# Adaptation by a Cochlear-Implant Patient to Upward Shifts in the Frequency Representation of Speech

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**The purpose of this project was to assess the degree to which a patient, after 1 wk of experience, could adapt to 3.2-mm and 6.8-mm basal shifts in the representation of speech. Only small deficits in performance were found after practice after the 3.2-mm shift. After practice after the 6.9-mm shift, scores on tests that emphasized amplitude envelope cues returned to baseline levels. Scores on vowel and sentence tests that emphasized frequency-based cues remained poor. Scores for "place," however, showed some recovery. Vowel recognition may be the limiting factor in recognizing basally shifted speech.**

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The purpose of this project was to assess a cochlear implant patient's ability to adapt to large shifts in the frequency representation of speech. There are relatively few reports of adaptation to large frequency shifts (Fu, Shannon, & Galvin, 2002; Kileny, Zimmerman-Phillips, Zwolan, & Kemink, 1992; McKay & Henshall, 2002) because the experiments require patients to use, for extended periods, processors that provide distorted representations of speech.

At issue in this project was the ability of a patient to adapt to 3.2-mm and 6.9-mm upward shifts in the frequency representation of speech and to determine whether acoustic cues that have a distinct representation in the time/amplitude domain, i.e., the cues to consonant voicing and manner, are less affected by the shifts than frequency-based cues. This project differed from a recent project of similar nature (Fu et al., 2002) in that frequency shifts were implemented by assigning a fixed set of frequency bands to electrodes located in successively more basal locations rather than by assigning different frequency bands to a fixed set of electrodes.

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## Method

### Subject

M.K. received the 4-channel Ineraid cochlear implant in 1990. In 1995 he was fit with a 6-channel Med El CIS Link processor. This project was conducted in the summer of 1998.

### Electrode Array

The Ineraid electrode array consists of 6 electrodes with 4-mm spacing (Eddington, Dobelle, Brackmann, Mladejovsky, & Parkin, 1978a). Electrode array intracochlear insertion depths for M.K. were estimated from in vivo ultra-high resolution computerized tomography (CT) scans (Ketten, Skinner, Wang, Vannier, Gates, & Neeley, 1998). A three dimensional reconstruction of the electrode array is shown in Figure 1. The most apical electrode (e1) was inserted 20.32 mm. The insertion depths for e2 to e6 were 17.12 mm, 13.42 mm, 9.72 mm, 6.01 mm and 1.80 mm, respectively. Note that the electrodes are not spaced at 4-mm intervals. The electrode balls are on 1-mm "stalks" and the angle of the stalks alters inter-electrode distances. An estimate of place frequencies, derived from Greenwood (1990), for e1-e6 is shown in Table 1.

### Stimulus Materials

The stimuli for the tests of sentence intelligibility were taken from the Hearing In Noise Test (HINT) lists of Nilsson, Soli, and Sullivan (1994). Twenty sentences were presented in each test condition and were scored for number of words correct. Different sentences were used in each test condition.

The stimuli for the tests of consonant identification were 16 male-voice consonants in the/aCa/context taken from the Iowa laser video disk (Tyler, Preece, & Tye-Murray, 1986). There were six repetitions of each stimulus for each test condition. The stimuli were randomized into a list for each test condition.

The stimuli for the tests of vowel identification were 13 synthetic vowels in /bVt/ format, i.e., "beet, bit, bet, bat, bought, but, boot, Bert, Bart, boat, bout, bite, bait." There were six repetitions of each stimulus. To force subjects to use frequency-based cues for identification, the vowels were synthesized with

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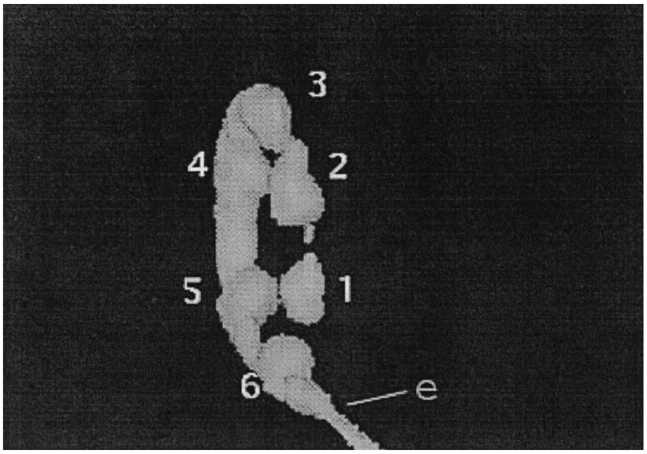


Figure 1. Three-dimensional reconstruction of M.K.'s electrode array. Electrodes are numbered 1 to 6 with 1 being the most apical electrode. The entry of the electrode carrier into the cochlea is indicated by "e." The broadening of the image at that point is a function of fibrotic and bony material around the carrier. Deposits of fibrotic and bony material can be seen on and between the electrodes.

equal vowel duration (Dorman, Dankowski, McCandless, & Smith, 1989, for details of synthesis).

### Procedure

M.K.'s 6-channel Med El CIS-Link processor was programmed, first, to output to channels 1,2,3,4. After 1 wk, M.K. was tested with the speech material. Immediately after testing, M.K.'s processor was configured to output to channels 2,3,4,5 and testing was repeated. After 1 wk of use of this processor, M.K. was tested again with the speech materials. M.K.'s processor was then reconfigured to output to 3,4,5,6 and testing was repeated. After 1 wk of use of this processor, M.K. was tested again. Table 1 lists the input filter center-frequencies and the estimated cochlear place frequencies for each condition.

Scores were plotted for envelope-based information (manner and voicing), for frequency based information (place of articulation, synthetic vowels)

TABLE 1. Input filter frequencies and place of stimulation, based on Greenwood (1990), for the three experimental conditions

| Channel | Filter Center Frequency | Place Frequencies for e1, e2, e3, e4 | Place Frequencies for e2, e3, e4, e5 | Place Frequencies for e3, e4, e5, e6 |
|---|---|---|---|---|
| 1 | 460 Hz | 1,111 Hz | 1,810 Hz | 3,115 Hz |
| 2 | 952 Hz | 1,810 Hz | 3,115 Hz | 5,291 Hz |
| 3 | 1971 Hz | 3,115 Hz | 5,291 Hz | 8,931 Hz |
| 4 | 4078 Hz | 5,291 Hz | 8,931 Hz | 16,093 Hz |

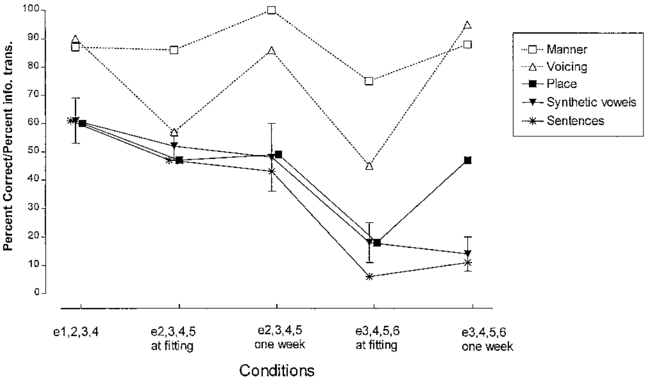


Figure 2. Effects of changes in filter-output to electrode assignments and of learning on the identification of envelope- and frequency-based cues for speech understanding. The most apical electrode is e1. Error bars indicate +/- 1 standard deviation.

and for material that combined envelope and frequency based information (the HINT sentences).

## RESULTS

### 3.2-mm Shift*

Immediately after shifting the signal from electrodes 1,2,3,4 to 2,3,4,5 the manner score was unchanged, the voicing score dropped by 33 percentage points, the synthetic vowel score dropped by 9 percentage points, the place score dropped by 13 percentage points, and the sentence score dropped by 14 percentage points (Fig. 2). Poor performance on voicing was due mainly to errors in the identification of fricative voicing. One week later, the voicing score improved 29 percentage points to a near baseline level. However, the synthetic vowel score showed no improvement (52% versus 48%), the place score showed no improvement (47% versus 49%) and the sentence score showed no improvement (47% versus 43%).

### 6.8-mm Shift

Immediately after shifting to electrodes 3,4,5,6 the manner score dropped by 12 percentage points, the voicing score dropped by 45 percentage points, the vowel score dropped by 43 percentage points, the place score dropped by 42 percentage points and the sentence score dropped by 55 percentage points. After 1 wk of experience, the manner and voicing scores improved to the baseline values. The place score improved from 18 percent to 47 percent information transfer but fell short of the baseline score of 60 percent. Neither the vowel score (18% correct

*The basal shift in millimeters is referenced to the change for the most apical electrode in the array.

versus 14% correct) nor the sentence score (6% correct versus 11% correct) improved.

## DISCUSSION

The immediate effects of the 3.2-mm shift from the experimental baseline were, with one exception, relatively small. The manner score was unaffected by the shift and the voicing score, which was affected, returned to the baseline value after 1 wk of experience. A similar outcome for envelope cues, i.e., either no change in scores immediately after shifting or a complete recovery of scores after experience, has been found for N22 patients after a 3-mo period of adaptation to an octave shift (Fu et al., 2002).

The scores for information in the frequency domain, i.e., vowel identity and consonant place, dropped by only 9 and 13 percentage points respectively. The scores for sentences dropped 14 points. These outcomes are somewhat better than expected given previous reports of octave shifts with N22 implant patients (Fu & Shannon, 1999; Fu et al., 2002). After 1 wk of adaptation, the scores for vowels, consonant place and sentences remained slightly below the baseline scores. Given this outcome, we conclude that the 3.2-mm shift resulted in a small but reliable decrease in recognition of frequency-based phonetic elements. This conclusion is consistent with the results and conclusions of Fu et al. (2002) who allowed N-22 patients 3 mo to adapt to an octave shift.

The immediate effects of the 6.8-mm shift were far larger than the effects of the 3.2-mm shift and affected all of the speech material. The large decrease in scores for envelope features, i.e., voicing and manner, demonstrates that envelope features are not completely independent of frequency location. After 1 wk of experience with the frequency-shifted signals, the scores on envelope features returned to the baseline level. Rosen, Faulkner, and Wilkinson (1999) report a similar outcome for a simulation of a 6.5-mm shift.

The scores for vowels and sentences remained very low after adaptation to the 6.8-mm shift condition. However, the place score increased from 18% to 47%. The score was nearly equal to the score achieved in the 3.2-mm shift condition (49%). The recovery of place scores, given the absence of recovery for vowel scores, suggests that the perceptual system may be more tolerant of upward frequency transposition for consonant place cues than for cues to vowel identity. If this is the case, then the recognition of vowels is the limiting factor in understanding frequency-shifted speech.

Overall, information derived from envelope cues was either resistant to degradation from frequency shifting or could be recovered after a period of adaptation. Relative to the frequencies in the input signal, signals in the 6.8-mm shift condition were up-shifted by 2-to-3 octaves and envelope information was recovered with greater than 90% accuracy after a period of adaptation (Table 1). The constancy of envelope information in the face of frequency shifts must be a significant factor in achieving speech recognition in quiet with cochlear implants.

Finally, the magnitude of the frequency shift in this experiment, and in other experiments of similar design, is open to question. If stimulation occurs principally at spiral ganglion cell bodies, then the Greenwood equation (used to generate Table 1) will not provide an appropriate estimate of frequency because the spiral ganglion only extends 1.87 turns around the modiolus in contrast to the 2.62 turns for the basilar membrane (Kawano, Soldon, & Clark, 1996). Evidence from pitch matching of electric stimulation in one ear and acoustic stimulation in the other, hearing-impaired ear suggests a more basally shifted frequency map for signals under 4 kHz than the map derived from the Greenwood equation (James, Blamey, Shallop, Incerti, & Nicholas, 2001). However, the pioneering pitch matching study by Eddington, Dobelle, Brackmann, Mladejovsky, and Parkin (1978b) reported data from a unilaterally deaf patient that was more nearly consistent with the frequency values derived from the Greenwood equation. At all events, because there are no in vivo measures of spiral ganglion cell survival or dendrite survival, all maps of place of stimulation for bilaterally deafened patients are "best guesses." The frequency values in Table 1 should be viewed in this light. In spite of this uncertainty, the weight of evidence from both patients and simulations indicates that envelope information is very robust in the face of frequency shifts.

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