subject over the first five and second five test sessions.

3. Results

Analyses of each test dataset were performed using repeated-measures ANOVA, with factors of simulated electrode position, talker, and practice (scores from the first set of five sessions compared to scores from the second set of five sessions). Vowel context was an additional factor in the analyses of consonant identification accuracy. Hyunh-Feldt Epsilon corrections were applied to all F tests of factors with more than 1 degree of freedom. Simulated electrode position is quantified hereafter in terms of the location of the most apical simulated electrode relative to the cochlear base (from 24.9 to 16.9 mm).

3.1 Sentences

The results are shown in Figure 1. ANOVA (see Table II) showed significant main effects of simulated electrode position and of talker, and a significant interaction of electrode position and talker. The effect of practice was close to significance, and there was a marginally significant interaction of electrode position and practice. This interaction represented a slight increase in scores in the two most basal simulated electrode positions on the second test run compared to the first. Because of the electrode position by talker interaction, data for the two talkers were subjected to two separate ANOVAs (see Table II). These showed main effects of electrode position for both talkers. There was no significant practice effect for the female talker, but the male talker data showed a significant practice effect and also a significant electrode position by practice interaction. Each of a further pair of sub-analyses of the male talker data for each of the first and second run showed highly significant main effects of electrode position. All of these interactions can be attributed to ceiling scores for the more apical electrode positions, and do not, therefore, lead to difficulties in interpretation. In every analysis and sub-analysis, planned comparisons between electrode positions showed that scores at 18.9 mm were significantly lower than for more apical electrode positions, while for at 16.9 mm, scores were significantly lower still. Scores for the 24.9, 22.9 and 20.9 mm electrode positions were equivalent, these all being at or very close to ceiling levels.

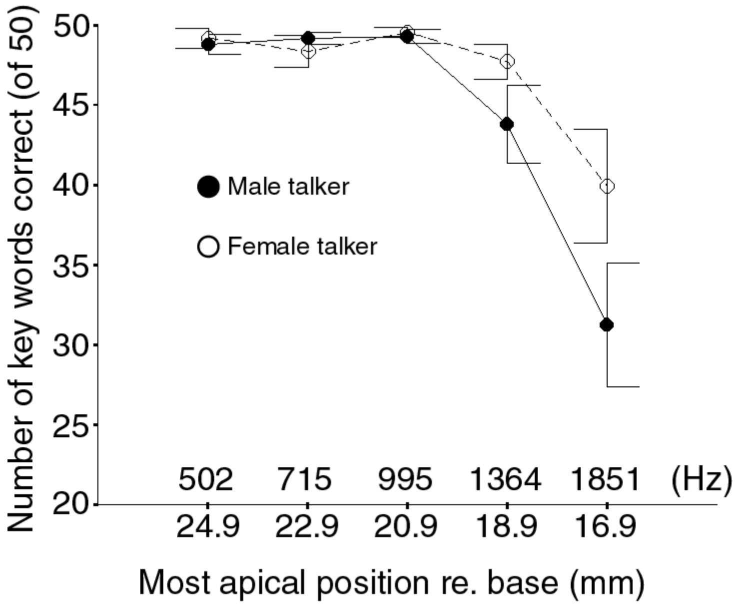

Figure 1: *Key words correct for BKB sentences as a function of simulated electrode positions. The centre frequency of the lowest band is indicated above the x-axis. Scores are shown for each of the two talkers. Solid symbols and rightward error bars, male talker; empty symbols and leftward error bars, female talker. Error bars here and in later figures show 95% confidence limits.*

Talker	Factor	df	F	p	η2	power
Both	Simulated electrode position	2.2, 13.1	88.2	<0.001	0.94	1.00
	Talker	1,6	55.4	<0.001	0.90	1.00
	Practice	1,6	5.81	0.052	0.49	
	Simulated electrode position * Talker	2.1,12.3	22.57	<0.001	0.79	1.00
	Simulated electrode position * Practice	2.3, 13.8	3.66	0.048	0.38	0.61
Male	Simulated electrode position	2.2, 15.2	54.5	<0.001	0.89	1.0
	Practice	1, 7	9.62	0.017	0.58	0.76
	Simulated electrode position * practice	2.9, 20.5	4.21	0.019	0.38	0.77
Female	Simulated electrode position	1.5, 9.6	36.1	<0.001	0.86	1.0

Table 2: *Significant terms in ANOVA of sentence data for both talkers and for the male and female talker separately. η2 indicates the eta-squared statistic, which estimates the proportion of the variance in the data that can be attributed to the factor. The power is the probability of correctly rejecting the hypothesis there is no effect of the tested factor given the observed effect size.*

3.1.1 Intervocalic Consonants

Accuracy in consonant identification as a function of simulated electrode position is shown for each talker in Figure 2. A repeated measures ANOVA with factors of electrode position, talker, vowel context and practice showed main effects of electrode position, context and practice. There were also several significant interactions involving vowel context. The vowel by electrode position interaction was highly significant [$F(6.65,46.6) = 15.1$, $p < 0.001$, power = 1]. The talker by vowel interaction [$F(2.14) = 14.6$, $p = 0.026$, power = 0.7] and the vowel by talker by electrode position interaction [$F(7.05,49.3) = 2.94$, $p = 0.012$, power = 0.89] also reached significance. Hence, separate ANOVAs were performed for each vowel context, using factors of electrode position, talker and practice.

Scores for each vowel context are displayed in Figure 3. With the exception of a modestly significant interaction between electrode position and talker for the /ɑ/ vowel context, only main effects were significant in these three sub-analyses. The significant terms in each case are shown in Table II. Electrode position was a highly significant factor for each vowel context. Talker significantly affected scores only for the /ɑ/ vowel. There was a significant effect of practice for the /ɑ/ and /i/ contexts, but not for /u/.

The electrode position by talker interaction seen for the /ɑ/ vowel context is illustrated in Figure 4. Electrode position has a similar effect on accuracy for both talkers except at 24.9 mm. Here it seems that the loss of information from the highest band present for the 22.9 mm most apical position (around 5923 Hz) leads to a decline in performance with the female speech only.

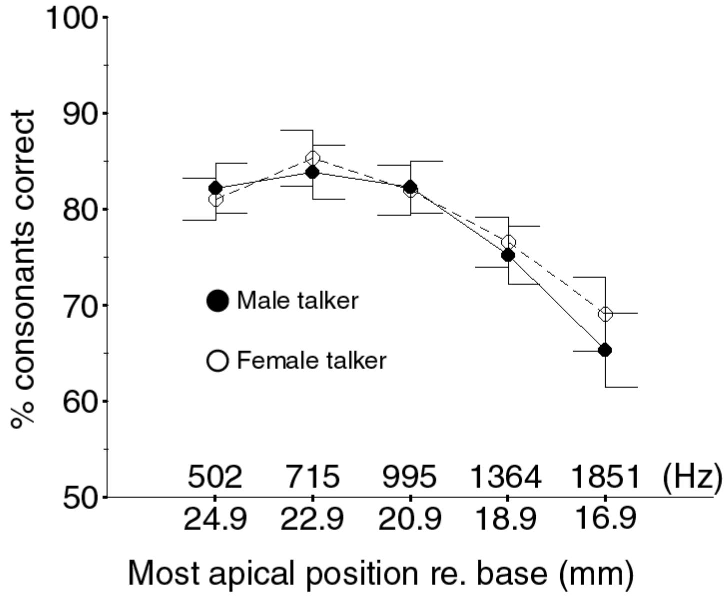

Figure 2: *Percentage correct consonant identification as a function of simulated electrode positions and talker. Solid symbols and rightward error bars, male talker; empty symbols and leftward error bars, female talker.*

Vowel context	Factor	df	F	p	η2	power
/ɑ/	Simulated electrode position	4, 28	53.46	<0.001	0.88	1.00
	Talker	1,7	18.90	0.0034	0.73	0.96
	Practice	1,7	26.50	0.0013	0.79	0.99
	Simulated electrode position * Talker	4,28	3.12	0.0306	0.31	0.74
/i/	Simulated electrode position	4,28	8.42	<0.001	0.55	0.99
	Practice	1,7	46.68	<0.001	0.87	1.00
/u/	Simulated electrode position	4,28	43.88	<0.001	0.86	1.00

Table 3: *Significant factors in ANOVAs of consonant identification accuracy for each vowel context.*

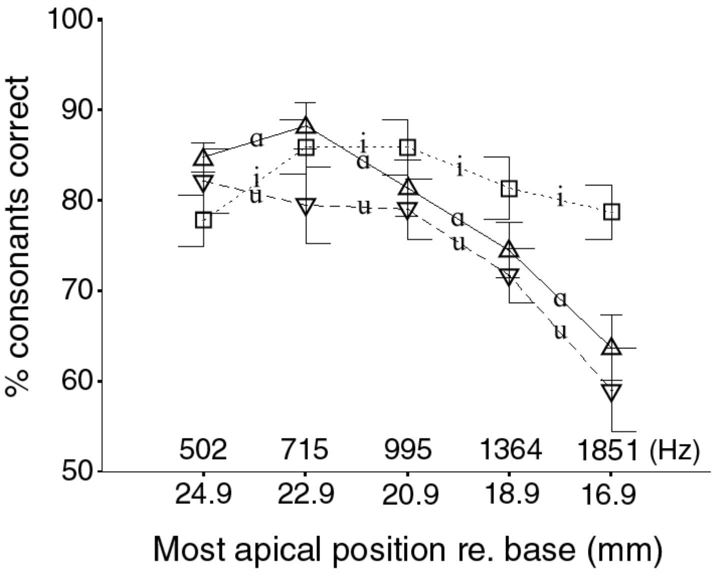

Figure 3: *Percentage correct consonant identification as a function of simulated electrode positions. Average scores over both talkers are shown for each of the three vowel contexts. Γ symbol and leftward error bars for /i/, B symbol and centred error bars for /a/, X symbol and rightward error bars for /u/.*

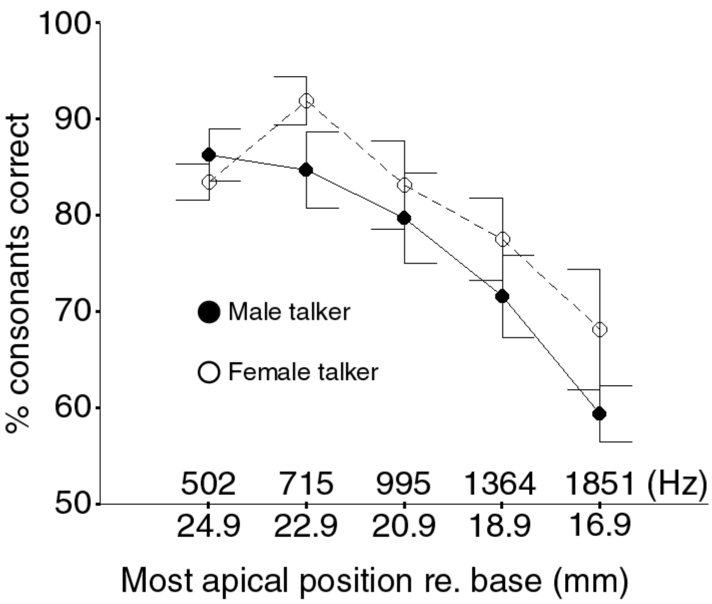

Figure 4: *Percentage correct consonant identification with /a/ vowel context as a function of simulated electrode positions and talker. Solid symbols and rightward error bars, male talker; empty symbols and leftward error bars, female talker.*

The effects of simulated electrode position, while strongly significant for each of the three vowel contexts, showed notable differences between the /i/ and the /ɑ/ and /u/ vowel contexts. These have been examined in detail using *a priori* contrasts based on the separate ANOVAs for each vowel context. For the /i/ context, accuracy varied relatively little with electrode position compared to the other contexts. There were nevertheless significant differences. Scores at the apical electrode position of 24.9 mm were significantly lower than those at 22.9mm, while the 22.9 and 20.9 mm scores were statistically equivalent. Scores at 18.9 mm were significantly lower than at 20.9 mm, while 18.9 and 16.9 mm apical positions showed no difference. For the /ɑ/ vowel context, *a priori* contrasts showed significant differences between each successive pair of simulated electrode positions, with accuracy at the 22.9 mm apical electrode position being highest. With the /u/ context, the 24.9, 22.9 and 20.9 mm apical position scores were statistically equivalent, while basal shifts in position to 18.9 and 16.9 mm each lead to significant decreases in performance.

For each of the three vowel contexts, consonant identification accuracy declined significantly at electrode positions of 18.9 mm or less from the cochlear base compared to more apical positions.

3.1.2 Vowel identification

A repeated measures ANOVA of accuracy in vowel identification showed all main effects (electrode position, talker and practice) to be significant. However, there were also strong interactions involving the talker factor; these being the talker by electrode position term [$F(4,28) = 34.5$, $p < 0.001$, power = 1.0] and the talker by electrode position by practice term [$F(4,28) = 6.31$, p = <0.001, power = 0.97]. Consequently, sub-analyses were performed for each of the two talkers. The significant terms in the two sub-analyses are summarised in Table IV.

Performance across the simulated electrode positions for each talker is shown in Figure 5. Planned contrasts based on the ANOVA of the male talker data showed that scores dropped significantly with each shift in position from the 22.9 mm apical electrode position onwards, while the 24.9 mm and 22.9 mm position scores did not differ significantly. For the female talker, each successive shift in electrode position produced a significant drop in performance.

Talker	**Source**	**df**	**F**	**p**	**η2**	**power**
Female	Simulated electrode position	4,28	99.4	<0.001	0.93	1
	Practice	1,7	118.9	<0.001	0.94	1
	Simulated electrode position * practice	4,28	3.74	0.0146	0.35	0.83
Male	Simulated electrode position	4,28	145.8	<0.001	0.95	1
	Practice	1,7	14.4	0.0067	0.67	0.90

Table 4: *Significant terms in ANOVAs of vowel accuracy for Female and Male talkers.*

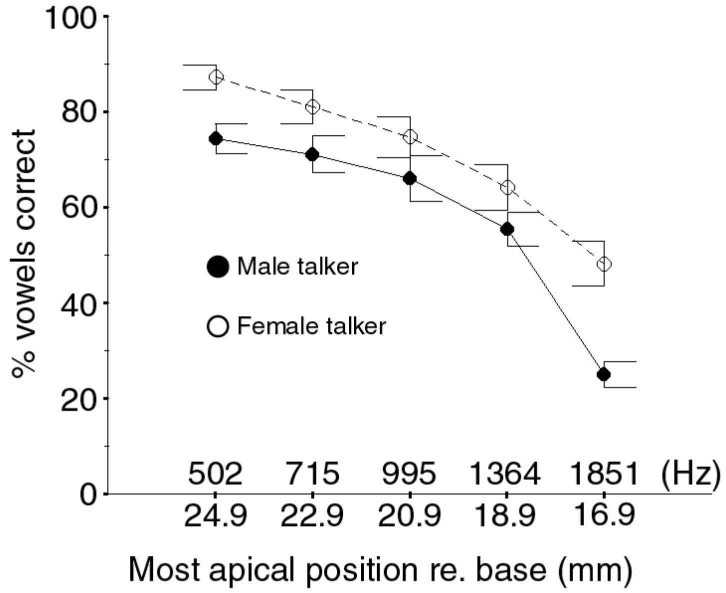

Figure 4: *Vowel identification accuracy as a function of simulated electrode positions. Solid symbols and rightward error bars, male talker; empty symbols and leftward error bars, female talker.*

Practice effects were significant for both talkers. The interaction found between electrode position and practice for the female talker (see Table 3) is primarily due to a larger practice effect at the 16.9 mm apical electrode position than at other positions.

3.2 Discussion

These simulations of cochlear electrode insertion depth show clear general trends for all of the speech materials used, as illustrated in Figure 6. If speech processors are set up so that analysis filters are matched to CF at electrode positions, it appears that apical electrode locations that are 19 mm or less from the base will give significantly poorer speech intelligibility than insertions that are 2 to 6 mm deeper. Further, this loss of intelligibility is likely to be greater for male than for female talkers. The exception to this overall trend of lower intelligibility with shallower insertion occurs where specific speech sounds carry critical cues to their identity in relatively high frequency regions (for example, in the region of the /i/ vowel F2 and F3).

The recent finding that 7 of 19 “full” insertions of the Nucleus array were to depths 19 mm or less from the base (Ketten et al., 1998), suggests that these relatively shallow insertions may be fairly common in implanted patients. Three of the cases studied by Ketten at al. showed the apical electrode to be 17 mm or less from the base of the cochlea. Our simulation of a processor that is tonotopically matched to an electrode 17 mm from the base shows a substantial loss of intelligibility compared to insertions that are 21 mm or more from the base. Here, sentence scores fall to just over 70% compared to 100% correct, and vowel scores are below 40% compared to 70% correct.

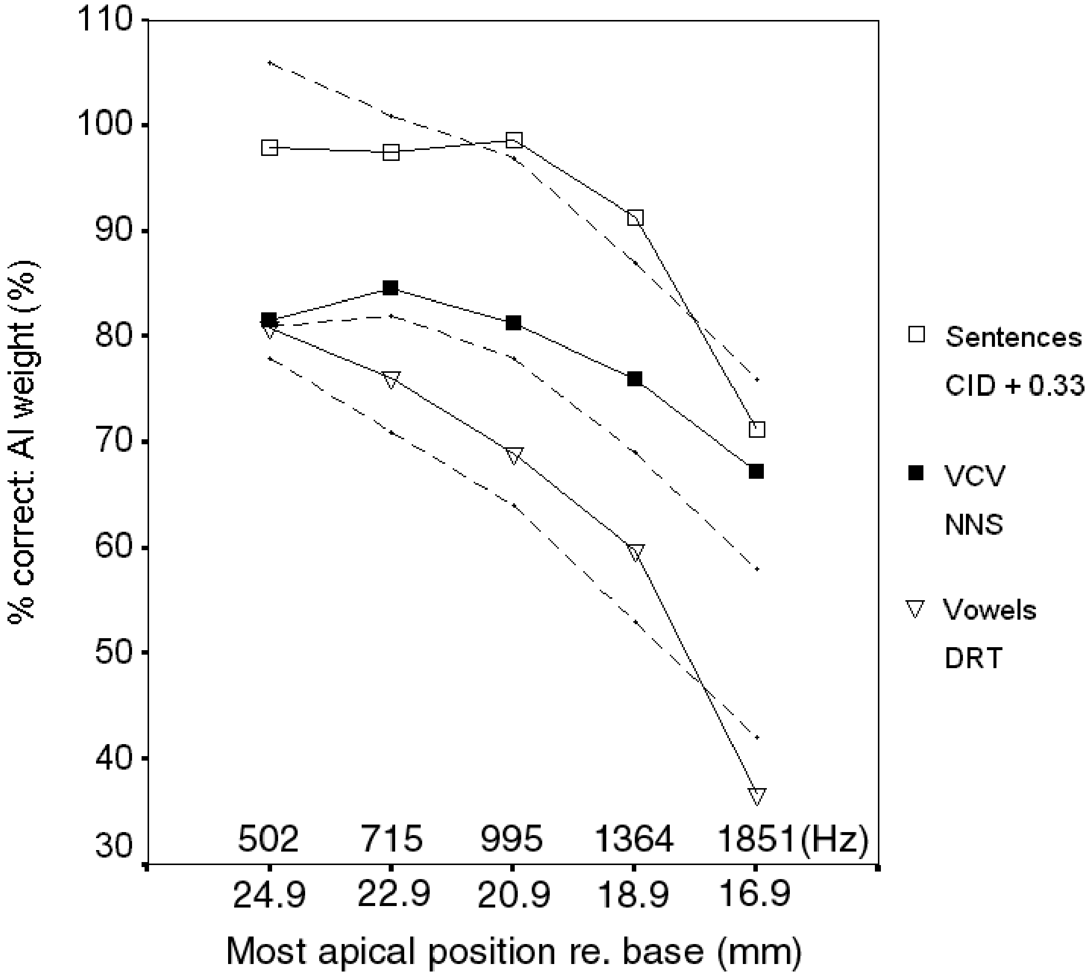

Figure 5: *Summary of effects of simulated electrode positions over speech materials. The symbols represent data: Γ sentences;] consonants; Ψ vowels. The solid lines show predicted relative scores over conditions from AI weightings for comparable materials (see text for details).*

Vowel identification data based on similar speech processing and manipulation of the presented frequency bands as that used here has been described by Fu & Shannon (1999). That study, however, did not investigate conditions that simulate insertion depths more than 21 mm from the base. That study and the present one agree in both showing a comparable, and relatively modest, decline in vowel identification over a range of most apical electrode positions from 25 to 21 mm from the base.

The effects of frequency range in each condition here fit fairly closely with predictions based on AI weightings for comparable material. Figure 6 includes these predictions. Predictions were derived from the "critical band" weights for CID sentences, from the NNS nonsense syllables for the vCv data, and from the Diagnostic Rhyme Test (DRT) for the vowel data (ANSI, 1998). A prediction of the relative intelligibility for each simulated electrode array position was derived by summing the critical band weights for those critical bands covered by each of the simulated processors. Where a critical band was not completely covered by one of the extreme processor filters, the critical band weight was reduced in proportion to the relative basilar membrane extent of the critical band that was covered by the processor band. The processor-weighted AI weightings for the NNS and DRT materials are directly displayed in Figure 6. The processor-weighted AI weights for the CID sentences were increased by 0.33 to align these with the sentence scores that are below ceiling. While AI weights are based on normal auditory frequency selectivity, the extension of AI proposed in the ANSI SII procedures makes the assumption that a broadening of frequency selectivity will lead to a proportional decrease in the AI weight in the affected frequency band (ANSI, 1998). Our processors represent frequency selectivity based on equal basilar membrane distance for each band, and normal auditory filter bandwidths are also closely related to basilar membrane distance (Greenwood, 1990). Hence the degree of broadening of selectivity compared to normal hearing is approximately the same for each processor filter band. Thus it would be expected that the AI weighting in each critical band covered by a processor would be equally affected by the broadening of selectivity represented by the processor filters. Therefore, the relative (although not the absolute) values of the processor-weighted AI weights over frequency should not depend on the degree of selectivity.

Although simulations suggest that speech processor filters centred below the CFs of electrode locations may be less ideal than filters matched to CFs, the unshifted control conditions employed in those studies have represented simulations of relatively deeply inserted electrodes. Where a patient has an electrode array that does not reach a depth of more than 19 mm from the base, speech intelligibility is likely to be less than ideal whatever fitting approach is taken. If the processor filters are matched to the electrode position CFs, significant low frequency information will be lost. If, on the other hand, the processor filters are centred at frequencies below these CFs, upward shifting may cause difficulties. However, listeners are able to adapt at least to some extent to upward shifting (Rosen et al., 1999). Further research is required to estimate the costs associated with spectral shifting alongside the possible benefits of making low frequency information available after listeners have had sufficient experience to adapt to shifting. Only then can conclusions be drawn on the expected outcomes of fitting speech processors using shifted and tonopically mapped filter frequency allocations for less than ideal electrode insertion depths.

It should be noted too that for pre-lingually deafened patients, with no auditory experience of the distribution of auditory speech cues over frequency, it seems unlikely that upward shifting would have negative consequences. Here, the fitting approaches should maximise the speech information presented without regard for CFs at the locations of the electrodes.

4. Acknowledgements

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