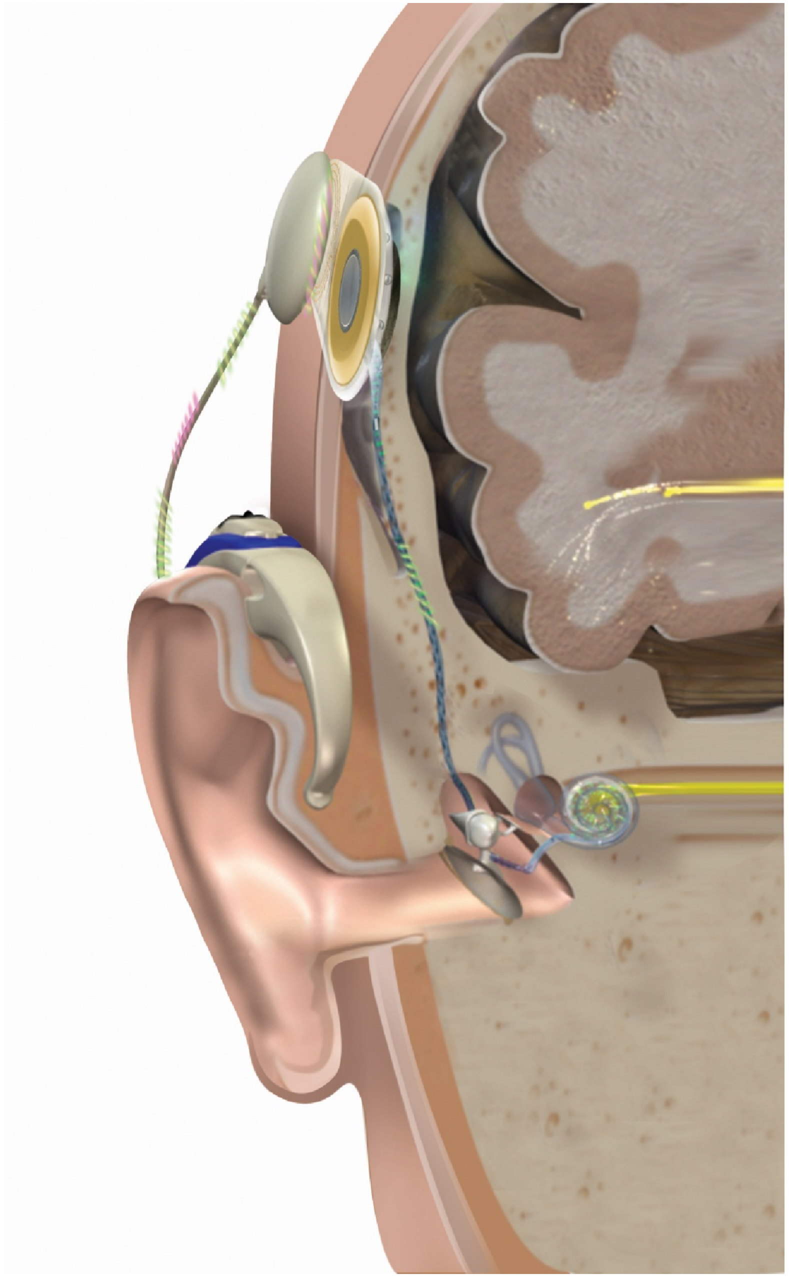


# AUDL 4007 & GS12 Auditory Perception

## Cochlear implants

# Who are cochlear implants for?

- People with little or no hearing
  - and little conductive component to the loss
- who receive little or no benefit from a hearing aid.
- Implants seem to work best in …
  - adults who had a significant period of relatively good hearing before becoming profoundly deaf, and who developed good language.
  - children who are young enough to develop language through an implant.

# Essential feature

- substitute for faulty or missing inner hair cell …
- by direct electrical stimulation of residual auditory nerve fibres
  - but brain stem implants are also being used
- Need, at a minimum …
  - microphone + ‘processor’
  - electrodes in the cochlea
  - a way to connect them (radio transmission)


1
2
3
4
5
6

1. Sound is received by the microphone of the speech processor.

2. The sound is digitized, analyzed and transformed into coded signals.

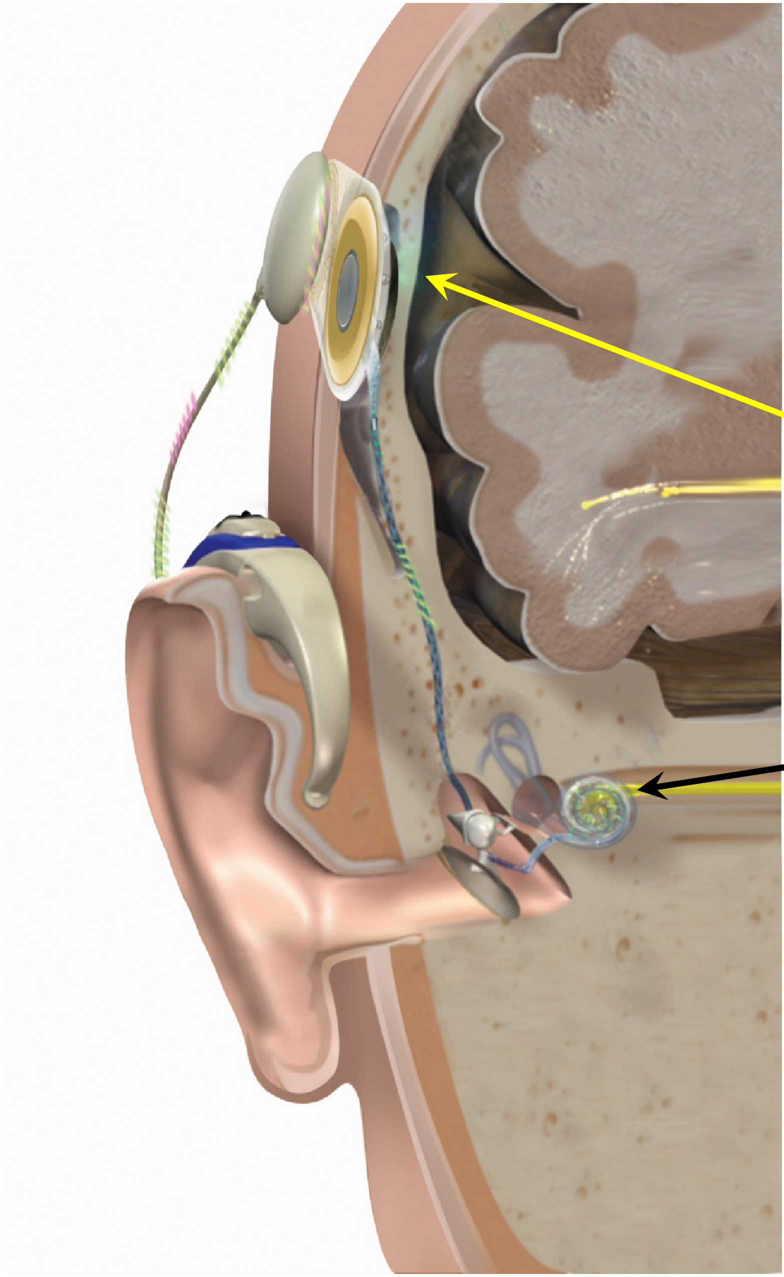
3. Coded signals are sent to the transmitter.

4. The transmitter sends the code across the skin to the internal implant where it is converted to electric signals.

5. Electric signals are sent to the electrode array to stimulate the residual auditory nerve fibres in the cochlea.

6. Signals travel to the brain, carrying information about sound.

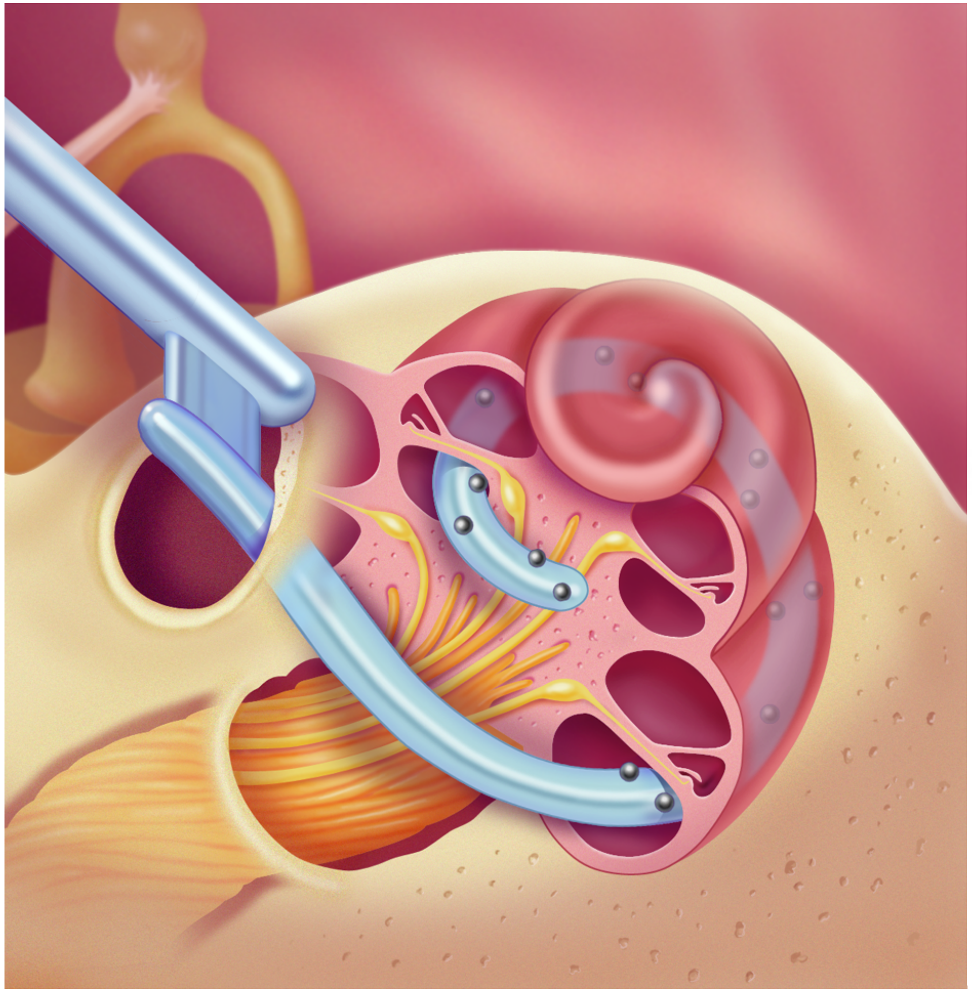
# The implant in place

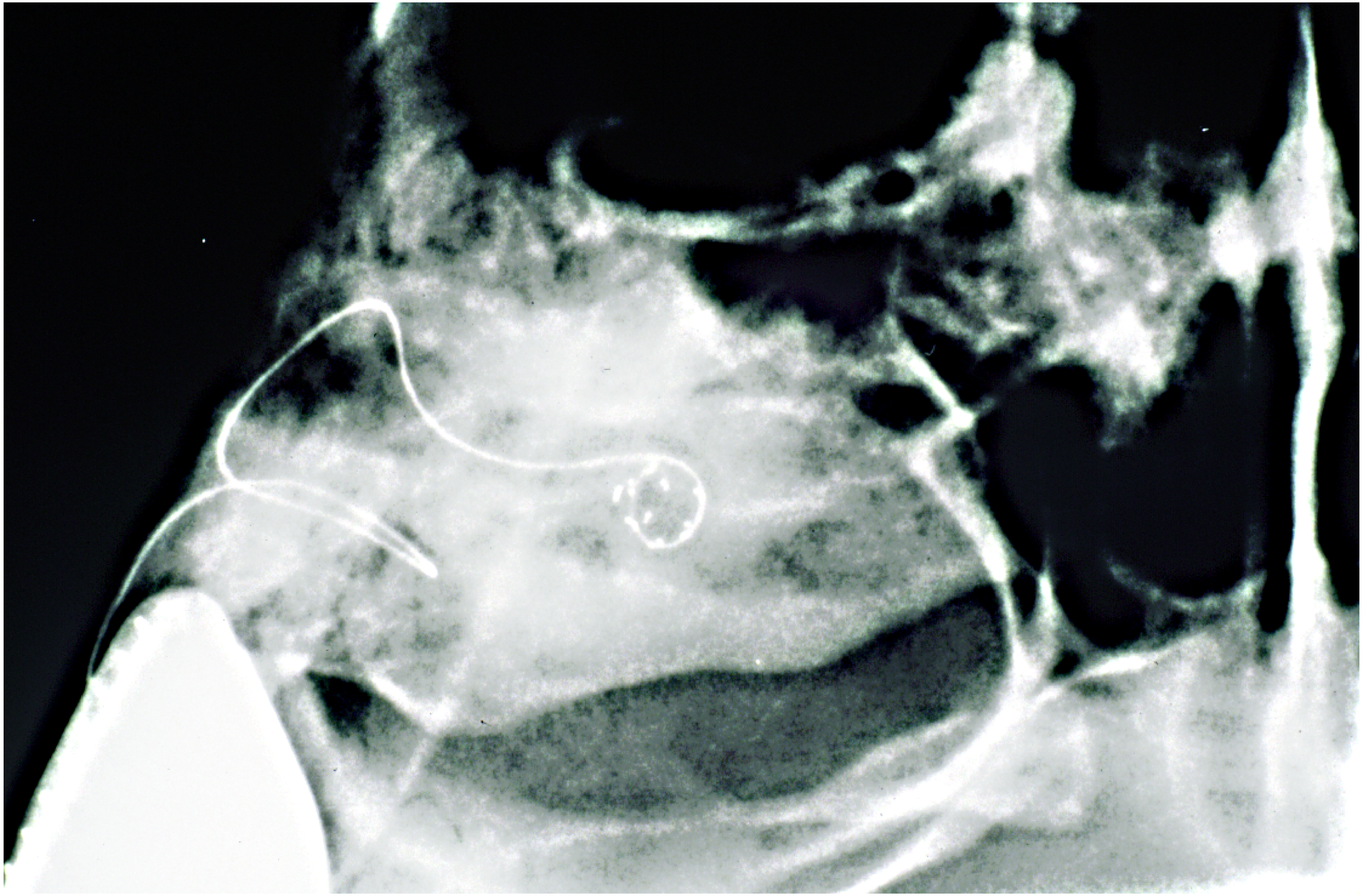


*Implanted radio receiver*

*Electrode inserted in inner ear*

# The electrode array





# What are the *essential* purposes of a speech processor?

- To transduce acoustical signals into an electrical form.
- To process the acoustic signal in various ways (*e.g.*, filter, compress).
- To convert (or code) the resulting electrical signals into a form appropriate for stimulation of the auditory nerve.

# What other functions can and might be implemented in a speech processor?

- Minimising the effects of background noise.
- The possibility of different processing schemes for different situations.
- Enhancing speech features that contribute most to speech intelligibility.

# What should an implant do?

- Mimic the most important functions of the normal ear.
- So what does a normal ear do?
  - transduction
  - frequency analysis
  - amplitude compression
  - preservation of temporal features, bot slow and fast (e.g., through envelope following and phase locking)

# Common elements in speech processing

- A microphone to transduce acoustic signals into electrical ones.
- Amplitude compression to address the very limited dynamic range of electro-cochlear stimulation.
- Use of the ‘place’ principle for multiple electrodes (mapping low to high frequency components onto apical to basal cochlear places).

# But speech processing schemes vary significantly in other ways

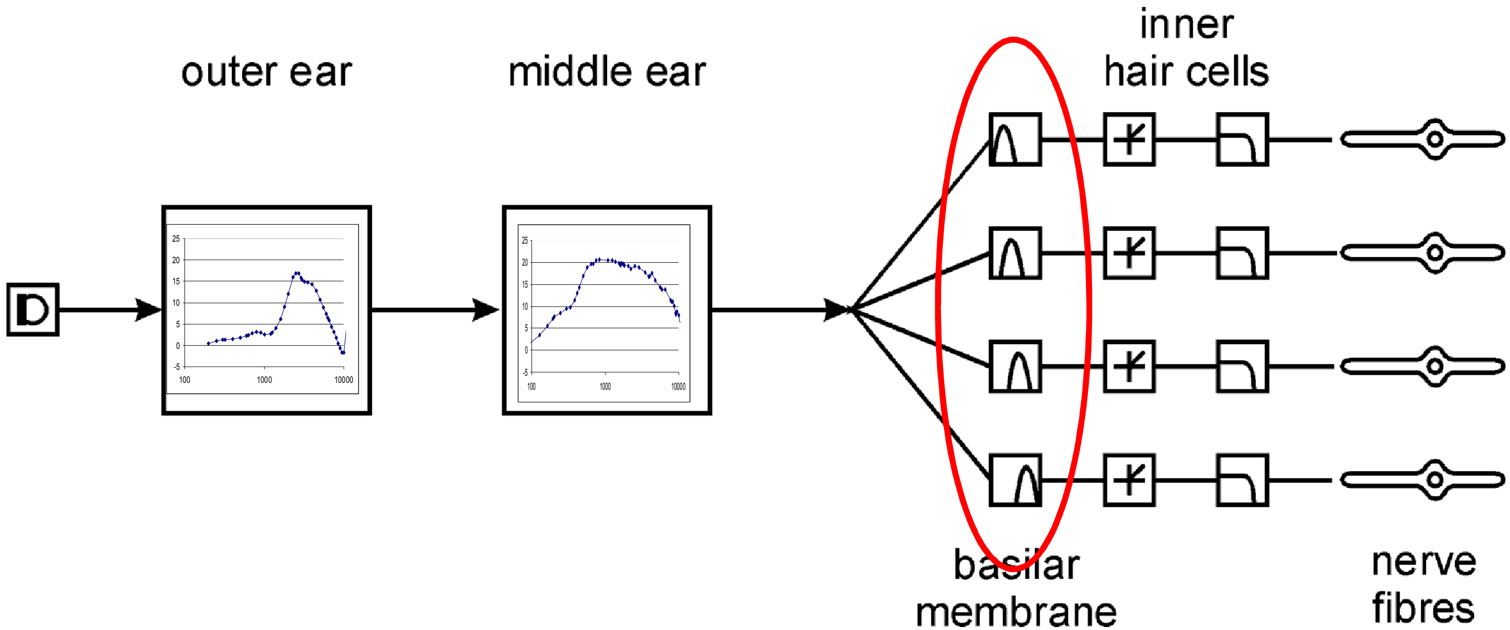
- Pulsatile vs. continuously varying (‘wavey’) stimulation.
  - Not to be confused with analogue vs. digital implementations. All electrical stimulation is analogue.
- Simultaneous vs. non-simultaneous presentation of currents to different electrodes.
  - Non-simultaneous stimulation *requires* pulsatile stimulation

# Multi-channel systems

- All contemporary systems present different waveforms to different electrodes
  – to mimic the frequency analysis of the normal mammalian cochlea.
- Think of the peripheral auditory system as analogous to a *filter bank*.

# The filter bank analogy

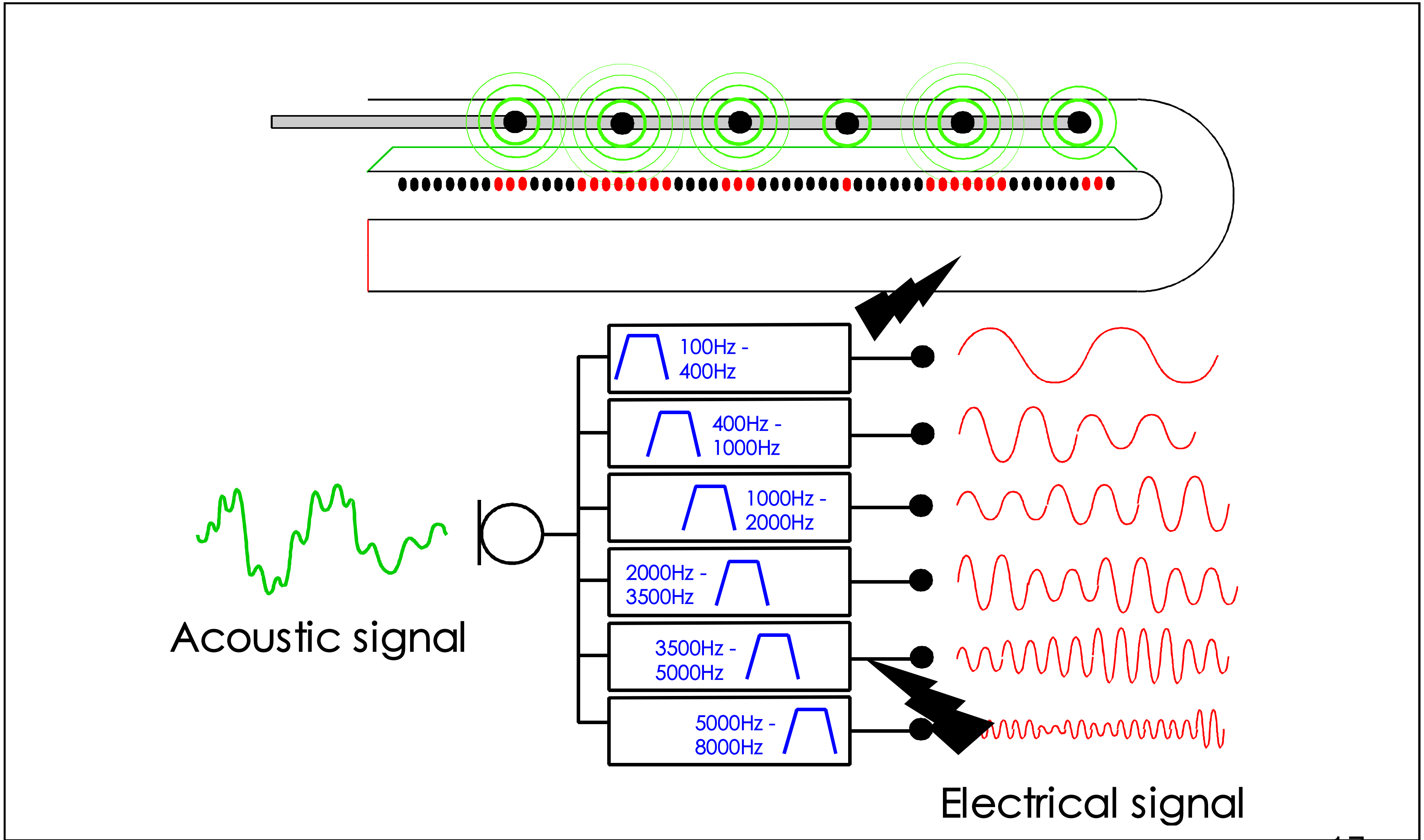
- Imagine each afferent auditory nerve fibre has a bandpass filter attached to its input
  - centre frequencies decreasing from base to apex



# The no-brainer cochlear implant speech processing strategy …

- Use an electronic filter bank to substitute for the auditory filter bank (the mechanics of the basilar membrane).

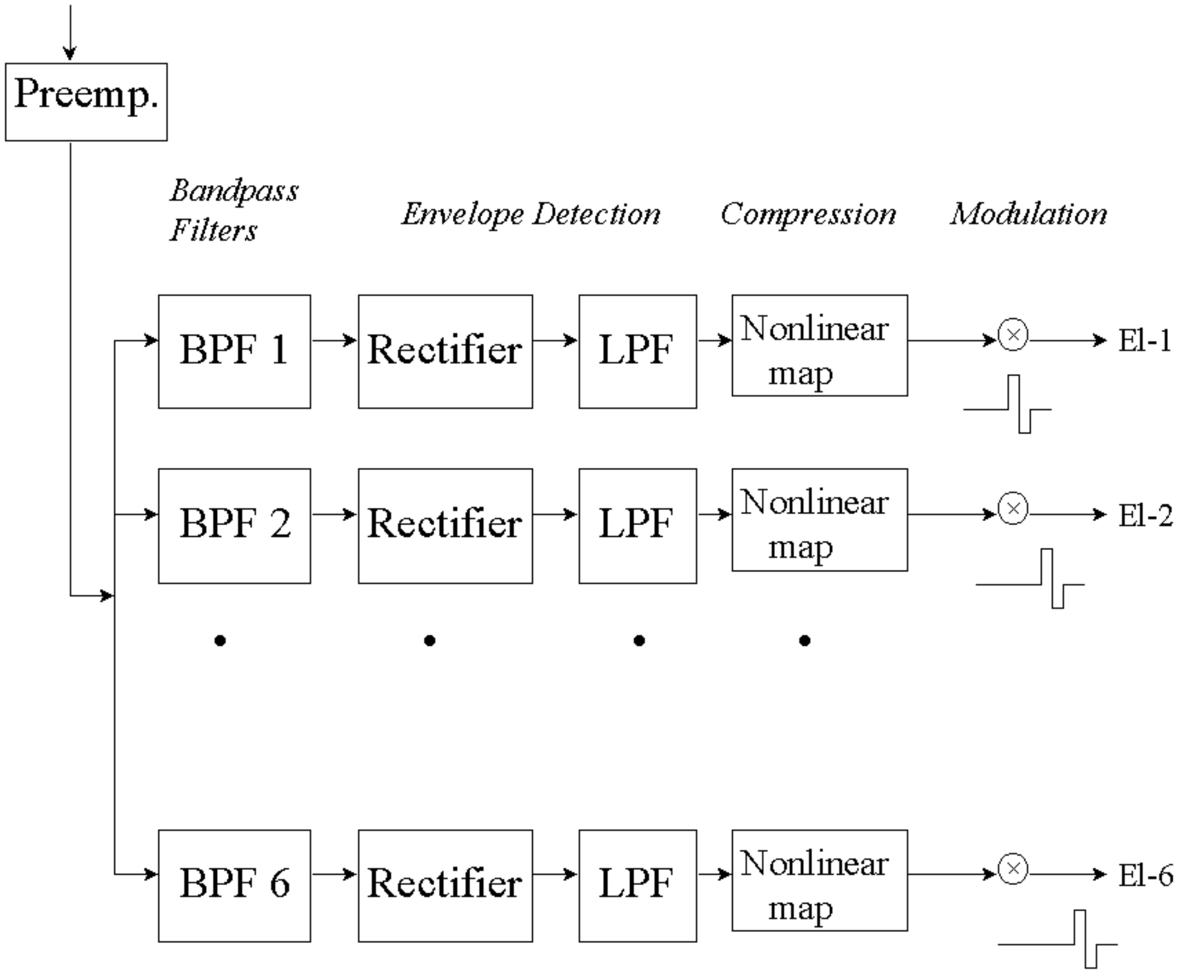
# A simple speech processing scheme for a cochlear implant: Compressed Analogue (CA)



# The most common current method: Continuous Interleaved Sampling (CIS)

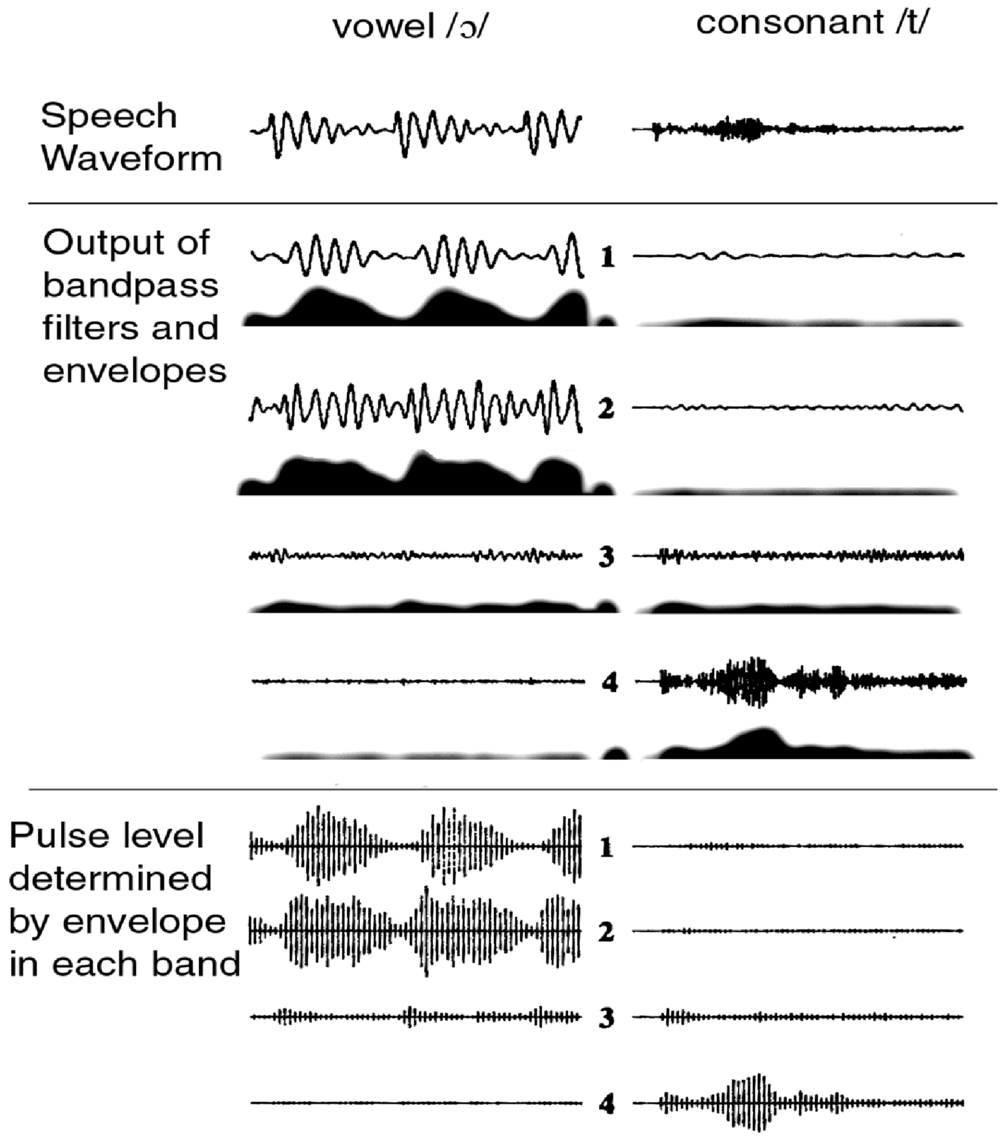
- Use  a filter bank approach to represent spectral shape …
- with non-simultaneous pulatile stimulation to minimise electrode interactions
- with pulse amplitudes modulated by the *envelope* of the bandpass filter outputs.

# Continuous Interleaved Sampling




from Philipos Louizou: http://www.utdallas.edu/~loizou/cimplants/tutorial/

# Continuous Interleaved Sampling




0.5

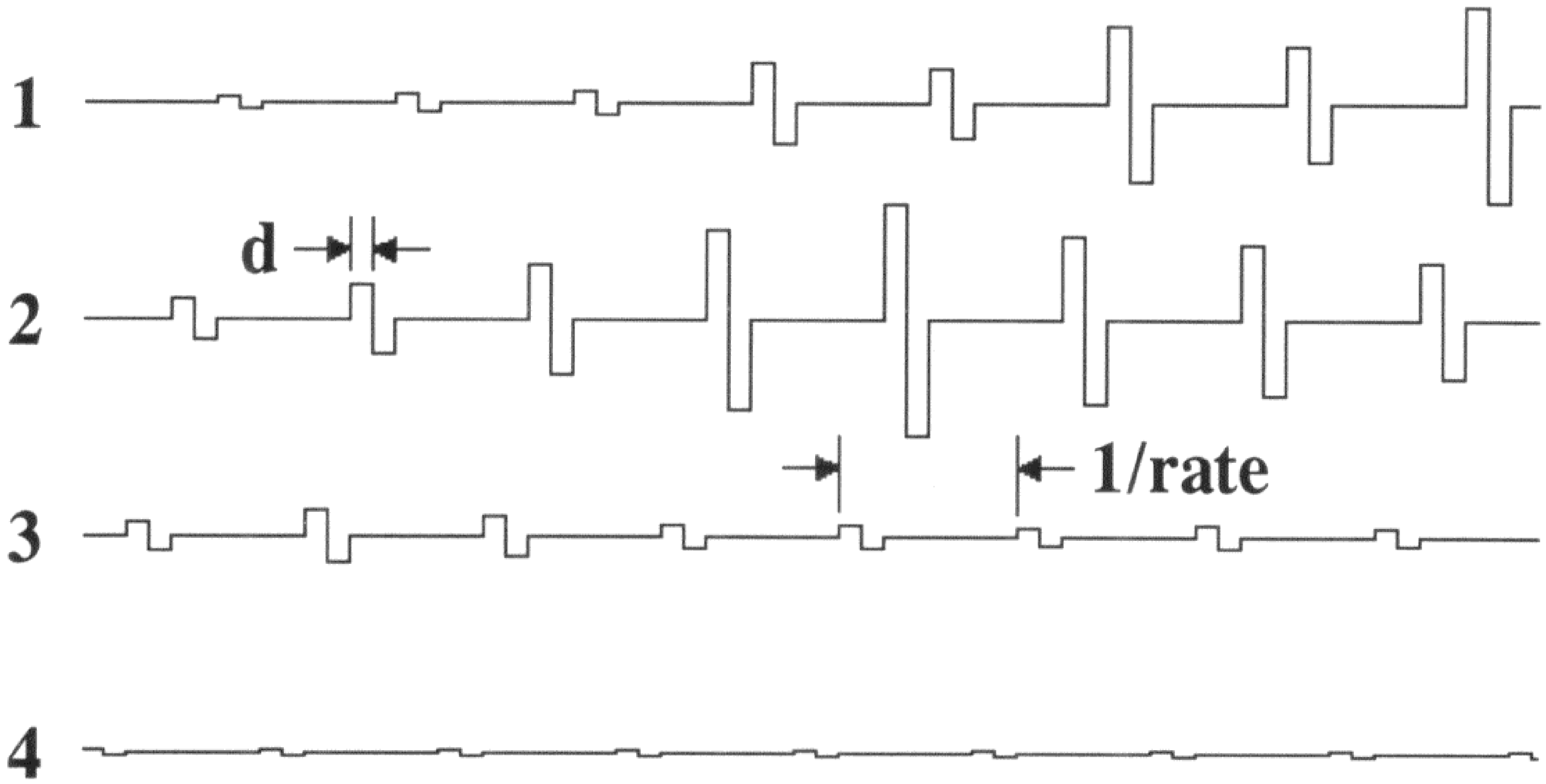
1

2

4

kHz

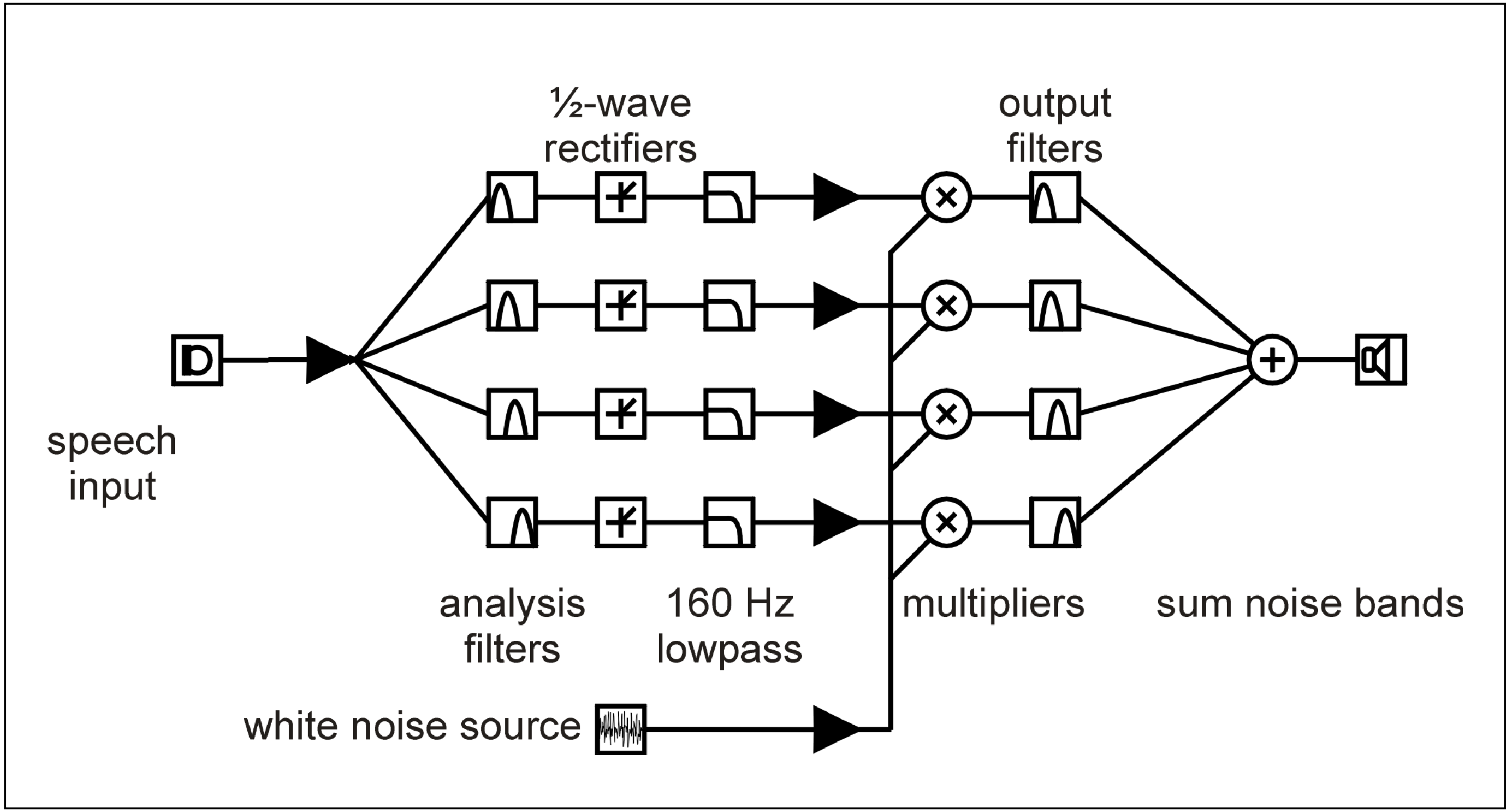
# CIS in detail



# Simulations can give us some idea of what an implant user might experience
# But …*caveat perceptor*!

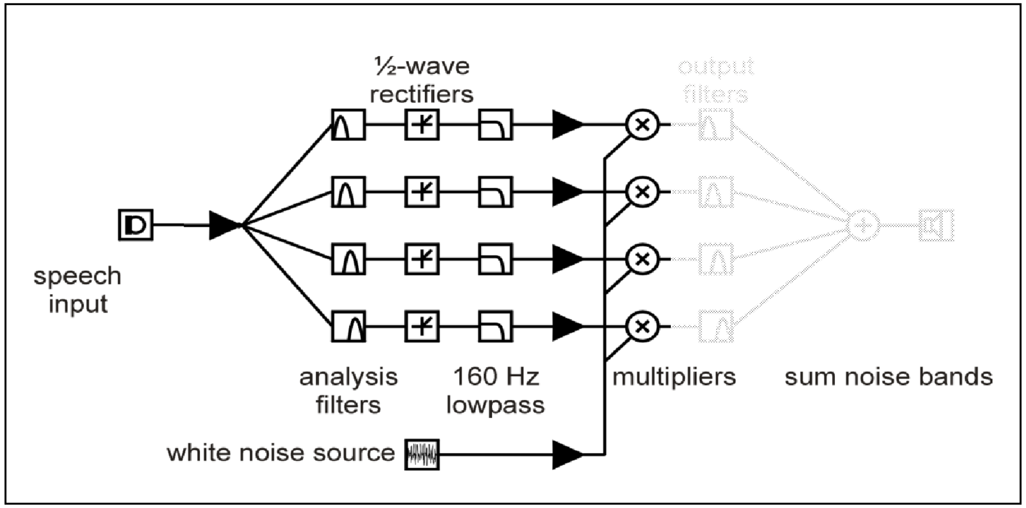
- These are not exactly what an implant sounds like …
- but you can get some idea about the kind of information that gets through.

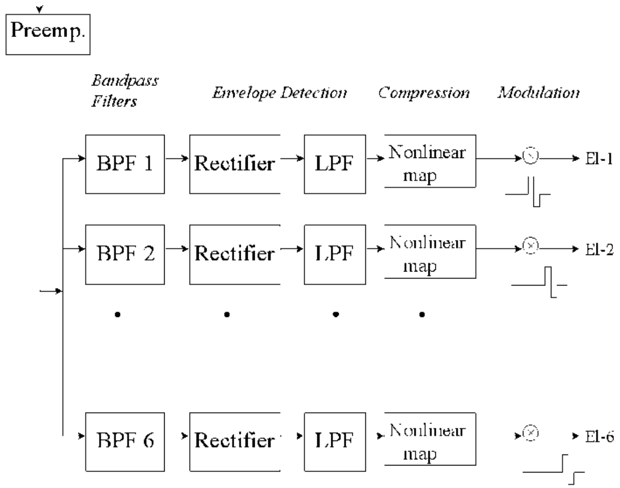
# Noise-excited Vocoding

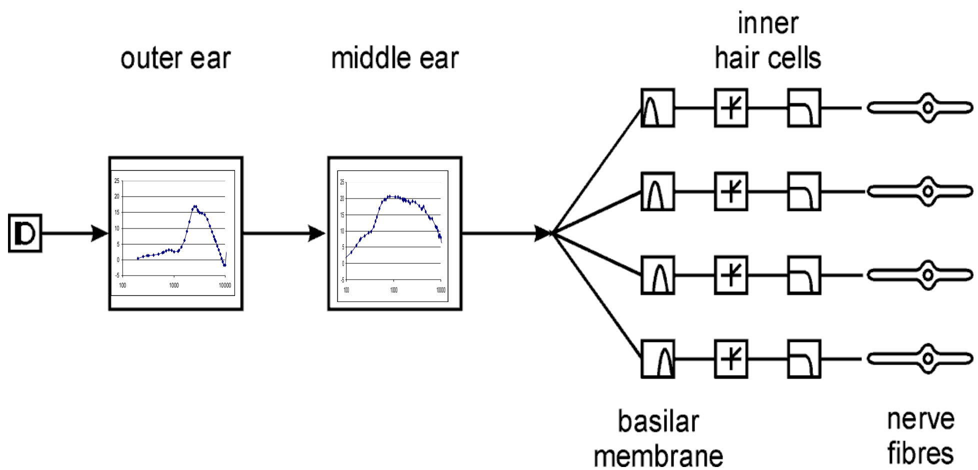



Note important variants in rectification, lowpass filter cutoffs, etc.

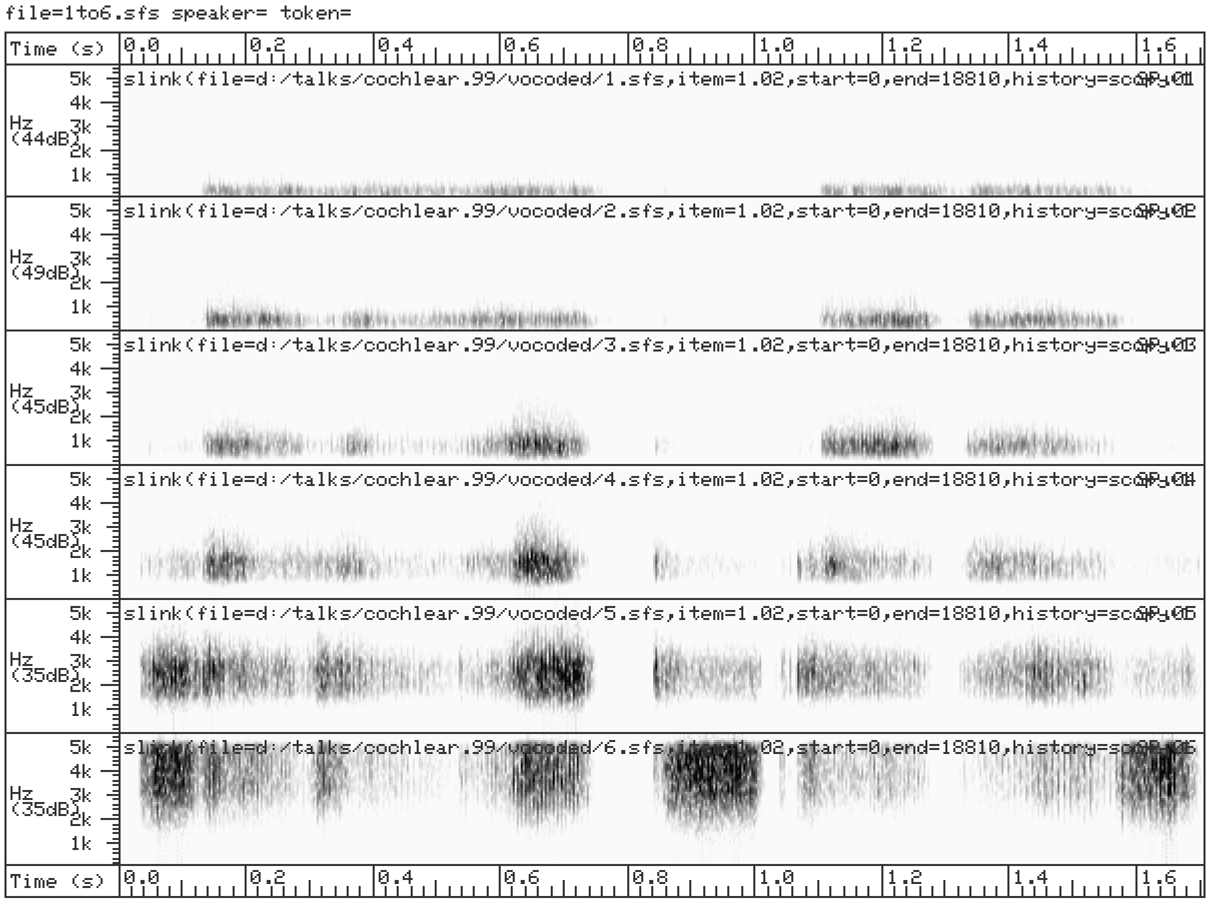
# Note similarity to CIS (and normal cochlear) processing



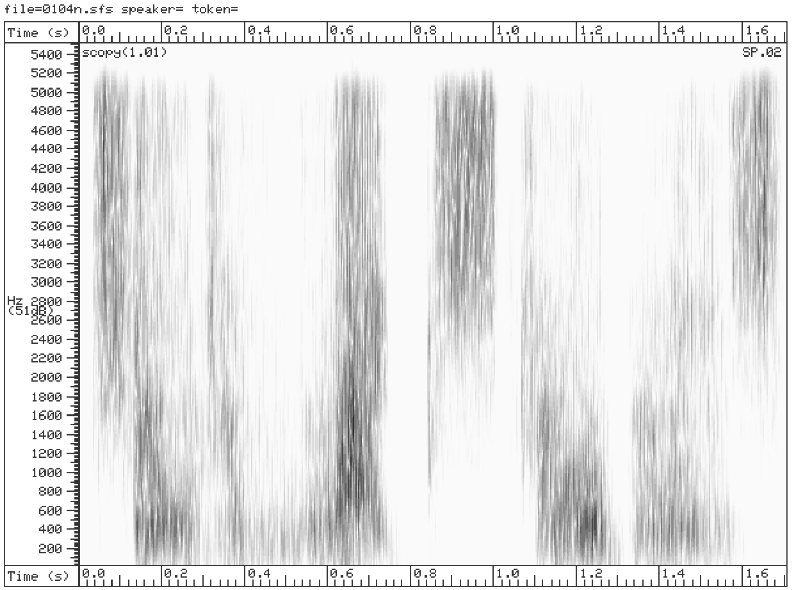



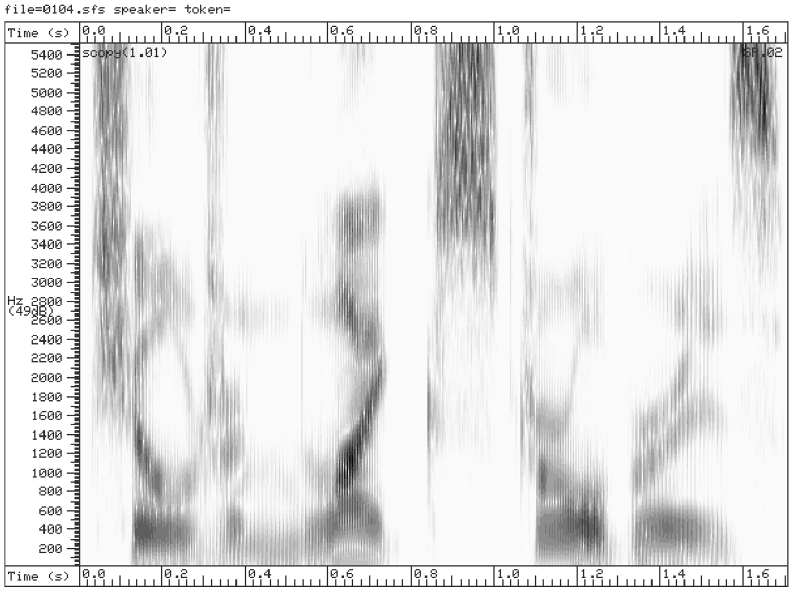
# Separate channels in a 6-channel simulation



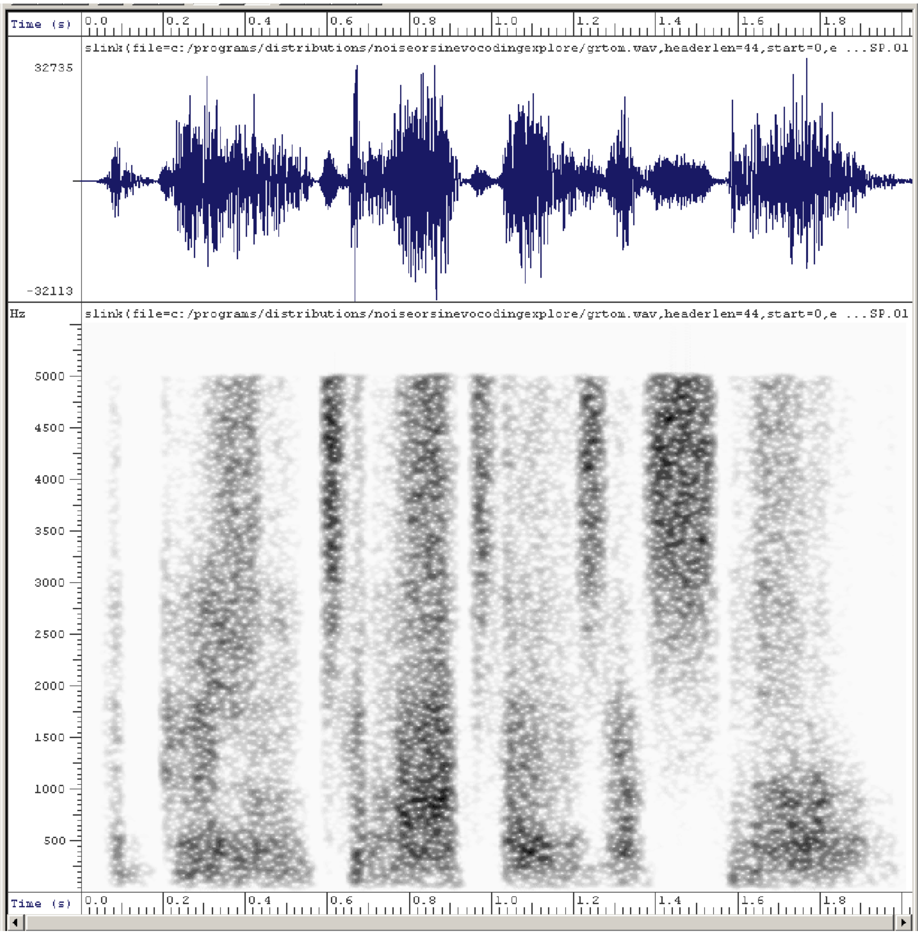
# ... and when summed together.

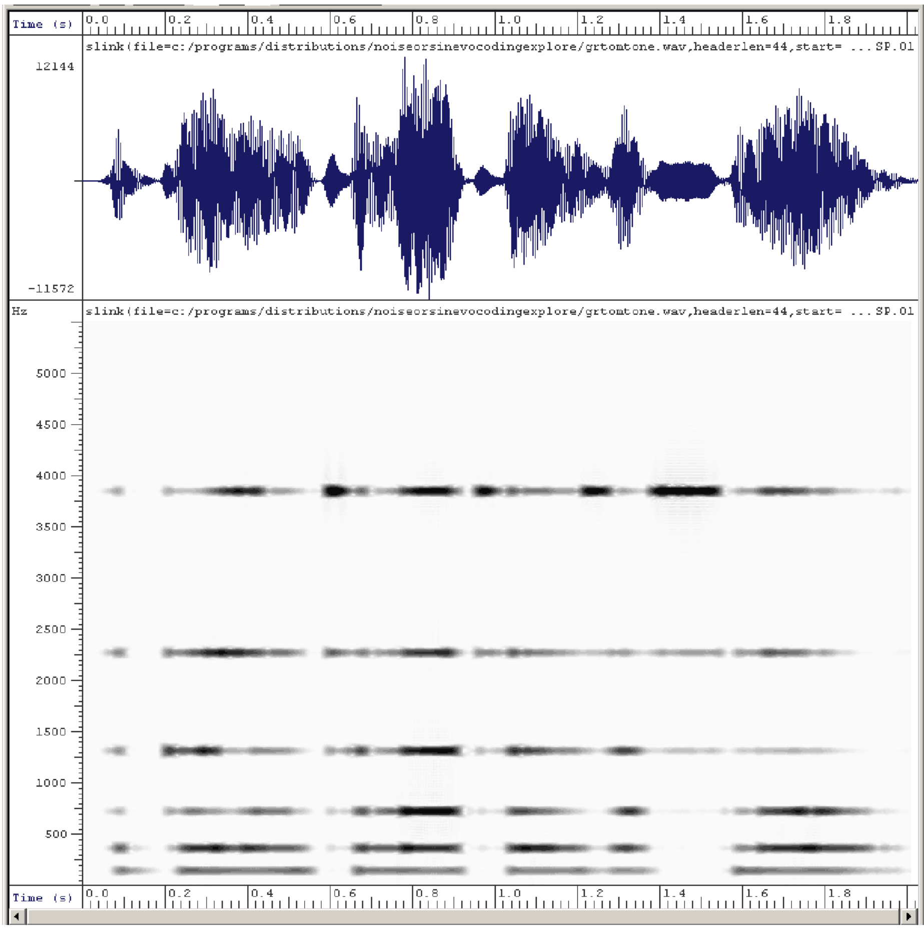
Children like strawberries.



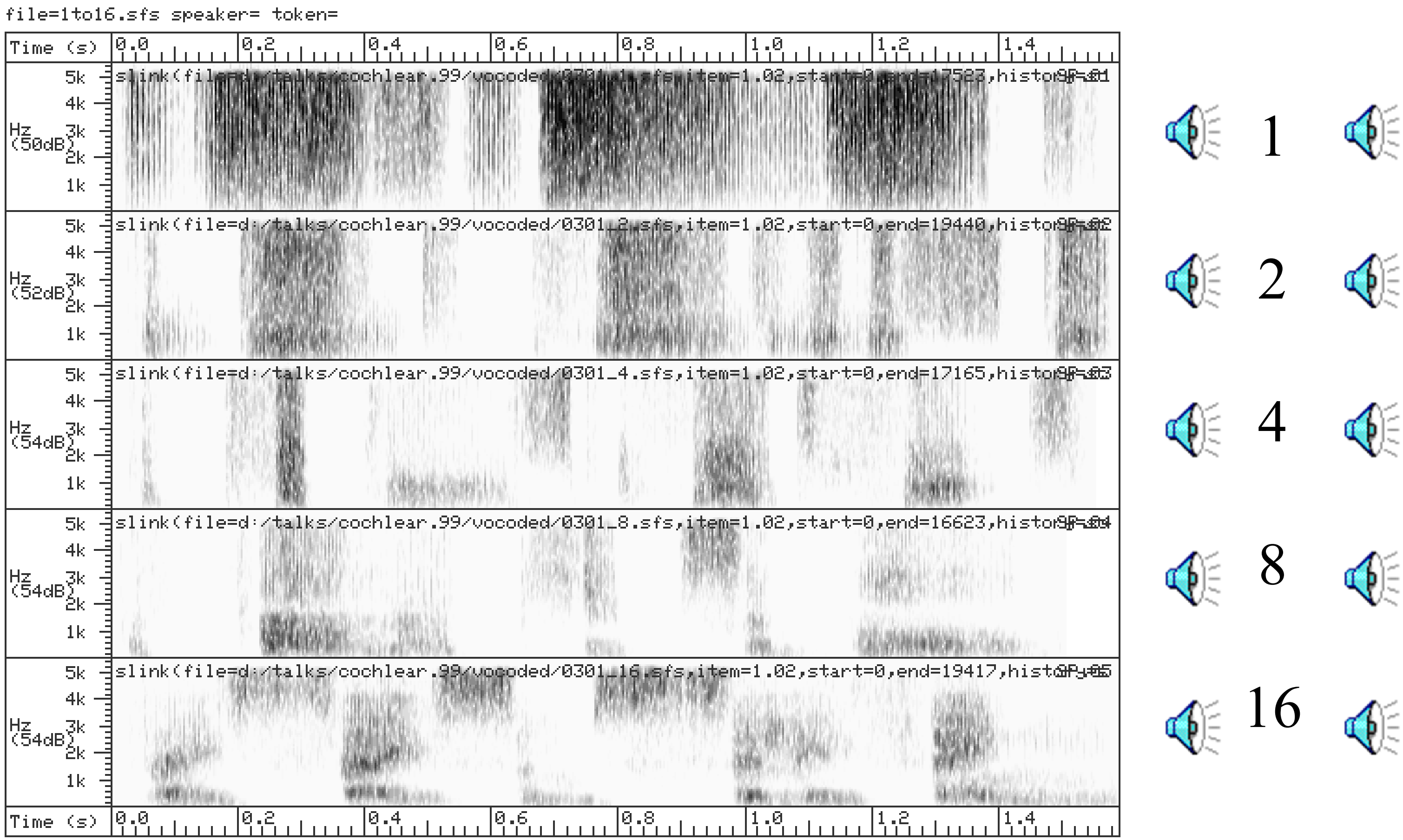



# Never mind the quality...
# feel the intelligibility.



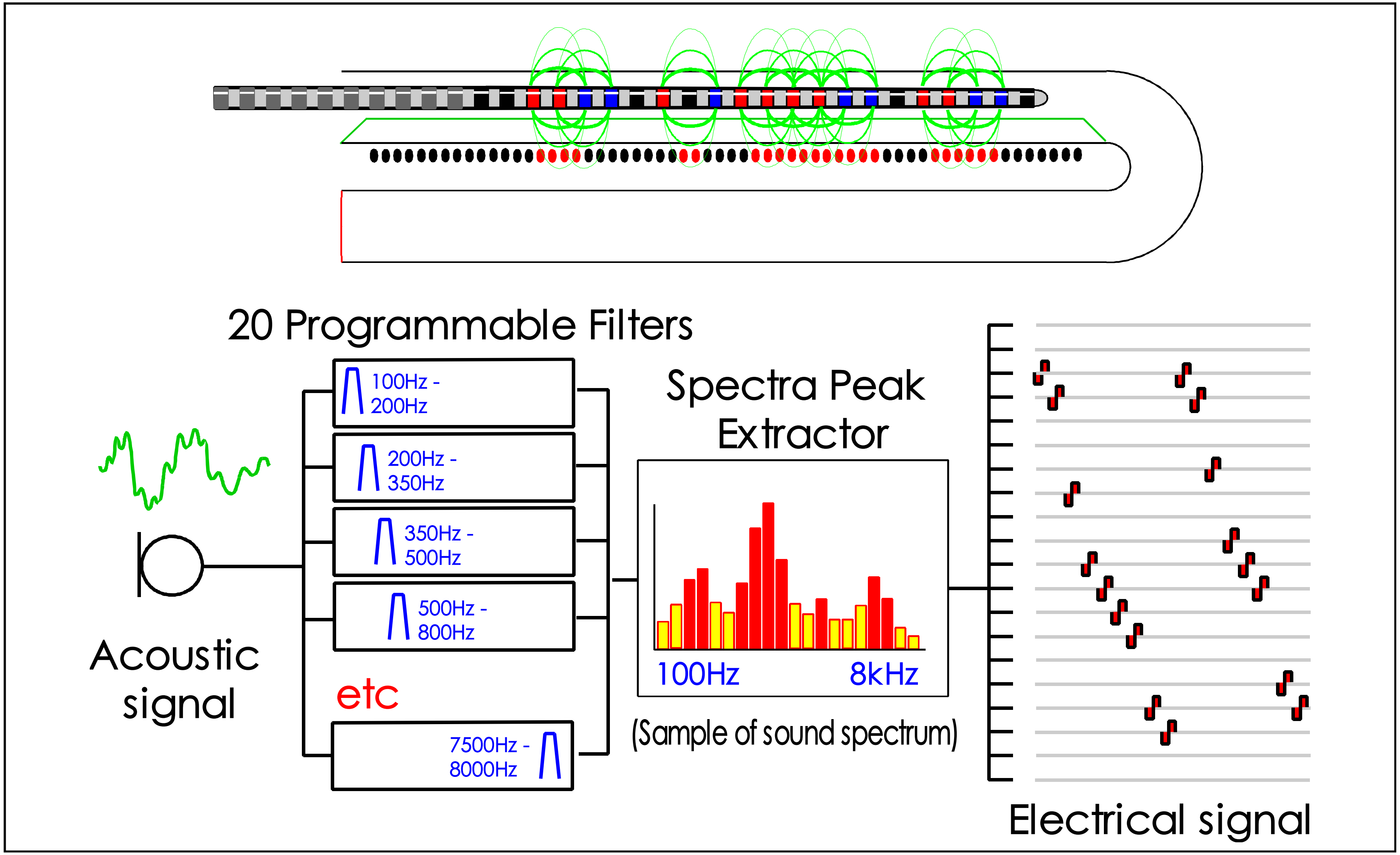
# Effects of channel number



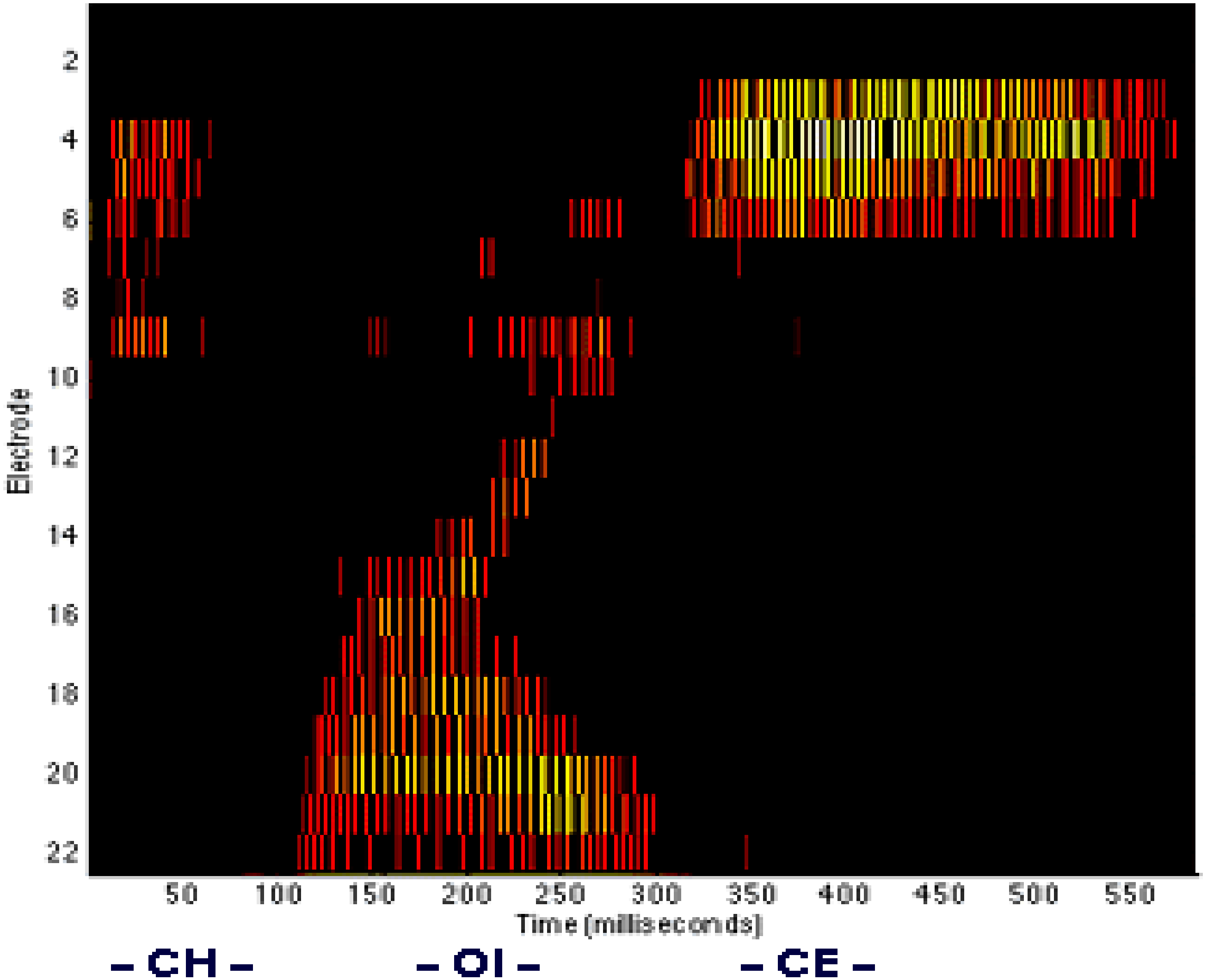
# Other schemes: Necessity is the mother of invention

- The problem (historically)
  - How could devices running at relatively slow rates be used for CIS, which required high rates of pulsatile stimulation?
- The solution
  - Pick and present pulses only at the significant peaks in the spectrum.

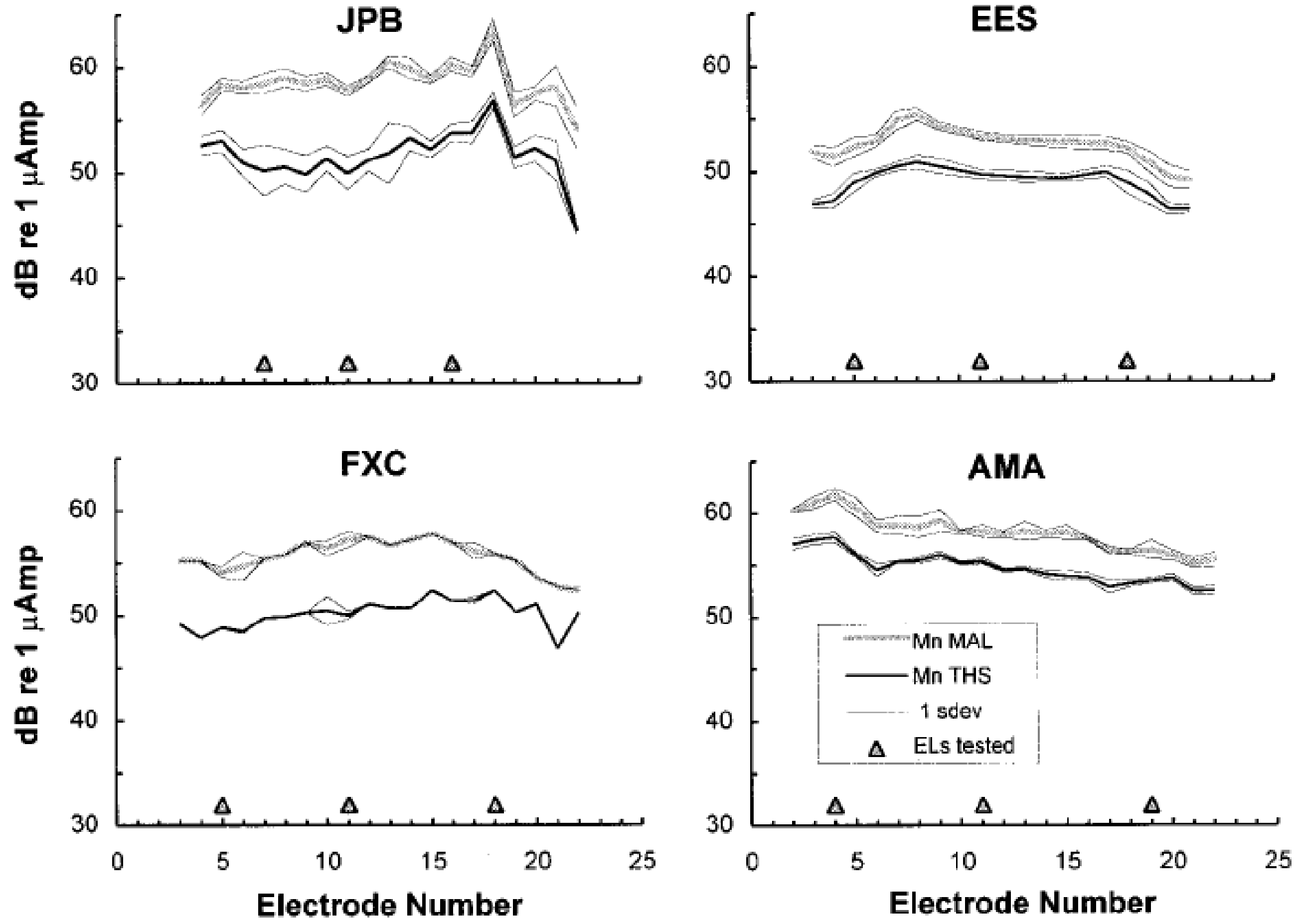
# Spectral Peak Strategy – SPEAK
# (n of m strategies)



# SPEAK stimulation pattern



# Restricted dynamic range means compression is crucial




Absolute thresholds and maximum acceptable loudness levels
Nelson *et al.* (1996) JASA

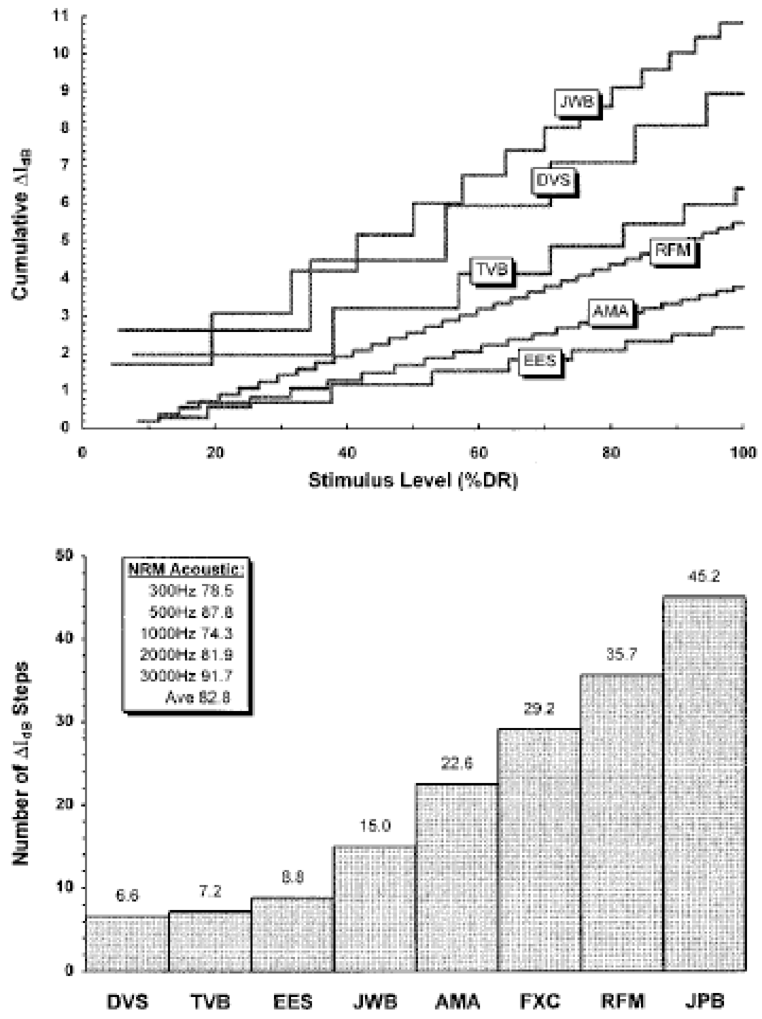



FIG. 9. Cumulative discriminable intensity steps across dynamic range and the number of discriminable intensity steps per subject. *Upper panel*: Cumulative $\Delta I_{dB}$ $\{10\log(I+\Delta I)-10\log(I)\}$ as a function of stimulus level in percent dynamic range (%DR in dB), which were calculated from the composite Weber functions in Fig. 6. Curves for JPB and FXC were not plotted because they overlapped with the curve for RFM. *Lower panel*: The total number of discriminable intensity steps across dynamic range is given for each of the eight subjects. The total number of discriminable intensity steps for normal acoustic hearing, calculated from Weber fractions reported by Schroder *et al.* (1994), are shown for each of five frequencies within the inset.

Intensity jnds in electrical (opposed to acoustic) stimulation:

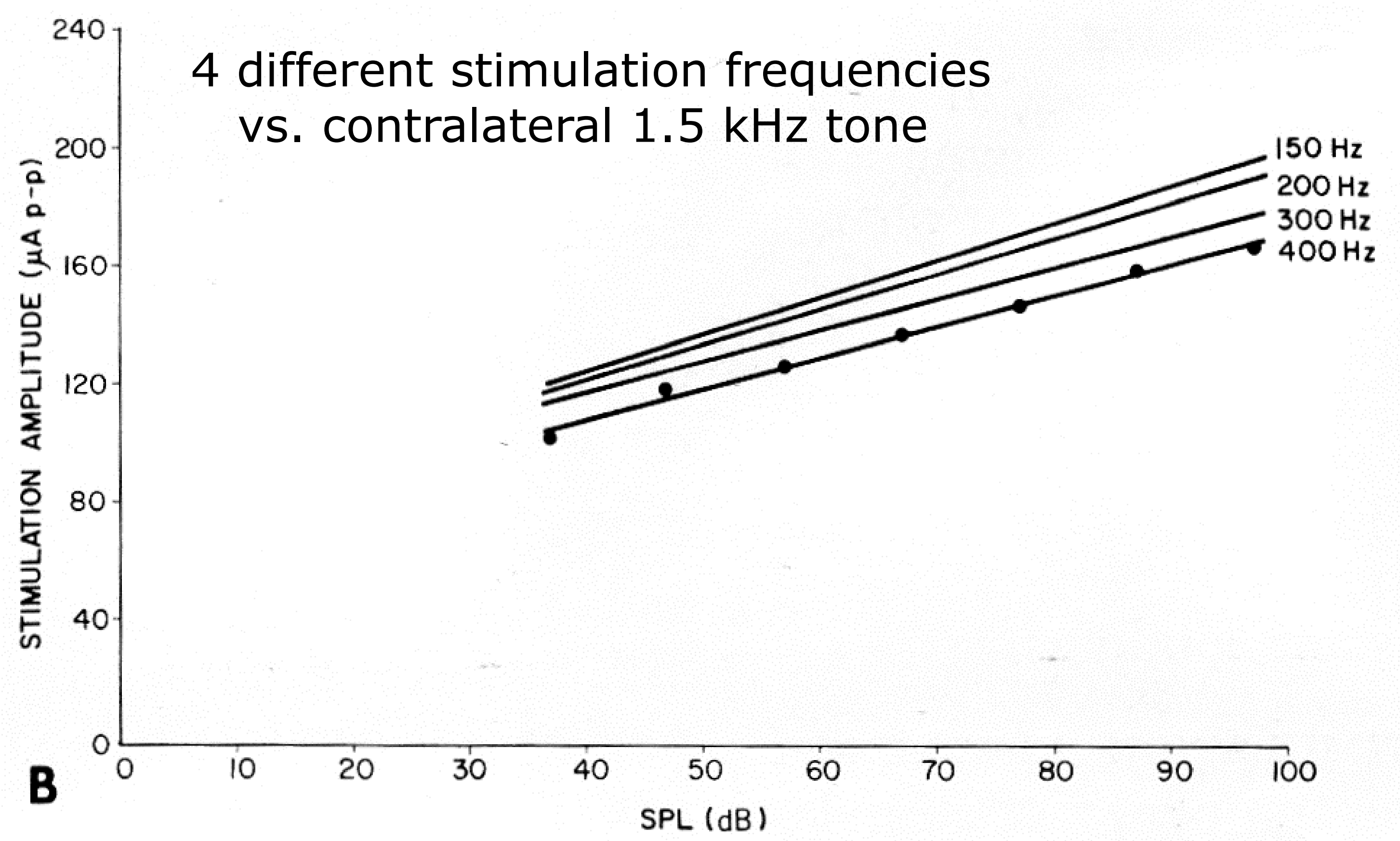
1) ‘miss’ Weber’s Law more

2) are typically smaller, but not by enough to offset reduced dynamic range.

CI users here had 7-45 discriminable steps in the total dynamic range, compared to ≈ 83 in normal hearing

Nelson *et al.* (1996) JASA

# Acoustic/electrical loudness matches




Eddington *et al.* 1978 Ann Otol Rhinol Laryngol

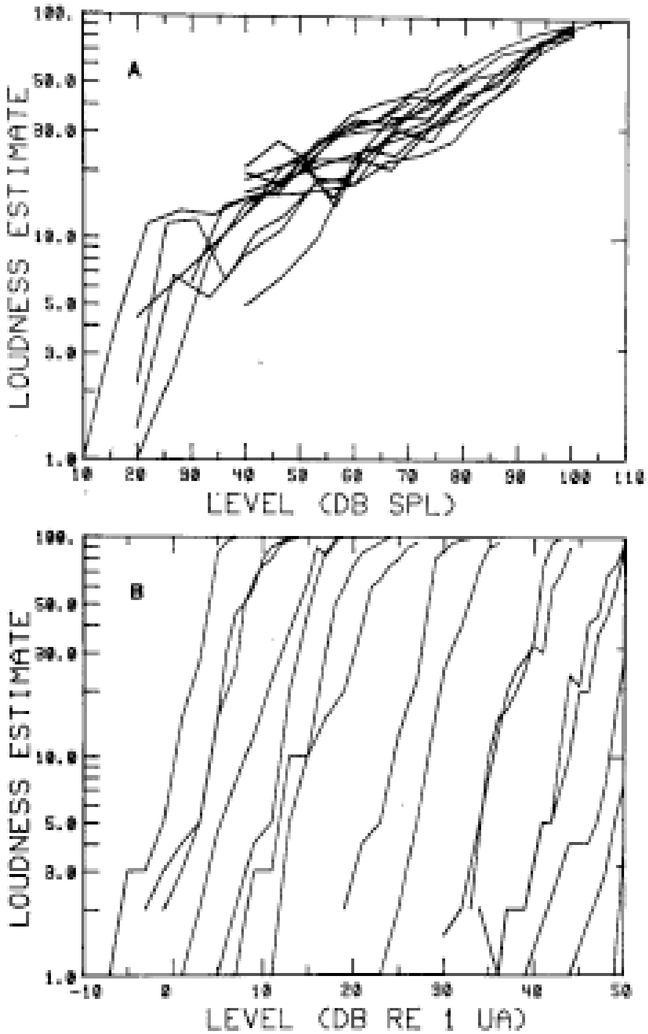
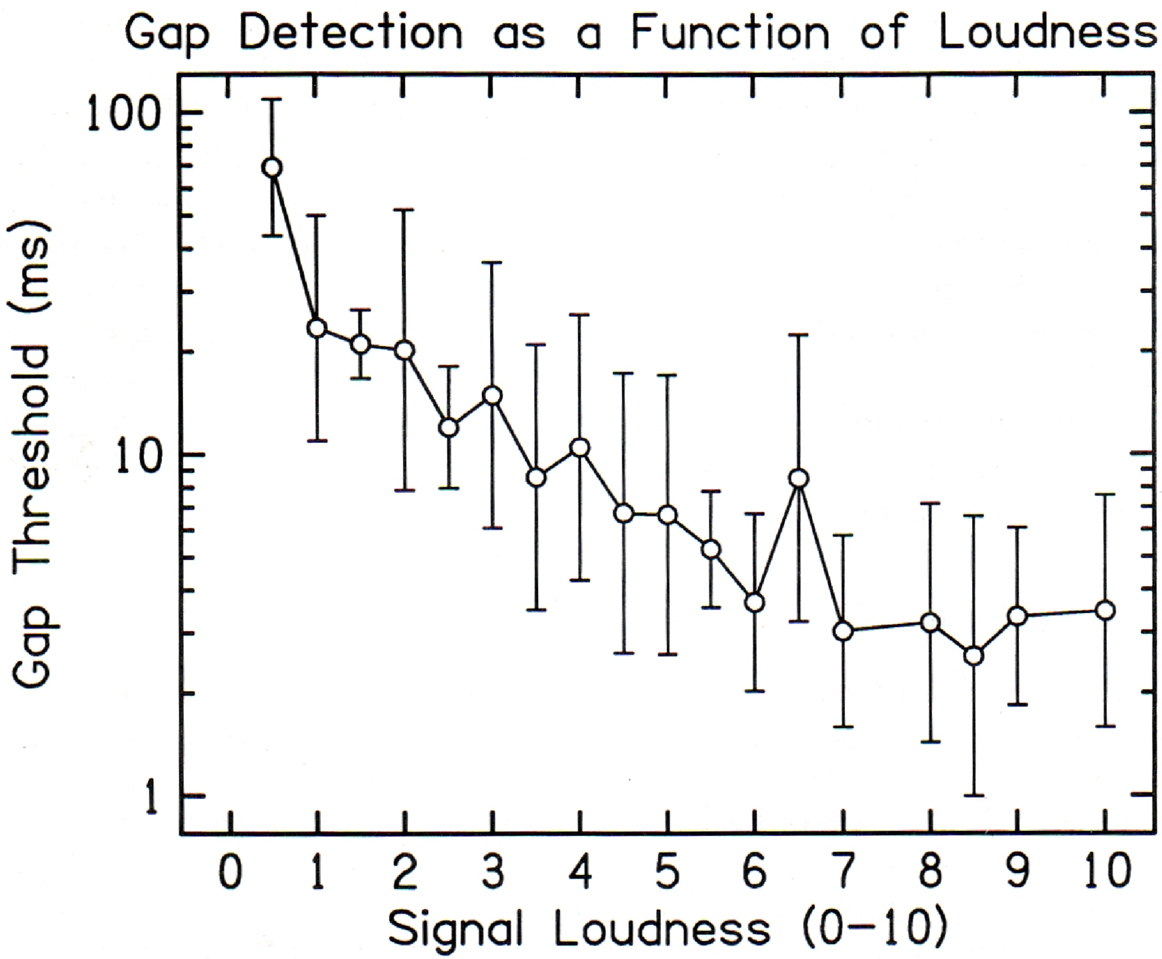



Fig. 3. Comparison of loudness vs. stimulus intensity curves for loudness estimates from normals (A) and implant subjects (B). The loudness estimation data for the four normal hearing subjects was all collected at 1000 Hz. The exponent of the power function was inversely related to the dynamic range for electrical stimulation. Examples shown are for 100 Hz, where the dynamic range was 30 dB, and for 1000 Hz, where the dynamic range was only 18 dB.

Loudness grows much faster in electrical stimulation (hyper-recruitment!)

# Temporal resolution: gap detection




Shannon 1993

# Temporal resolution: modulation detection (100 Hz)

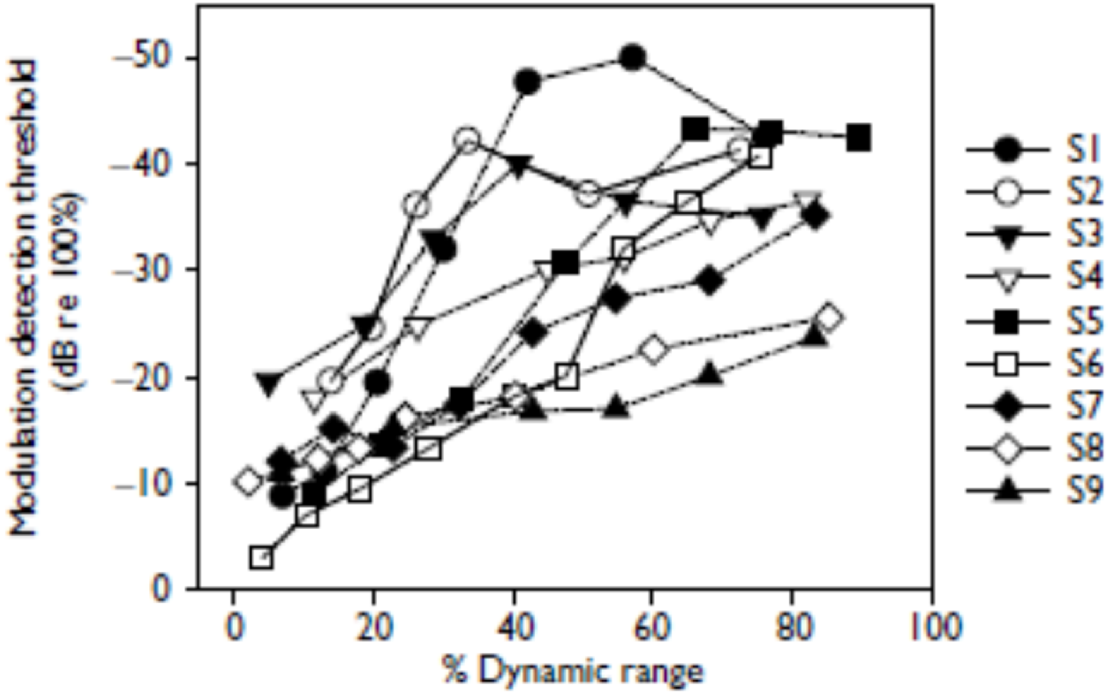
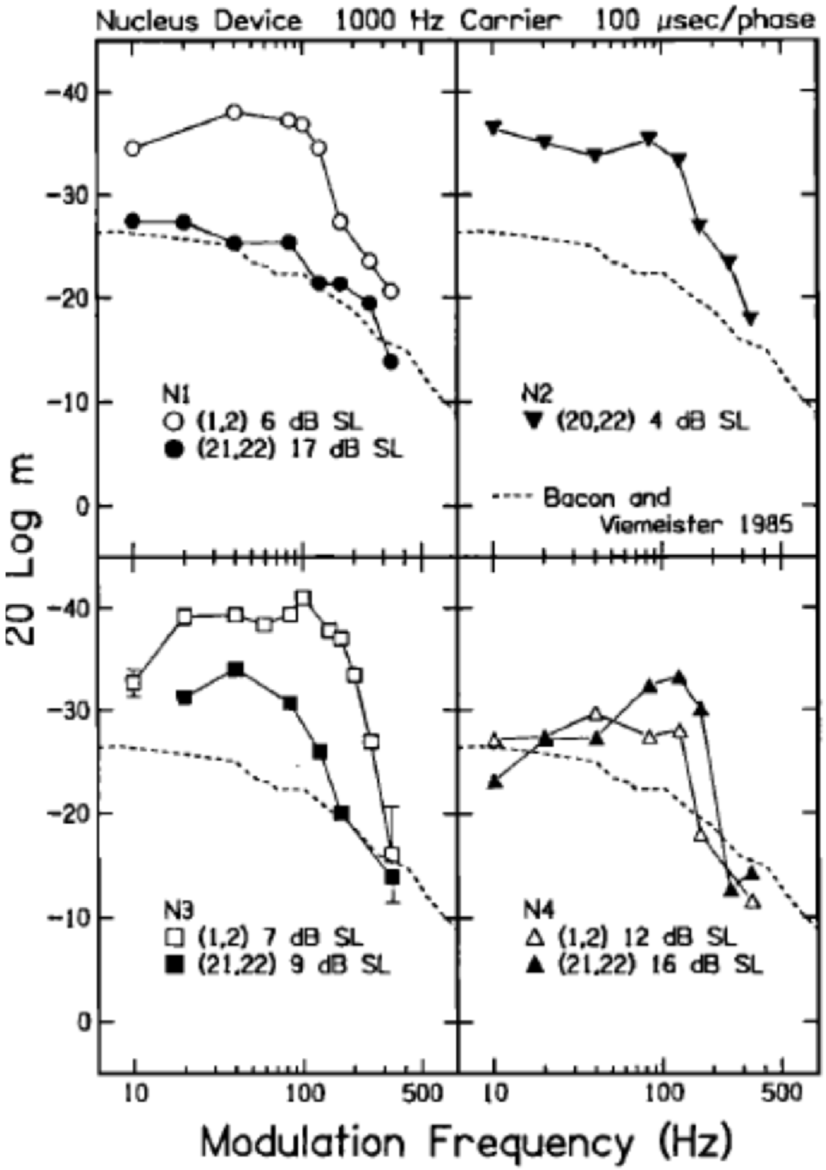



**Fig. 1.** Modulation detection thresholds as a function of the percentage of subjects' electric dynamic range

More dependent on level (as for intensity jnd's)

Fu 2002 NeuroReport




# Temporal resolution: TMTFs

More dependent on level

Otherwise similar to normal listeners (dashed lines)

Shannon 1992 J Acoust Soc Amer

# Relationships to performance with speech

modulation detection thresholds measured at 100 Hz, at a number of levels (previous slide)

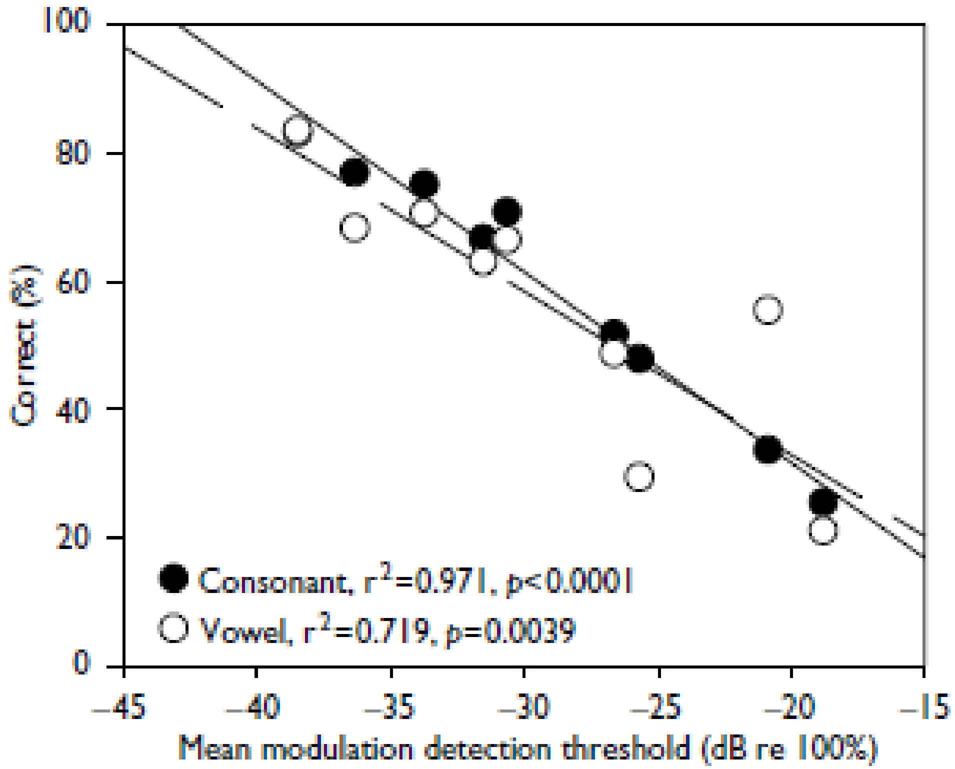


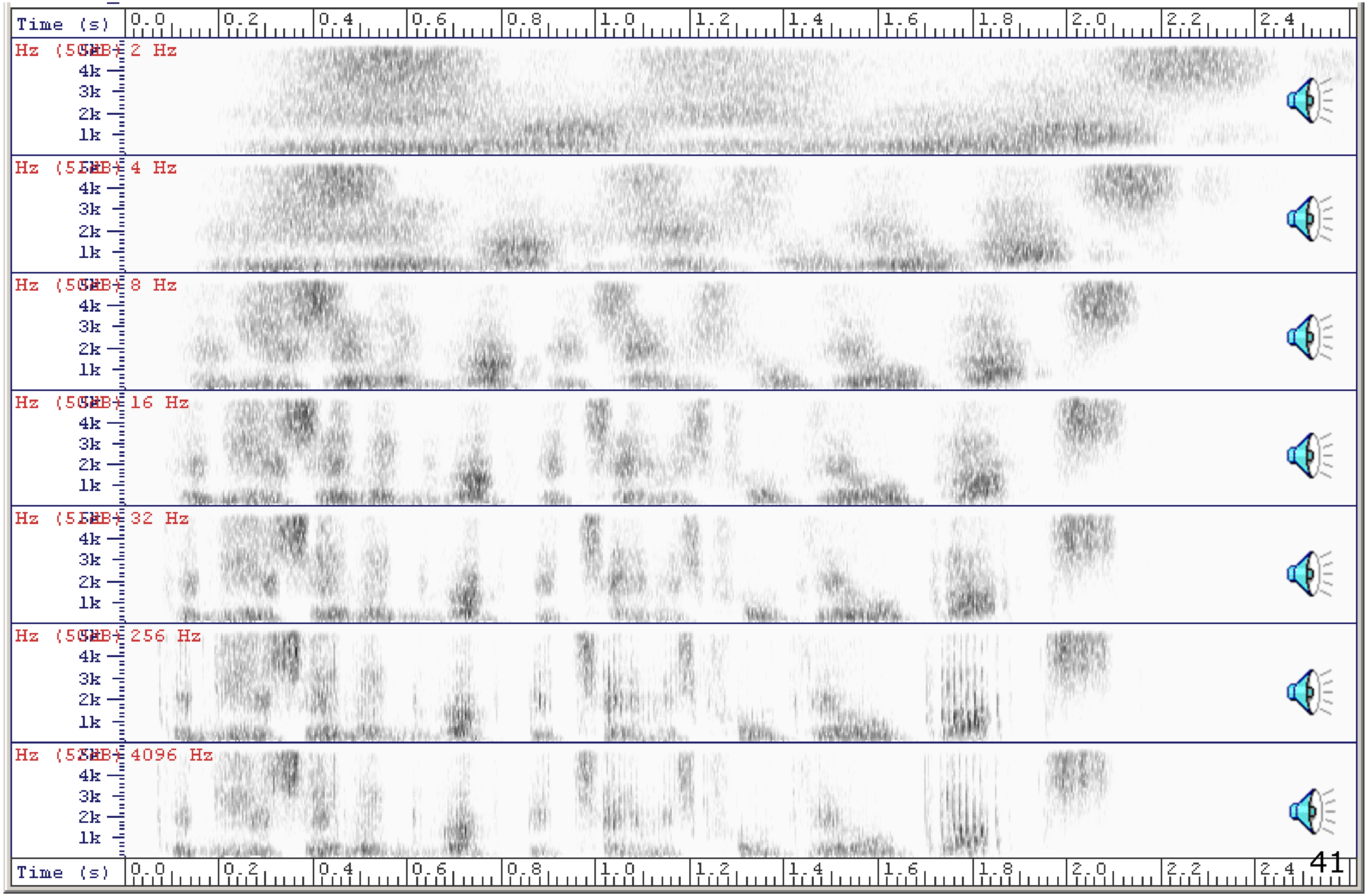

**Fig. 2.** Correlation between phoneme identification (percent correct) and subjects' mean modulation detection thresholds (calculated across each subject's entire dynamic range). Consonant scores and linear regression are shown by the filled circles and solid line. Vowel scores and linear regression are shown by the open circles and dashed line.

Fu 2002 NeuroReport

# Perceiving variations in amount of activity across electrodes

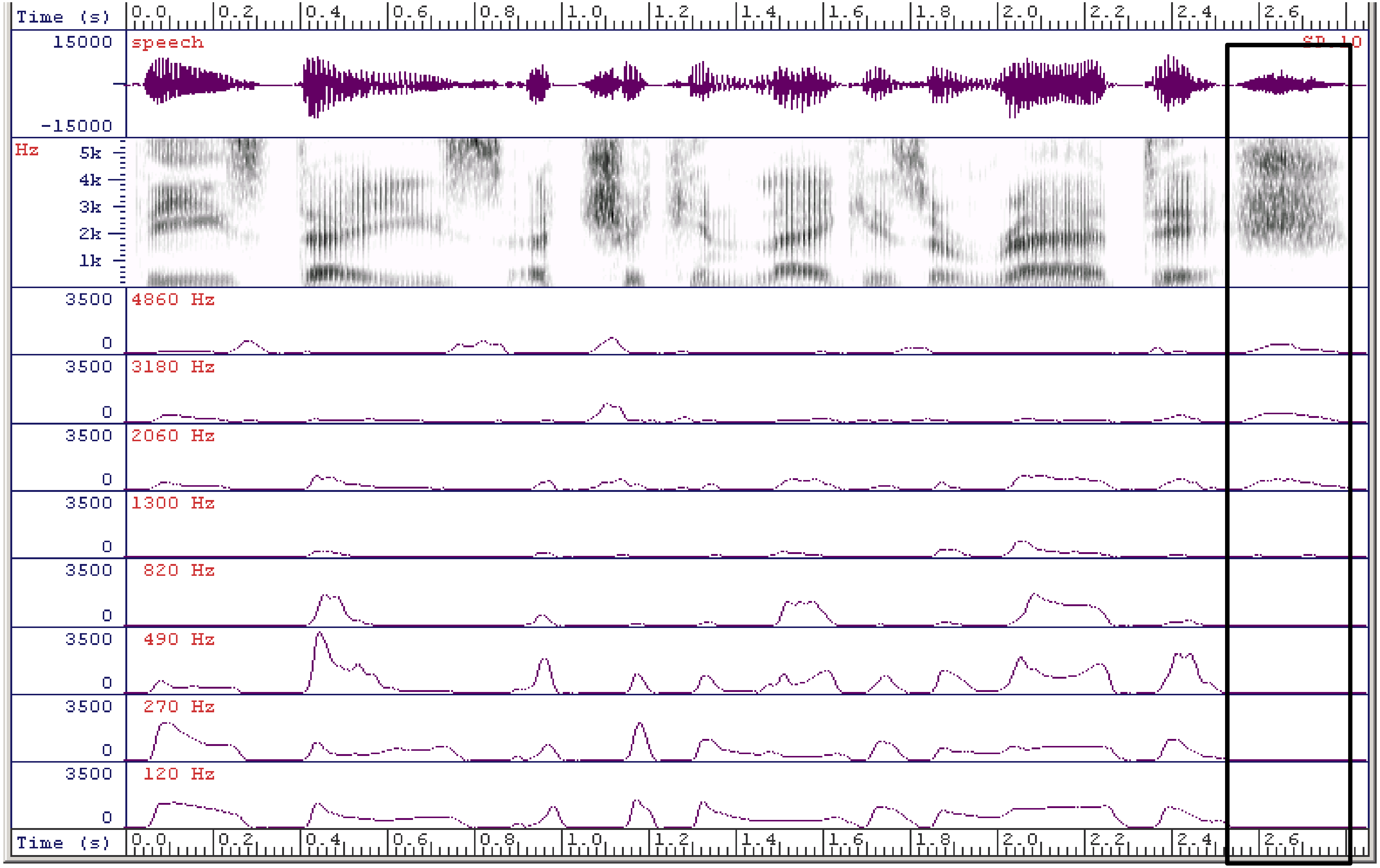
- Essential for signaling of …
  - spectral shape
- Spectral shape is encoded by relatively slow level changes across electrodes
- Striking fact
  - preservation of fast modulation rates not necessary for intelligibility in noise-vocoded speech

# Restricting modulation rates allowable in noise-excited vocoding

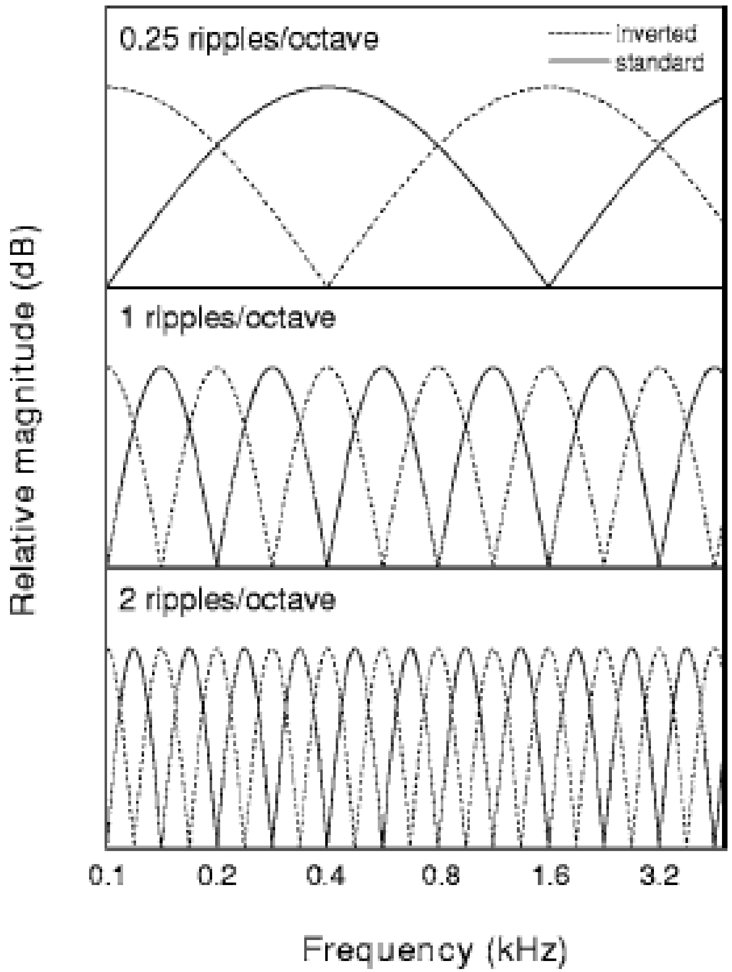


# Slow level changes across channels

**Th-ee-z d- ay - s a ch-i-ck - en-l-e-g is a r-a- re d -i - sh**



# Discrimination of rippled noise




find the maximum ripple density at which it is possible to discriminate ‘standard’ ripple noise from its inverted version

‘This test is hypothesized to provide a direct measure of the ability of listeners to perceive the frequency locations of spectral peaks in a broadband acoustic signal.’

Henry *et al.* 2005 J Acoust Soc Am

# Discrimination of rippled noise

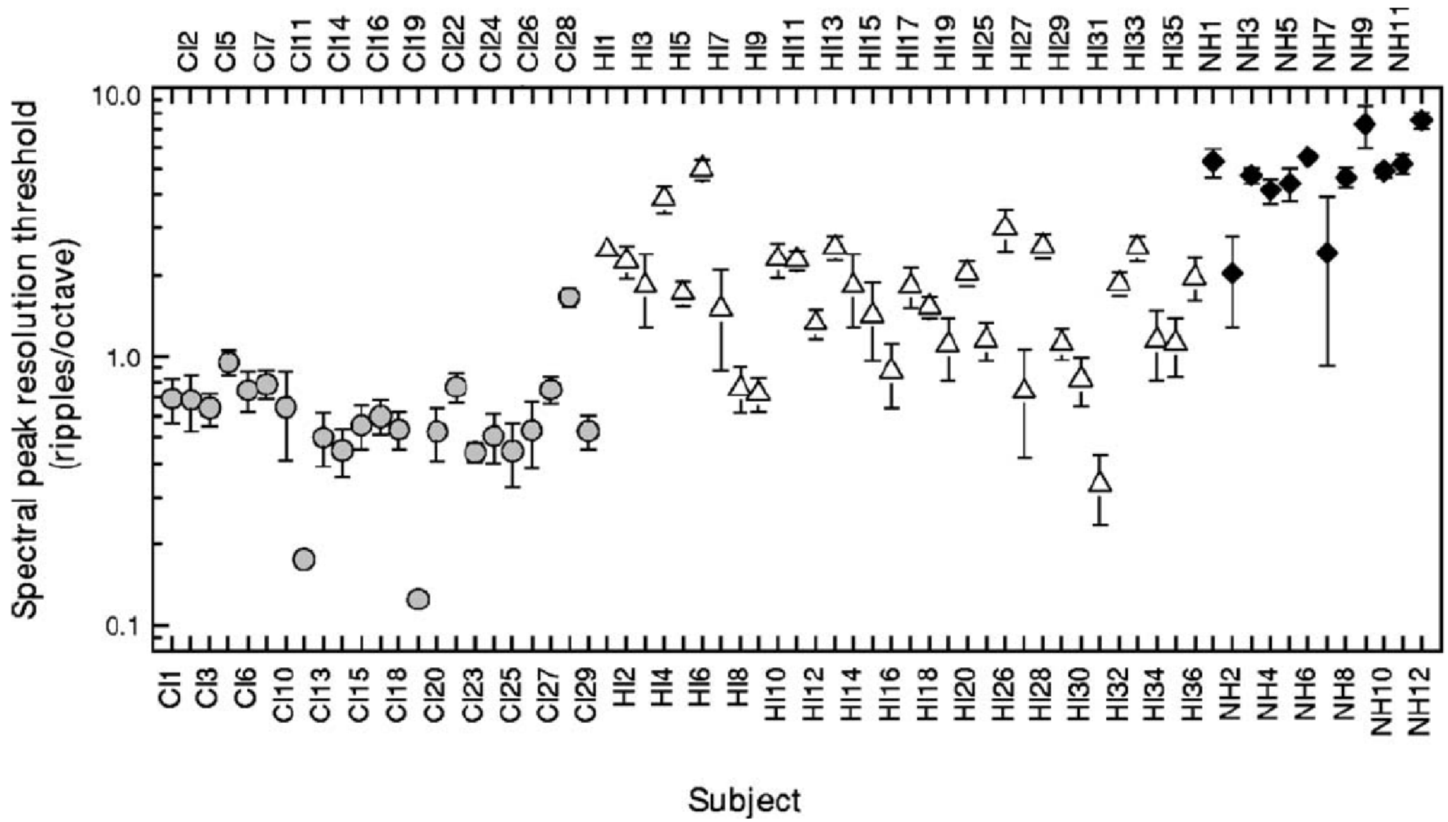
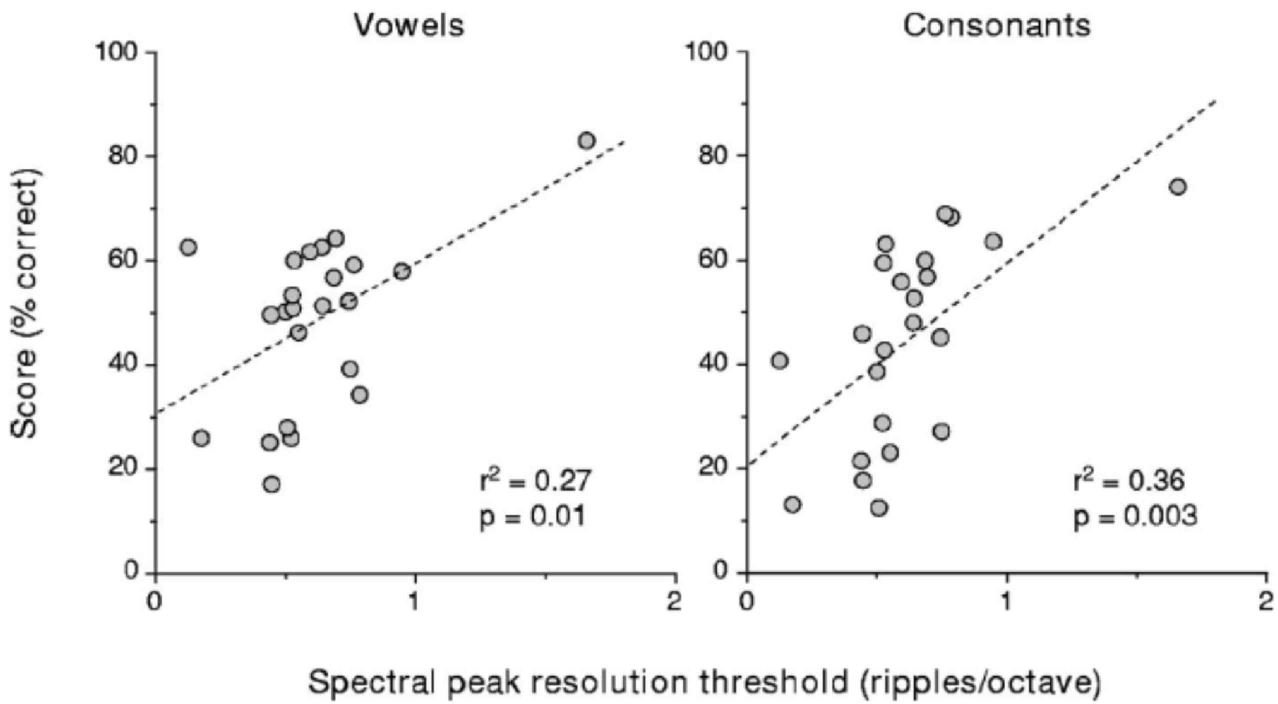



FIG. 2. Thresholds for spectral peak resolution for NH, HI, and CI subjects. Error bars represent ± one standard deviation.

Henry *et al.* 2005 J Acoust Soc Am

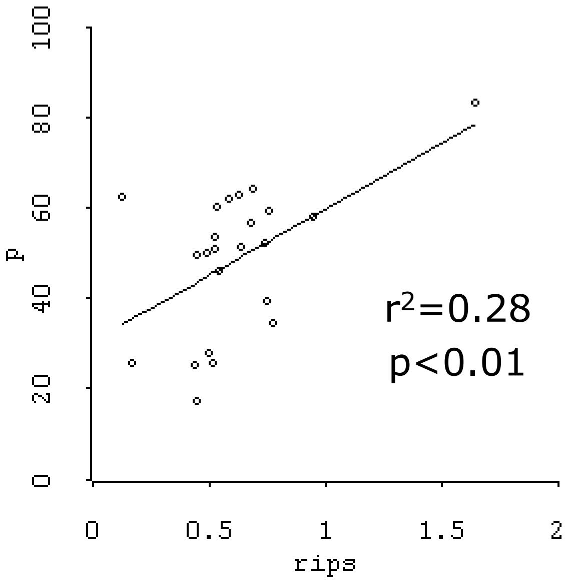
# Relationships to performance with speech in quiet

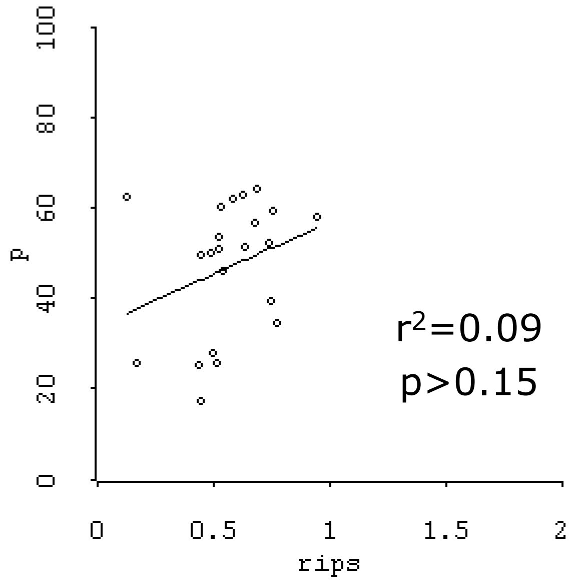
12 hVd by 20 talkers 16 VCVs by 4 talkers




Henry *et al.* 2005 J Acoust Soc Am

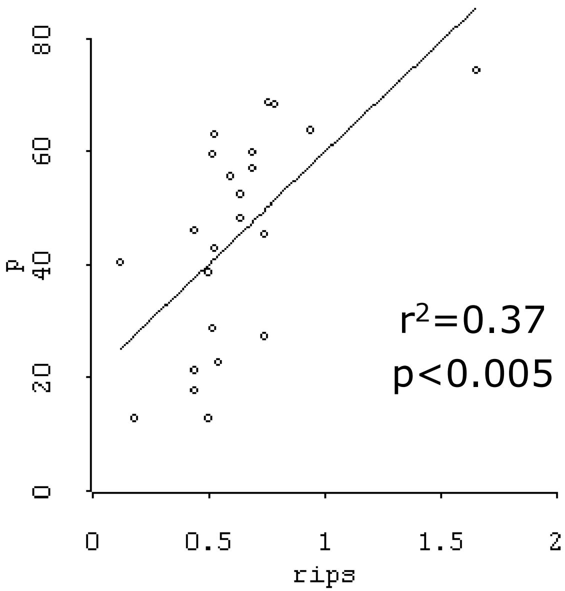
# Statistical interlude: The effect of outliers

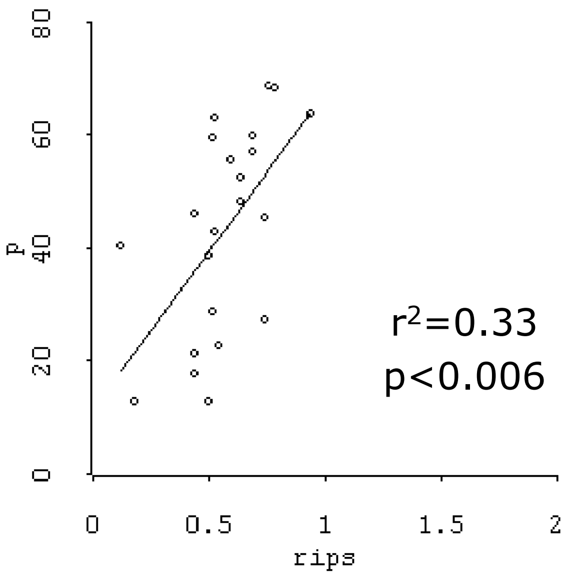



vowels

# Statistical interlude: The effect of outliers




consonants

# Relationships to performance with speech in noise

SRT determined for selection of one of 12 spondees

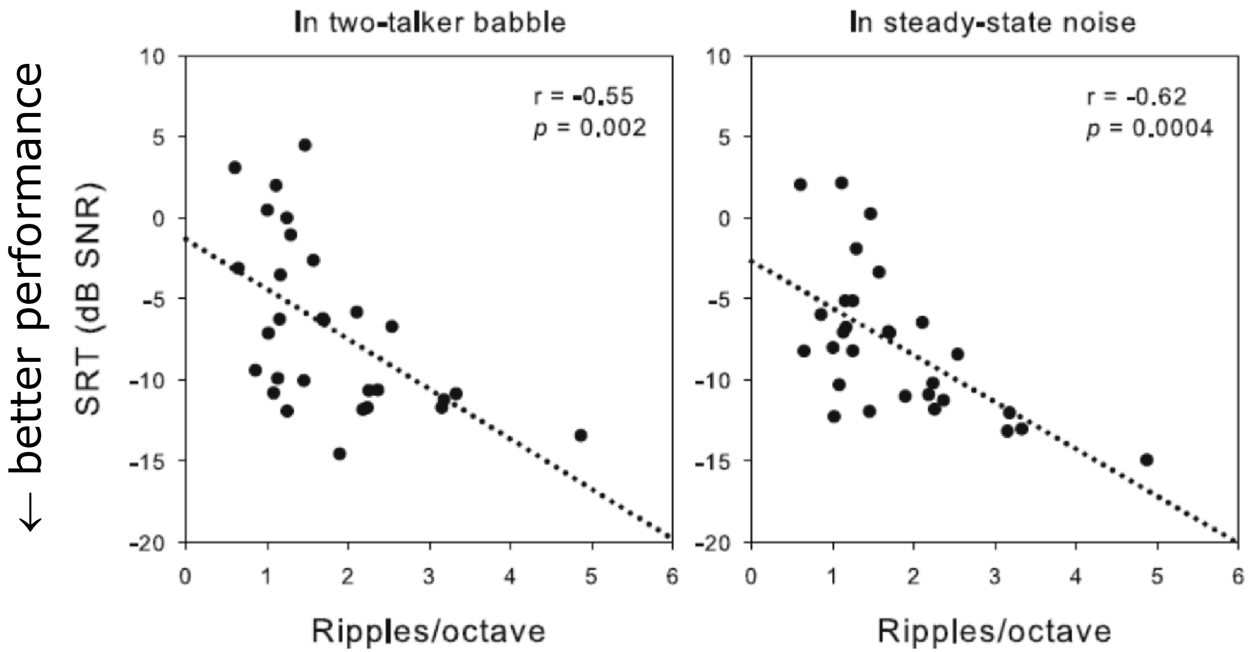


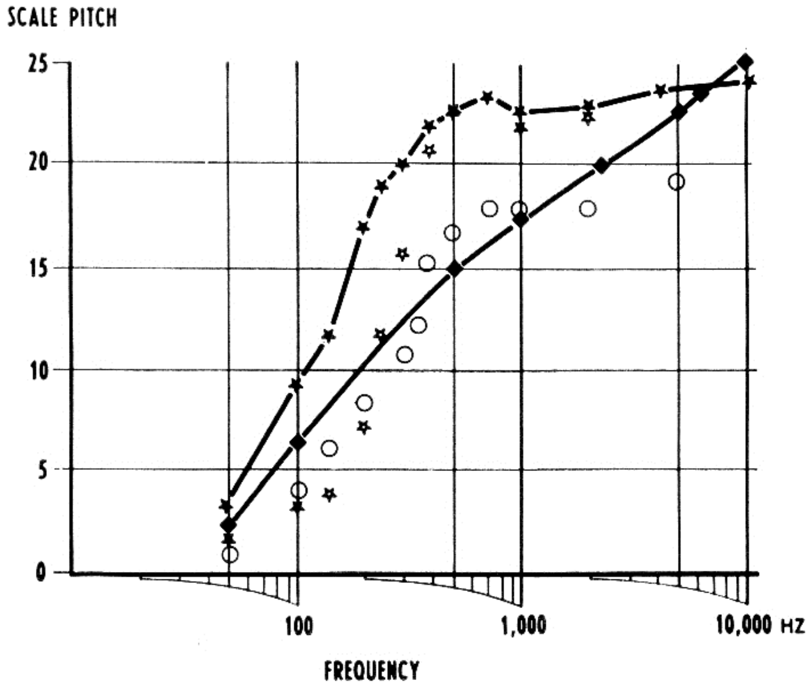

**FIG. 6.** Spectral-ripple discrimination is correlated with speech perception in noise. The figure shows the relationship between the spectral-ripple thresholds and SRTs in two-talker babble (*left panel*) and steady-state noise (*right panel*) using data from the first six repetitions. Linear regressions are represented by the *dotted lines*.

Won *et al.* 2005 JARO

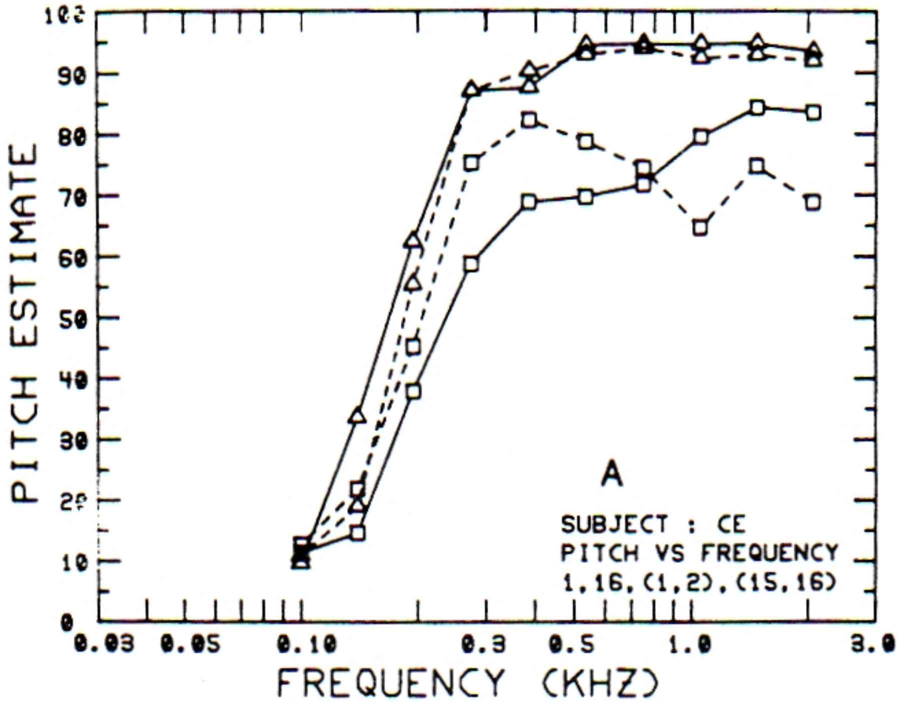
# Why is speech melody (*voice pitch)* important to hear?

- Contributes to speech intelligibility in all languages
- A good supplement to lipread information
- May play an important role in separating speech from background noises
- Appears to play a more crucial role for the young child developing language
- Crucial in so-called *tone* languages

# Pitch based on a purely temporal code



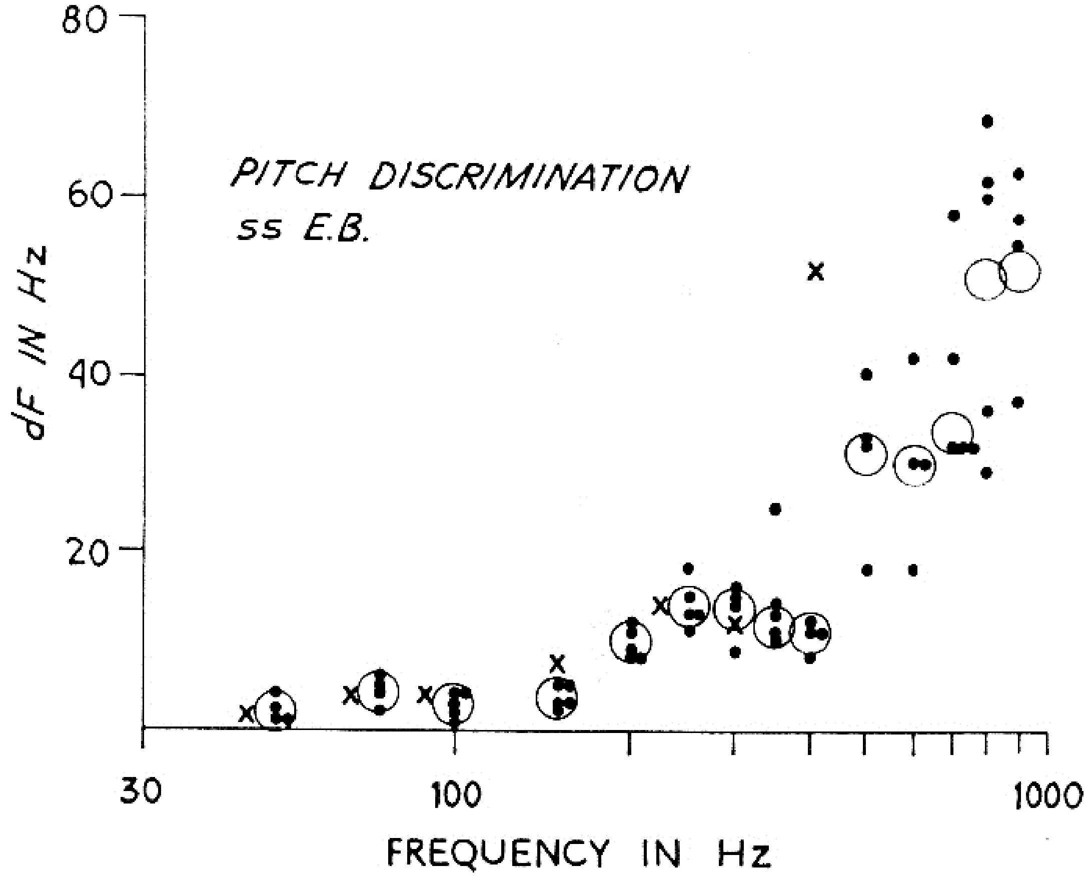

Merzenich *et al.* 1973




Shannon 1993

limited to 300 Hz or so

# Pitch based on a purely temporal code




Best normal performance for normal listeners about 0.2 % over entire range

Merzenich *et al.* 1973

# Melody recognition

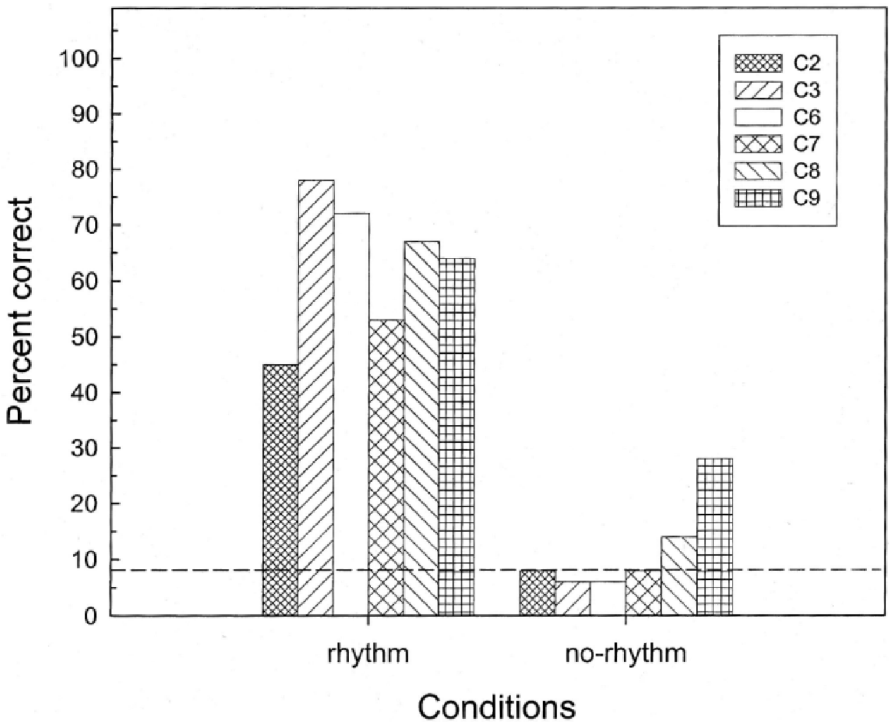
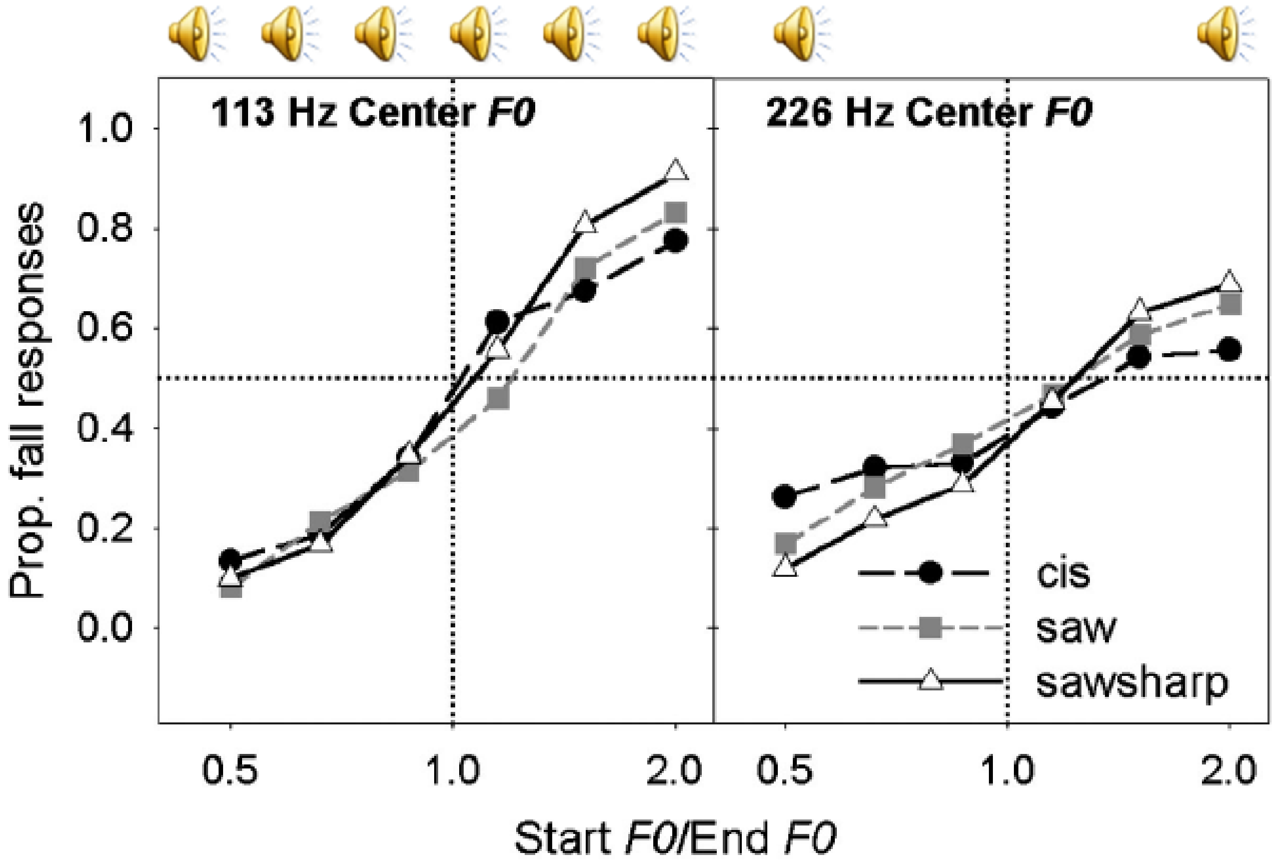



**Figure 4. Melody identification scores from individual cochlear implant listeners with the original melodies. The horizontal dashed line indicates the mean chance performance. The vertical bars represent different subjects in each condition.**

12 songs familiar to most people, synthesised with and without natural rhythm

Kong *et al.* (2004)

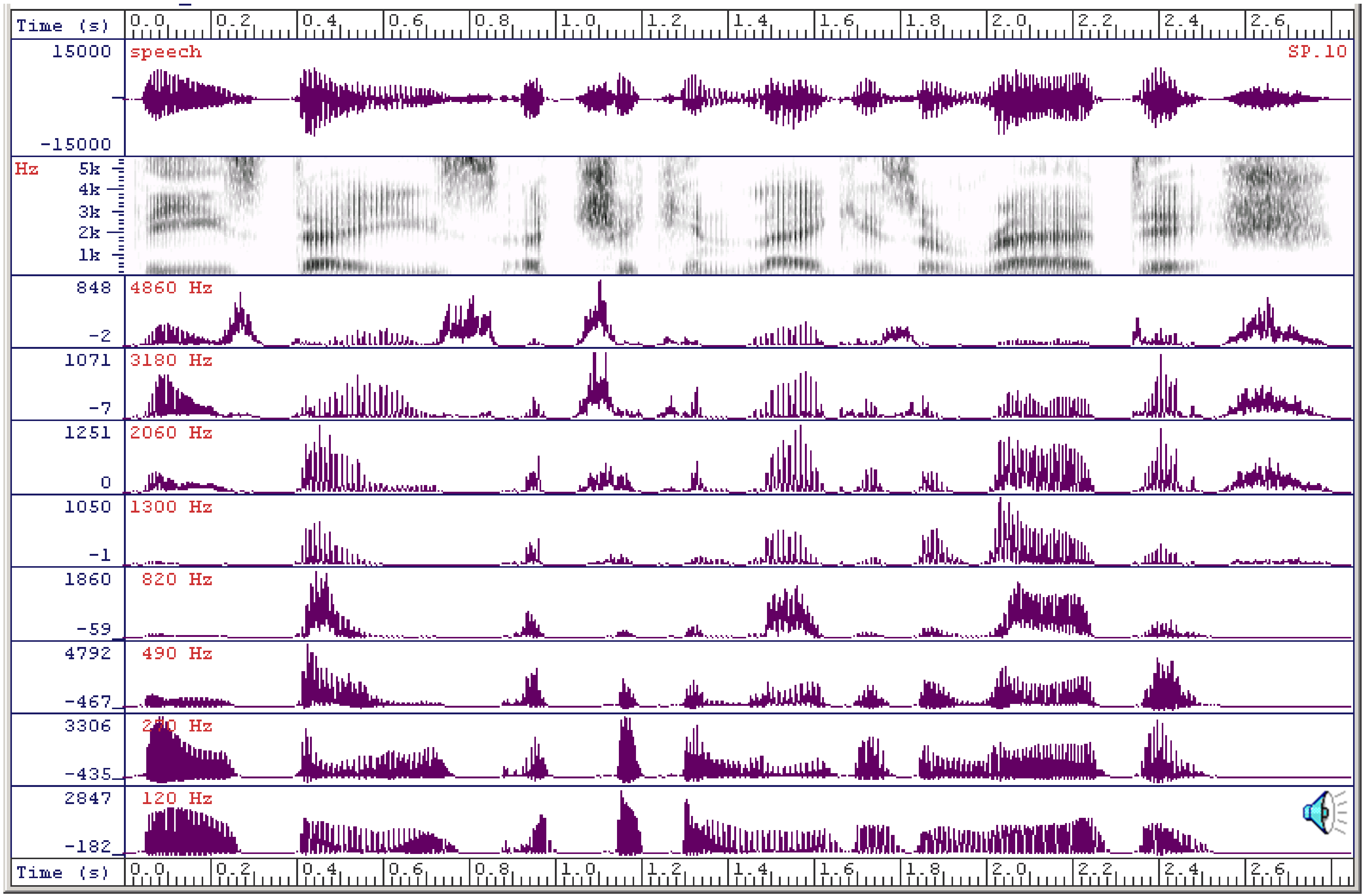
# CI users classifying rise/fall contours on diphthongs



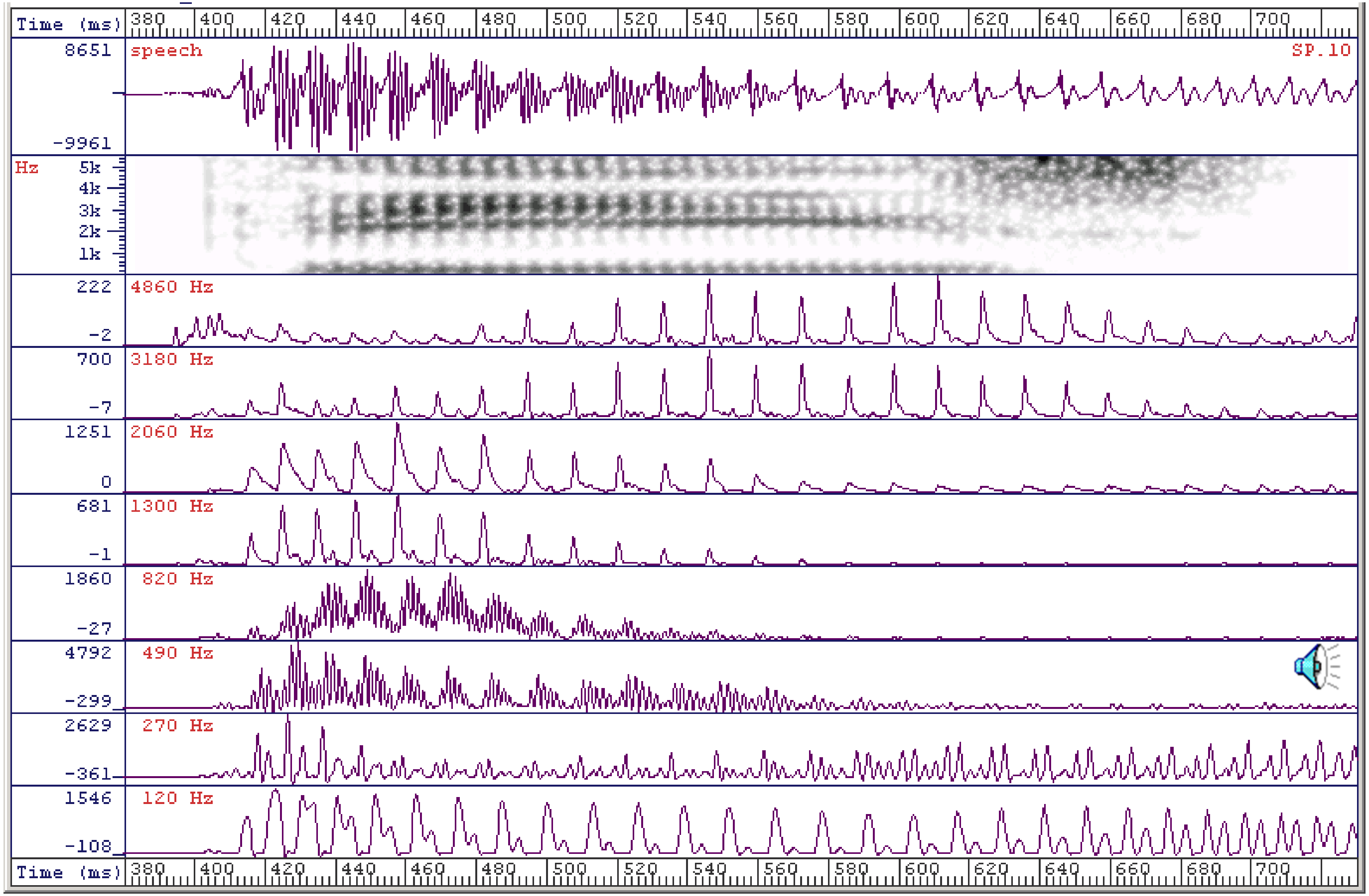

Green *et al.* 2004 J Acoust Soc Amer

# Melody coded as periodicity in rapid within-channel patterns

**Th-ee-z d- ay - s a ch-i-ck - en-l-e-g is a r-a- re d -i - sh**



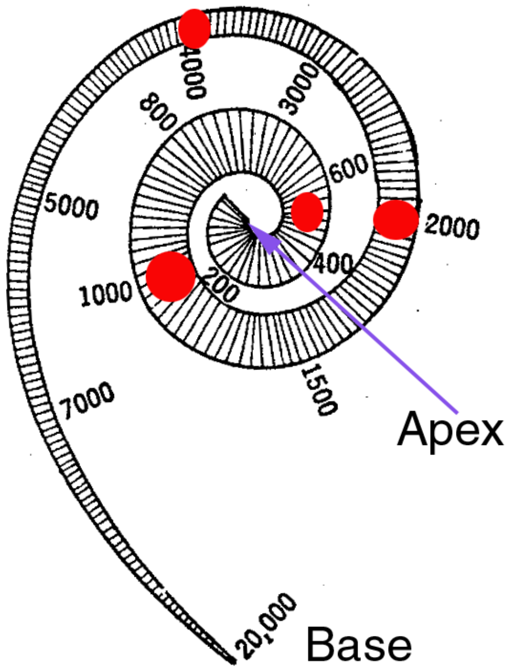
# The representation of melody can be messy!



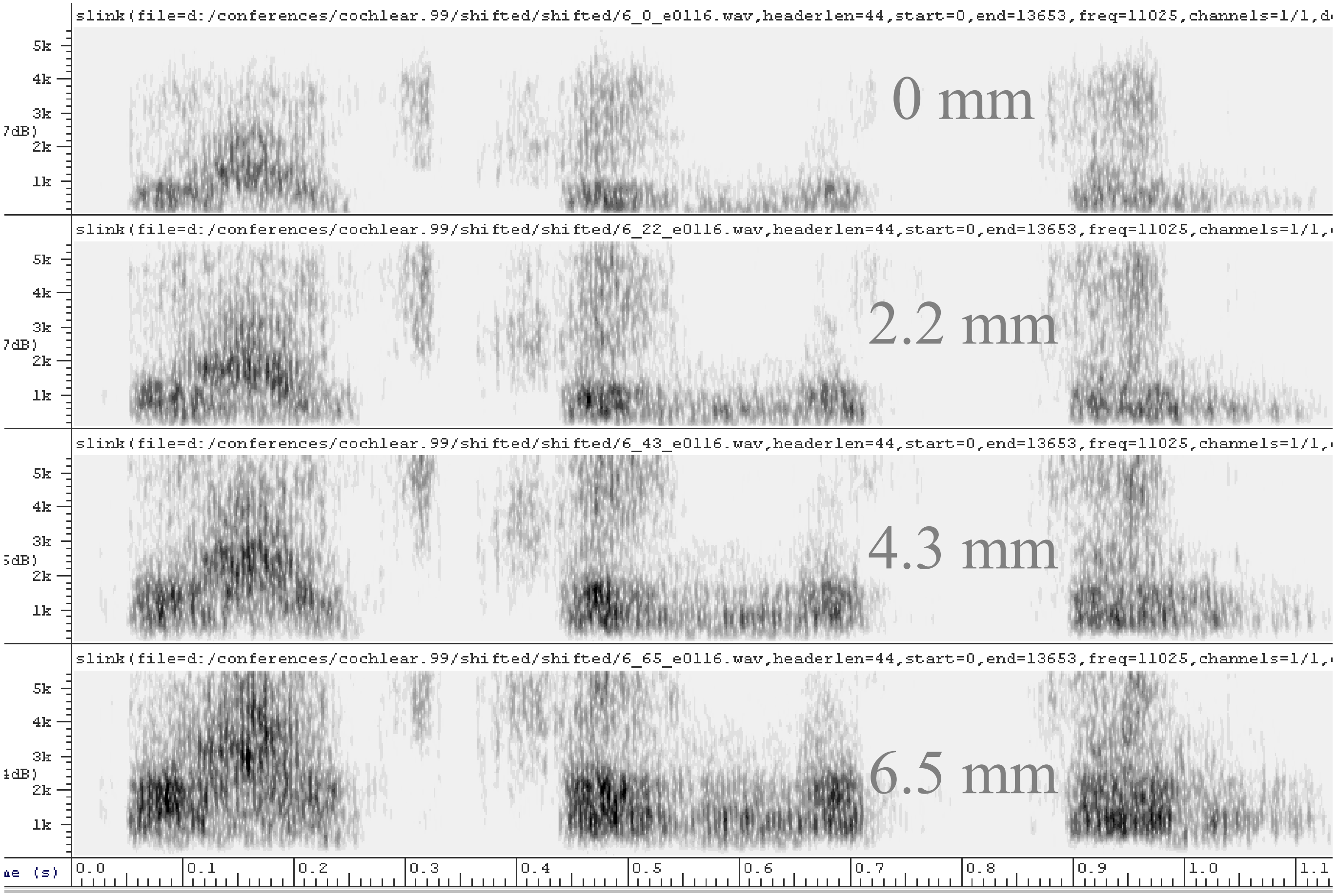
# Perception of fundamental pitch in complex waves is very poor

- Lower harmonics cannot be resolved as in normal hearing
- Phase-locking seems ‘different’
- Mis-match between place of excitation and temporal pattern may be important

# What happens when an electrode is incompletely inserted?

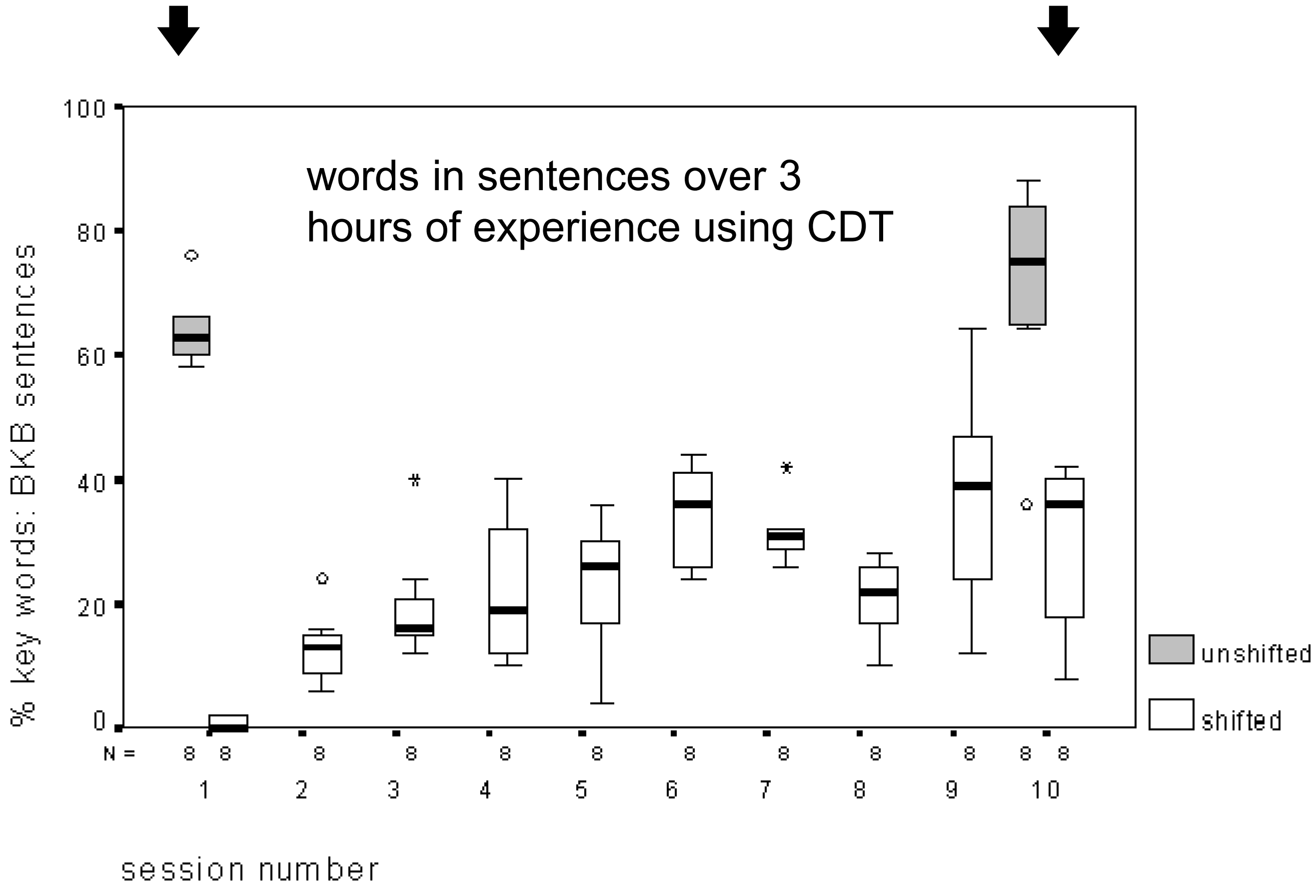


# Simulations of incomplete insertions



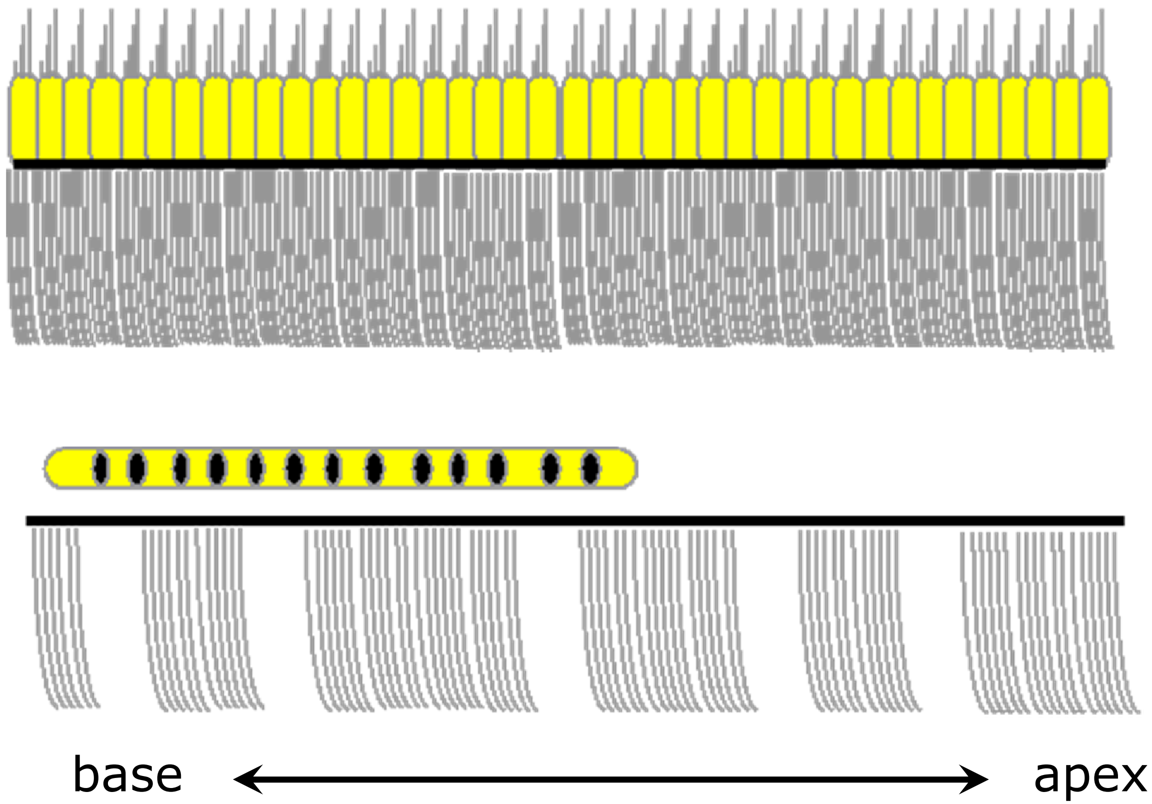
# Can the deleterious effects of spectral shifting be overcome over time?

Pre-training Post-training




normal listeners in simulations: Rosen *et al.* 1999 J Acoust Soc Am

# Hair cell substitution?

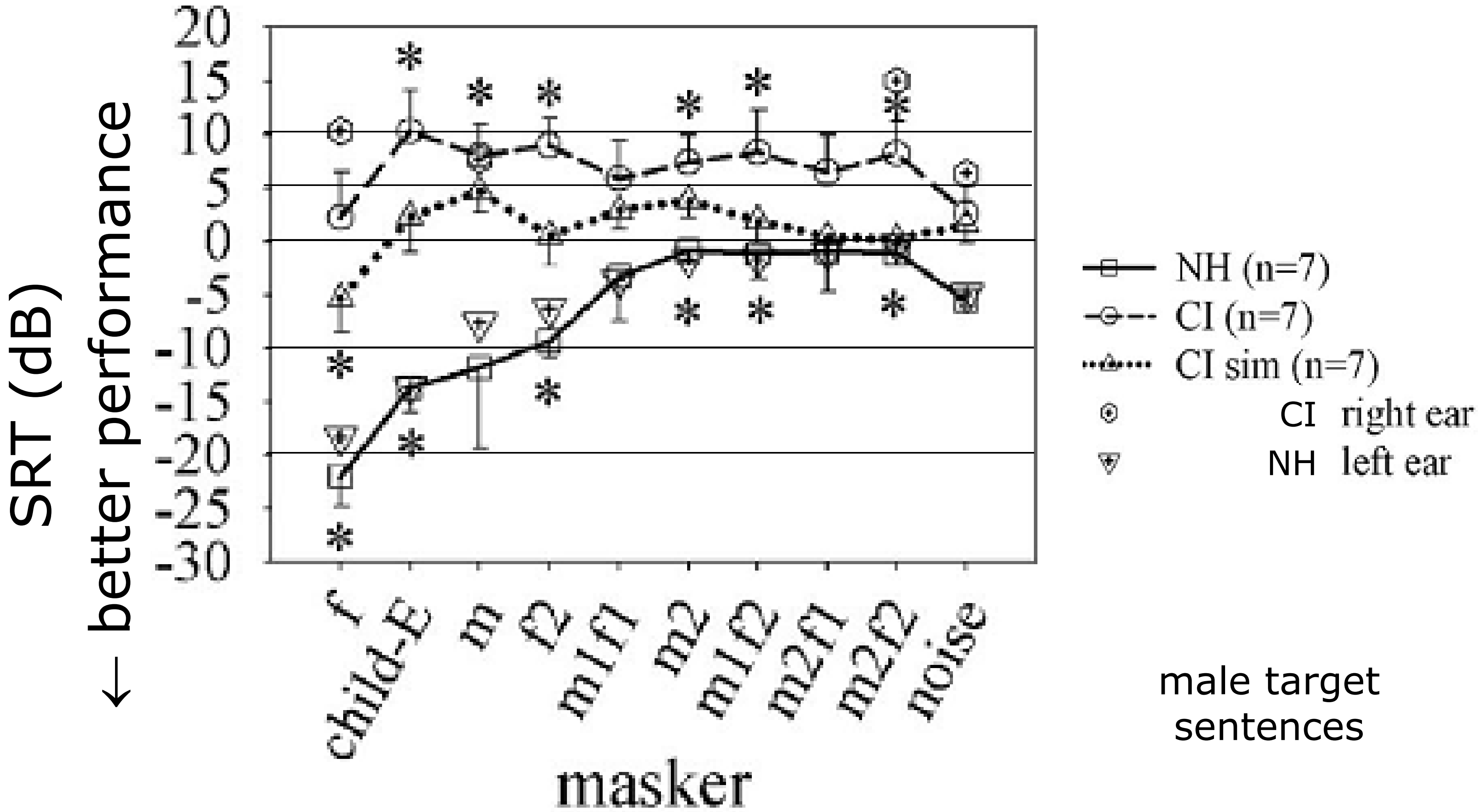



from Lynne Werner: http://depts.washington.edu/sphsc461/CI_notes.htm

# Why is a CI not as good as normal hearing?

- It’s a *damaged* auditory system, presumably with accompanying neural degeneration (e.g. dead regions)
- Electrodes may not extend fully along the length of the basilar membrane (BM), so mis-matched tuning and restricted access to apical regions (where nerve survival is typically greatest)
- 3000 IHCs vs. a couple of dozen electrodes, hence poorer frequency selectivity
- Current spreads across BM, hence poorer frequency selectivity
- Less independence of firing across nerve fibres, appears to affect temporal coding
- Small dynamic ranges but intensity jnd’s not correspondingly smaller, hence fewer discriminable steps in loudness
- But good temporal and intensity resolution

# A pessimist's view of CIs




male target sentences

Cullington, H. E., and Zeng, F. G. (**2008**). "Speech recognition with varying numbers and types of competing talkers by normal-hearing, cochlear-implant, and implant simulation subjects," J. Acoust. Soc. Am. **123**, 450-461.

# *Electro-Acoustic* or *Bimodal* stimulation: Combining the best of both worlds

- Terminology can be confusing
  - Bimodal stimulation – here typically refers to contralaterally fitted CI and HA
    - although also used elsewhere to refer to auditory-visual or other sensory modality combinations
  - EAS: typically (but not always) referring to ipsilateral or hybrid combination of CI and HA
- Crucial aspect
  - Electrical and acoustical hearing combined

# Residual hearing

- Significant residual hearing is found in some 50% of adult CI candidates (UK CI study group, 2004)
  - Less strict selection criteria outside UK will increase this proportion
  - NICE has limited bilateral implantation in the UK to children
- Minimal residual hearing cannot in itself support effective speech communication in absence of lipreading
- But increasingly recognised as useful in combination with a cochlear implant

# Contralateral combination of CI+HA

## CNC words in quiet

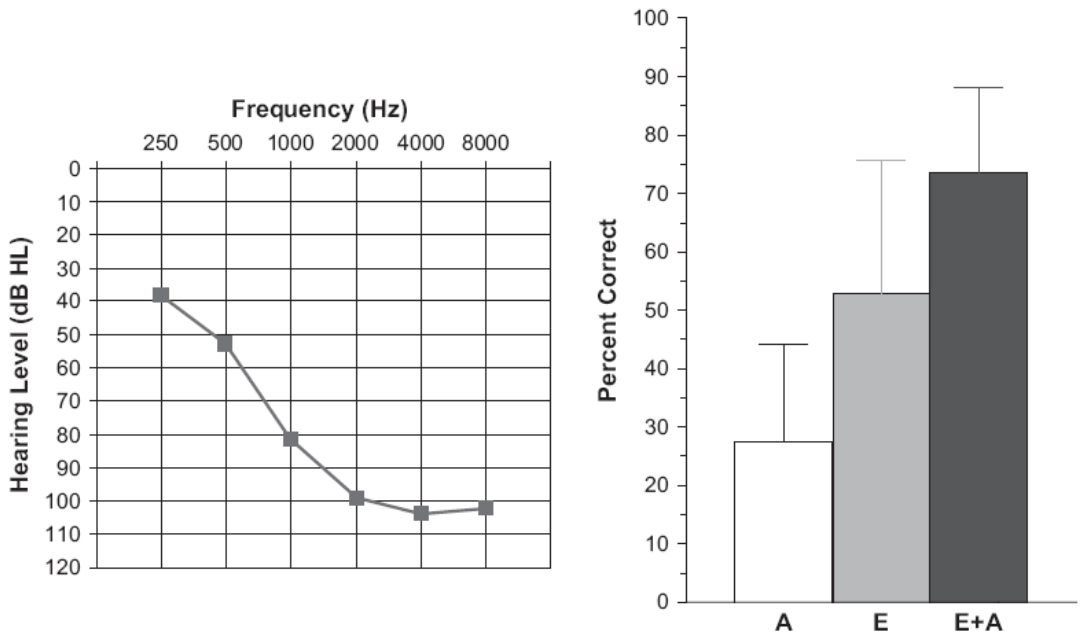
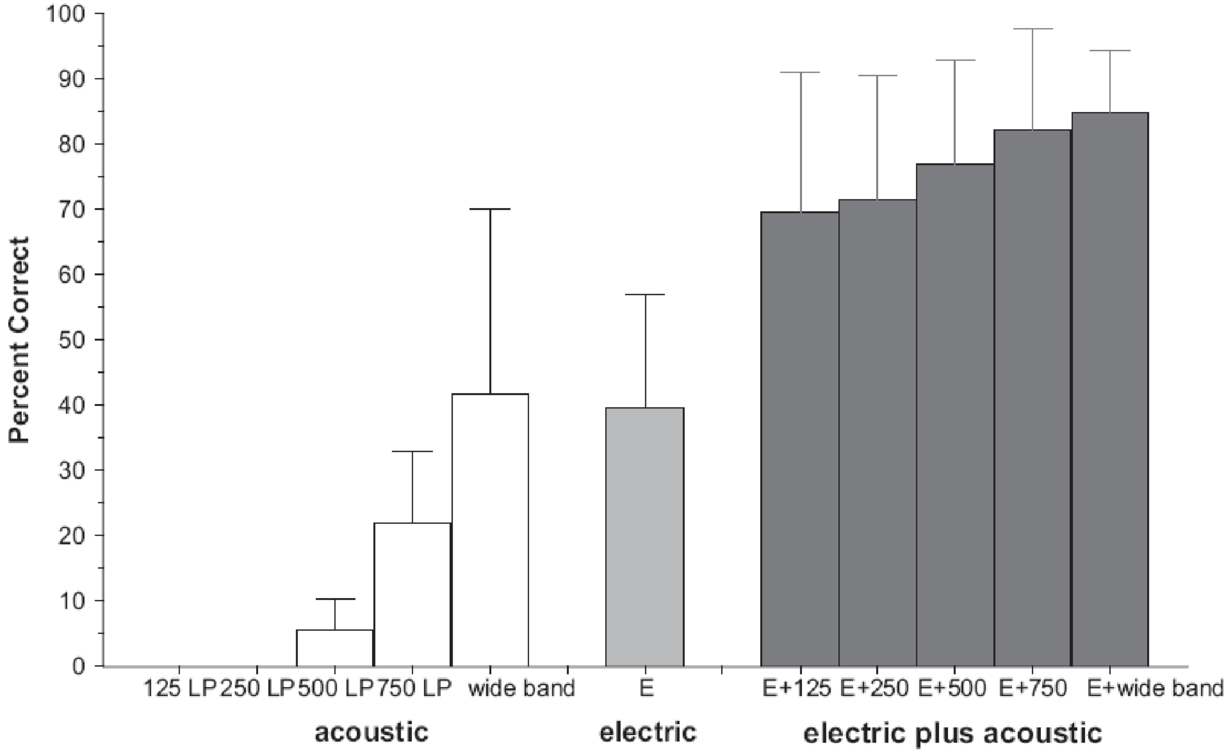



**Figure 1.** Left: audiogram for the contralateral ear of EAS patients. Right: CNC word recognition in acoustic only, electric (CI) only, and combined electric and acoustic (EAS) conditions (from Dorman et al, 2008). A = acoustic stimulation; E = electric stimulation; E+A = electric plus acoustic stimulation. Error bars indicate +1 standard deviation.

# Contralateral combination of CI+HA

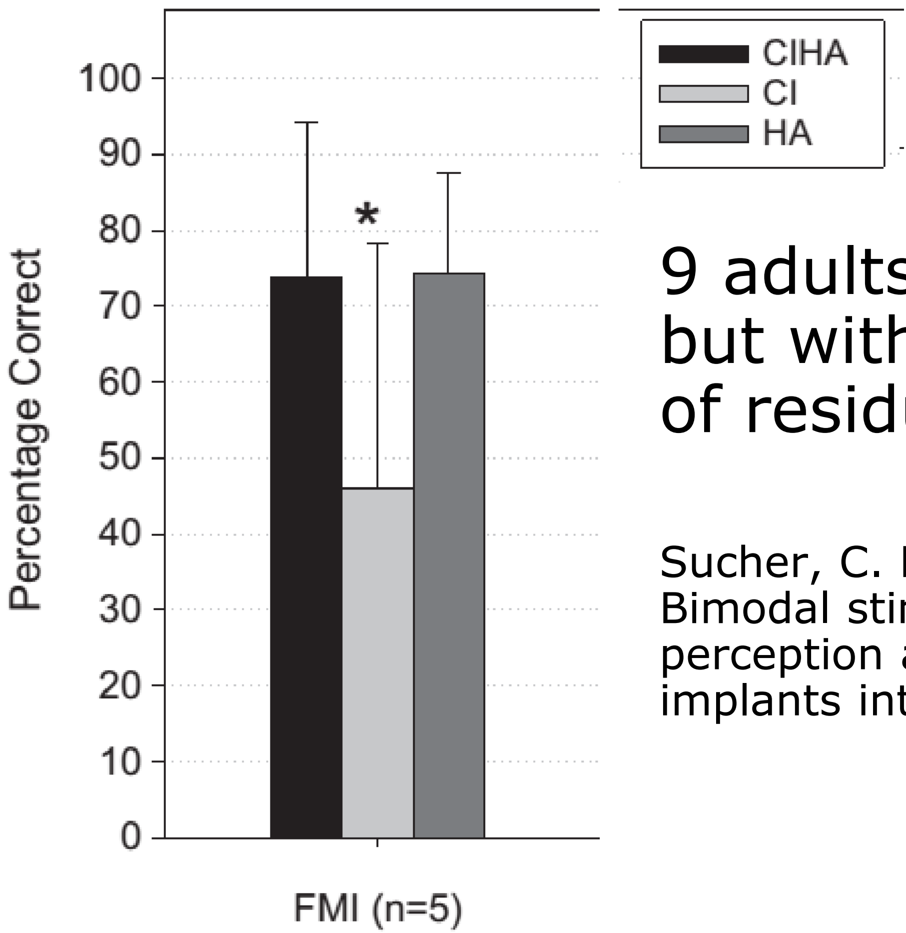
Sentences in noise

often substantial improvements with addition of hearing aid: most of the benefit is from low frequencies




AzBio sentence recognition at +10 dB SNR (bottom) for EAS patients in acoustic alone, electric alone, and EAS conditions. In the acoustic only and EAS conditions the acoustic signal was either wideband or low-pass (LP) filtered at 125, 250, 500, and 750 Hz. Error bars indicate +1 standard deviation. (From Zhang et al, 2010).

# Familiar Melody Identification




9 adults who use a CI+HA but with unspecified amounts of residual hearing

Sucher, C. M. & McDermott, H. J. (2009). Bimodal stimulation: benefits for music perception and sound quality. Cochlear implants international, 10 Suppl 1, 96-99.

# Better thresholds = better hearing

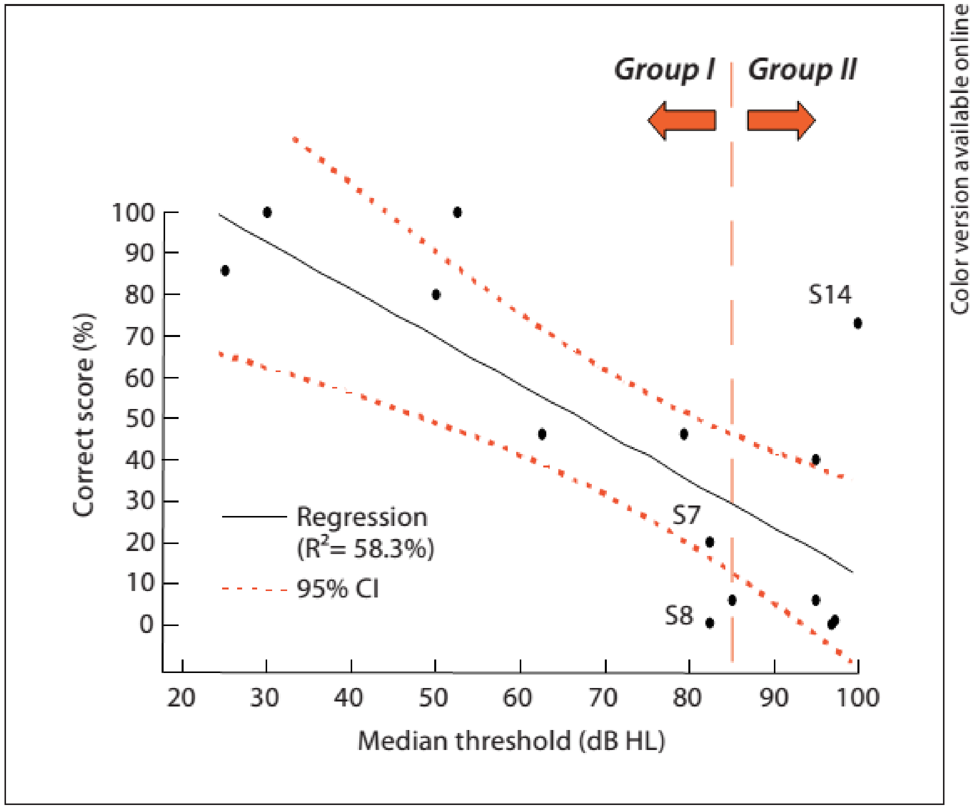
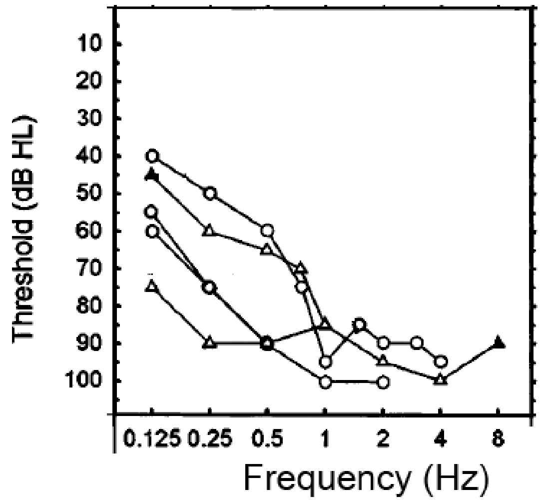


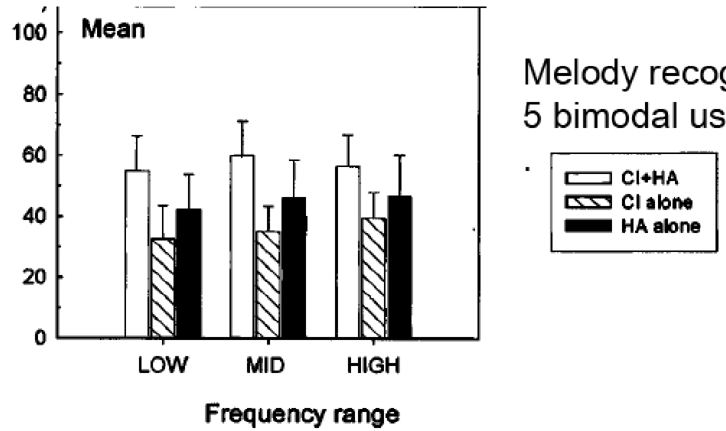

**Fig. 2.** Song recognition scores for no lyrics/HA alone plotted against median pure tone threshold. A significant correlation was found between recognition score and median threshold ($p < 0.01$, $R^2 = 58.3\%$). One subject, S14, with relatively high thresholds was an outlier with a recognition score of 73%.

El Fata, F., James, C. J., Laborde, M. L., & Fraysse, B. (2009). How Much Residual Hearing Is 'Useful' for Music Perception with Cochlear Implants? *Audiology and Neuro-Otology, 14,* 14-21.

# Pitch perception in people with profound hearing loss

Even with profound losses acoustic pitch perception will typically exceed that using a CI




Melody recognition from 5 bimodal users (Kong et al. 2005)

# Summary: Bimodal benefits

- Frequent improved speech recognition compared to single cochlear implant
  - largely due to low frequency cues from the hearing aid
- Residual hearing provides information not clearly signalled by CI.
  - Low frequency spectral structure – ? perhaps ?
  - Speech F0 and amplitude could signal when the CI is providing good information in fluctuating noise ? – Listening in the dips – AKA Glimpsing ?
  - Speech F0 and amplitude could also provide direct speech information e.g. consonant voicing and manner, speech melody
  - Melodic information
- Doubtful that Bimodal fittings (contralateral EAS) can support spatial hearing in typical UK candidates whose hearing does not extend above 1 kHz
  - ILD cues for localization are too small to be useful unless residual hearing extends well above 1 kHz
  - ITD cues for localization are missing at least with current CI systems as pulse timing cannot resolve fine time differences