WELDON SCHOOL OF BIOMEDICAL ENGINEERING

The Effects of Hearing Aid Amplification on Robust Neural Coding of Speech

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25 Nov, 2013

PURDUE ENGINEERING

The Problem:

Hearing Aids Perform Poorly in Noisy Environments

- > 360 Million people world-wide have a disabling hearing loss (>34 Million in the US)
- Only 20% of hearing-impaired Americans own hearing aids
  – 50% of patients are dissatisfied with the performance of their hearing aids in noisy environments.

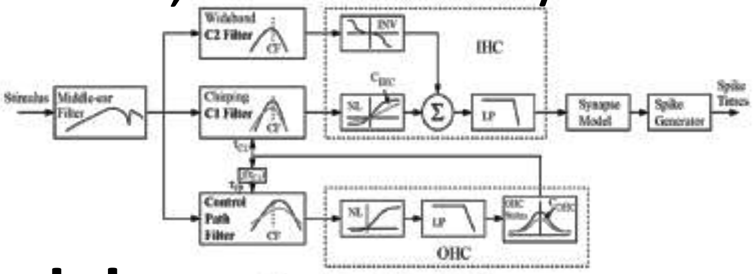
Kochkin, S. MarkeTrak VII: Hearing Loss Population Tops 31 Million People, The Hearing Review, Vol. 12(7) July 2005, pp. 16-29
Kochkin, S. "MarkeTrak VIII: 25-year trends in the hearing health market." Hearing Review 16.11 (2009): 12-31.
Stevens, Gretchen, et al. "Global and regional hearing impairment prevalence: an analysis of 42 studies in 29 countries." *The European Journal of Public Health* 23.1 (2013): 146-152.

Hearing Aids May Not Be Providing The Best Signal to the Ear

- The hearing aid has no idea which of the many sound sources you are trying to listen to…
  – It could assume the person/object of interest is directly in front of you (e.g., use a directional microphone) , but this does not work well for multiple sound sources
  – Perhaps the hearing aid is not presenting the best signal to the ear…
  – What should the signal be?

Research Approach

- **Computational Model**
  - Explore ideas, test stimuli/methods/analyses



(From Zilany & Bruce 2007)

- **Animal Model**
  - Confirm that modeling results carry over to the real world

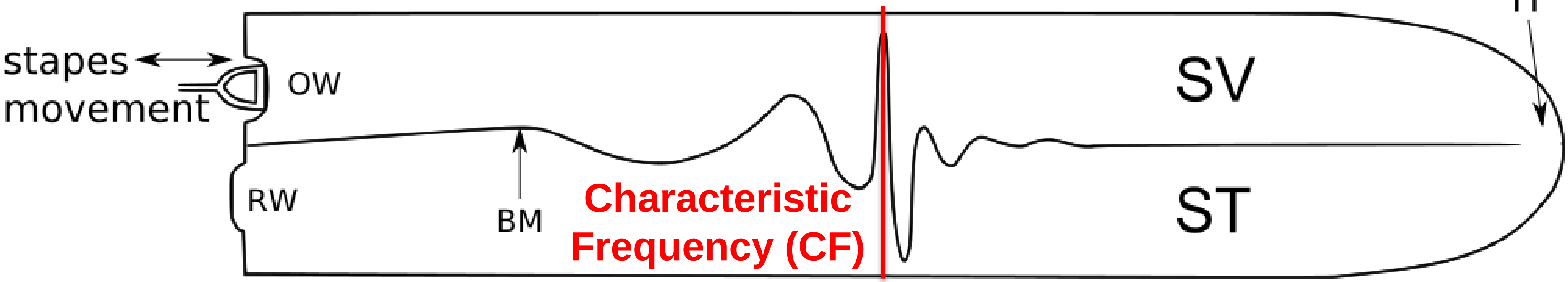
Topics

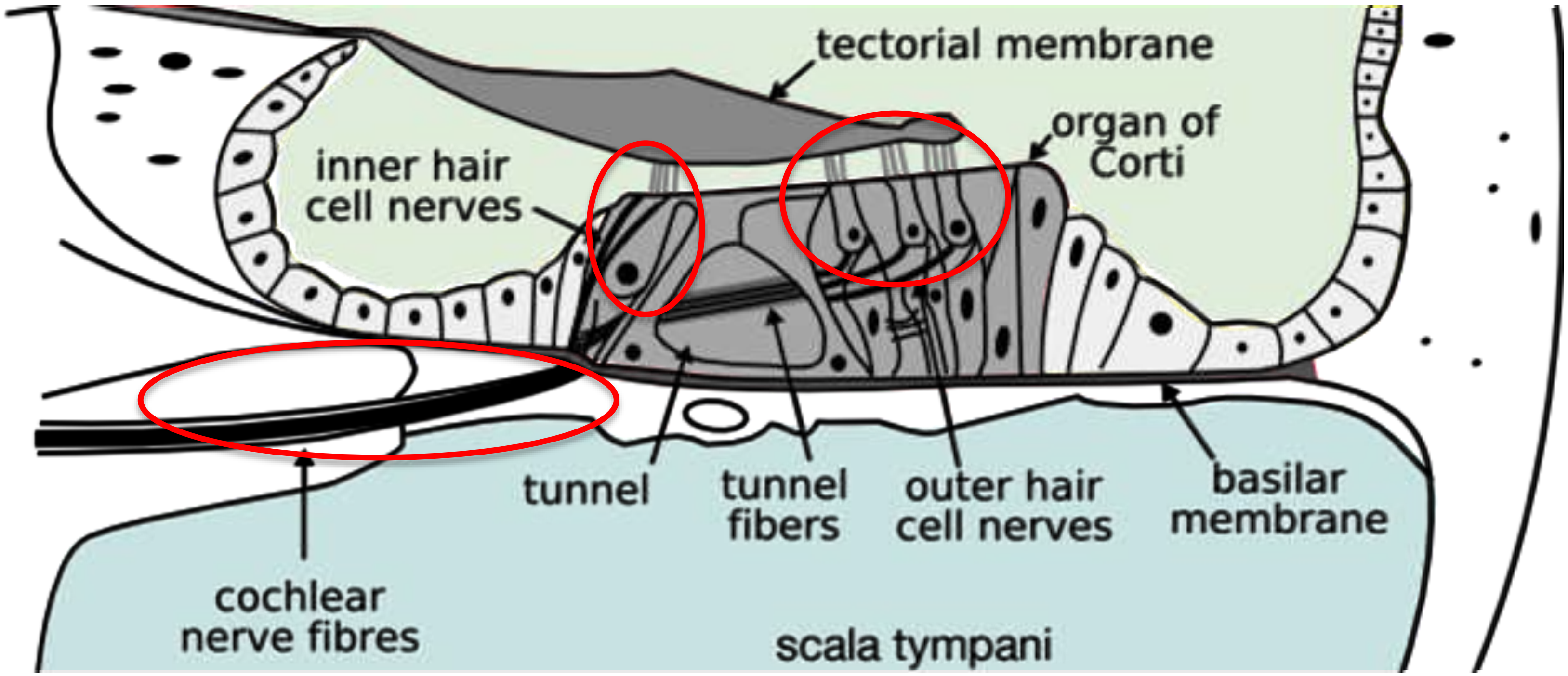
0. Brief Review of Neural Coding
1. Physiology-Based Hearing Aid Design

Spatiotemporal Coding:

   2. Effects of Hearing Impairment
   3. Impaired Coding of Vowels in Noise
   4. Impaired Coding of ***Aided*** Vowels in Noise

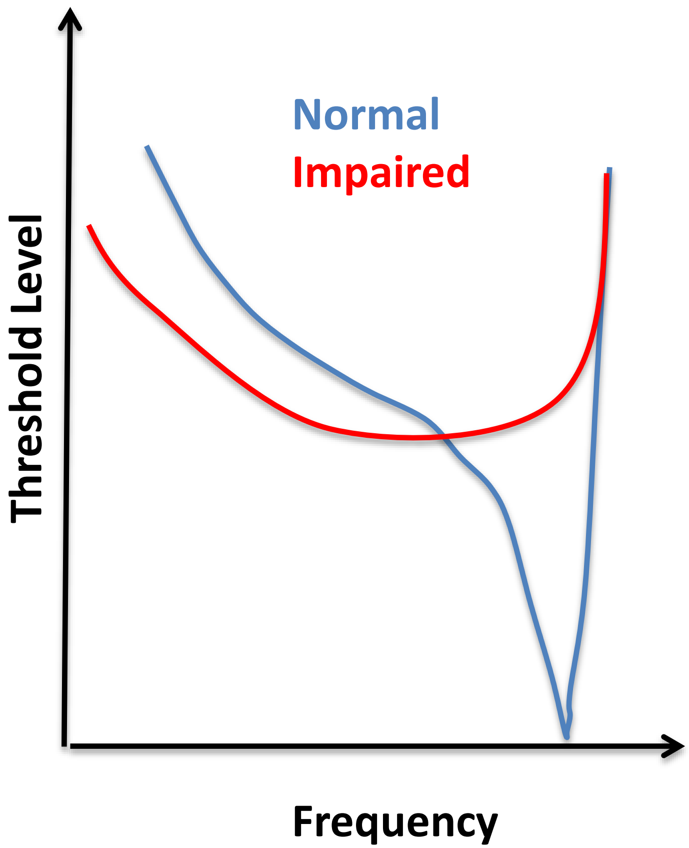
5. Limitations of Spatiotemporal Pattern Correction


stapes
movement
OW
RW
BM
Characteristic
Frequency (CF)
SV
ST
H


tectorial membrane
organ of
Corti
inner hair
cell nerves
tunnel
tunnel
fibers
outer hair
cell nerves
basilar
membrane
cochlear
nerve fibres
scala tympani

Auditory Nerve Tuning Curve

- **Electrode is inserted into auditory nerve bundle**
- **Measure lowest sound level which increases the neural firing rate above the spontaneous rate**
- **High-frequency slope is used to estimate CF (Liberman & Dodds, 1984)**



Liberman, M. C., and Dodds, L. W. (**1984**). "Single-neuron labeling and chronic cochlear pathology III Stereocilia damage and alterations of threshold tuning curves," Hearing Research, **16**, 55–74.

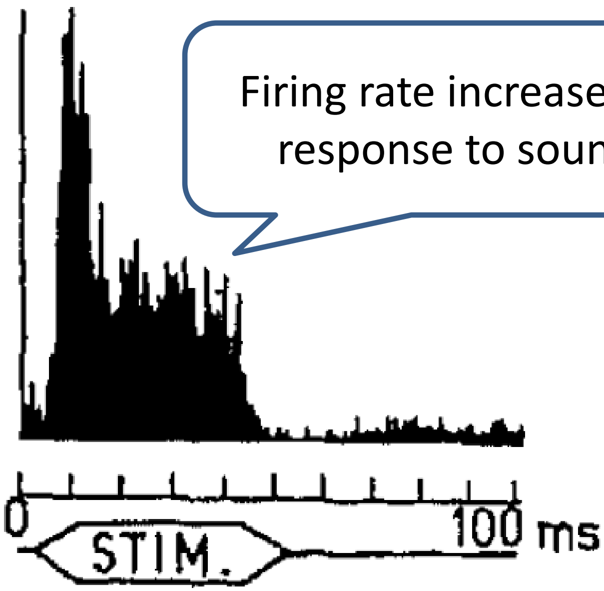
Neural Firing Rate & Phase Locking in the auditory nerve

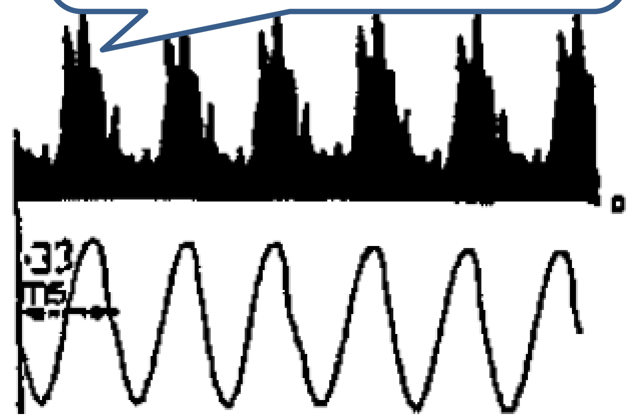
- Peri-Stimulus Time Histograms (based on several repetitions of the stimulus):

Firing rate increases in response to sound

Action potentials tend to "lock" to the phase of the stimulus waveform

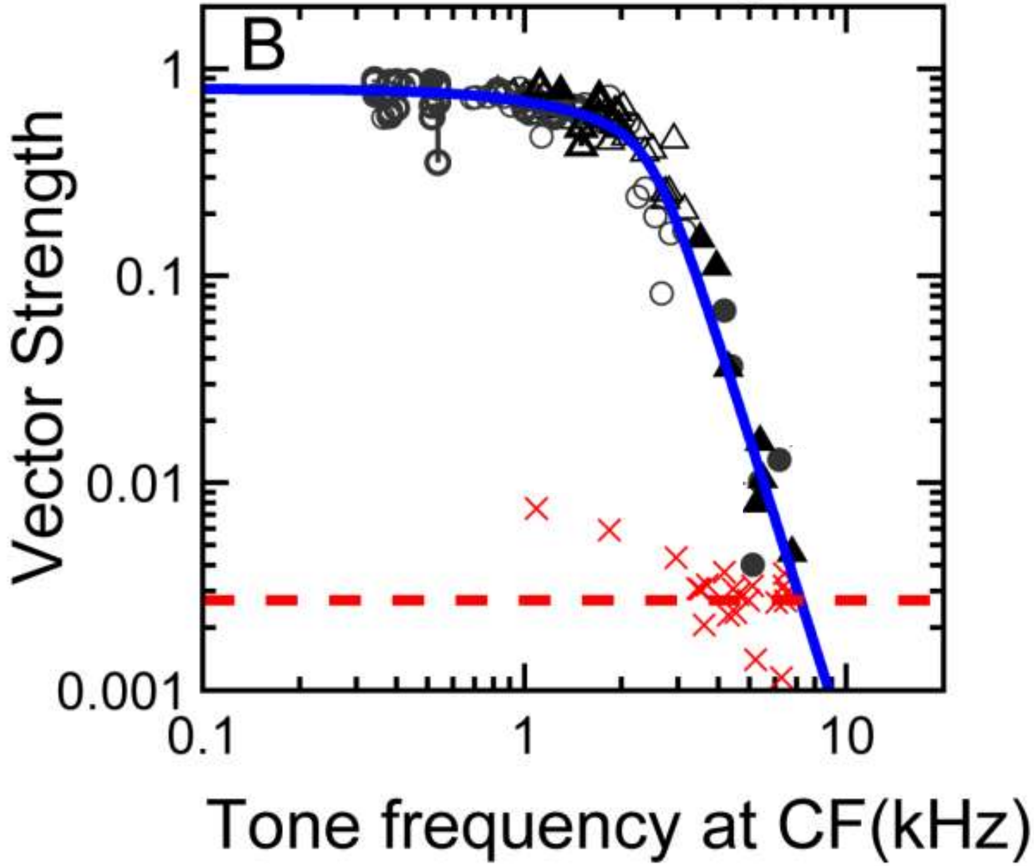
# of spikes





Harrison RV, Evans EF (1979) Some aspects of temporal coding by single cochlear fibres from regions of cochlear hair cell degeneration in the guinea pig. Arch Otorhinolaryngol 224:71--78.

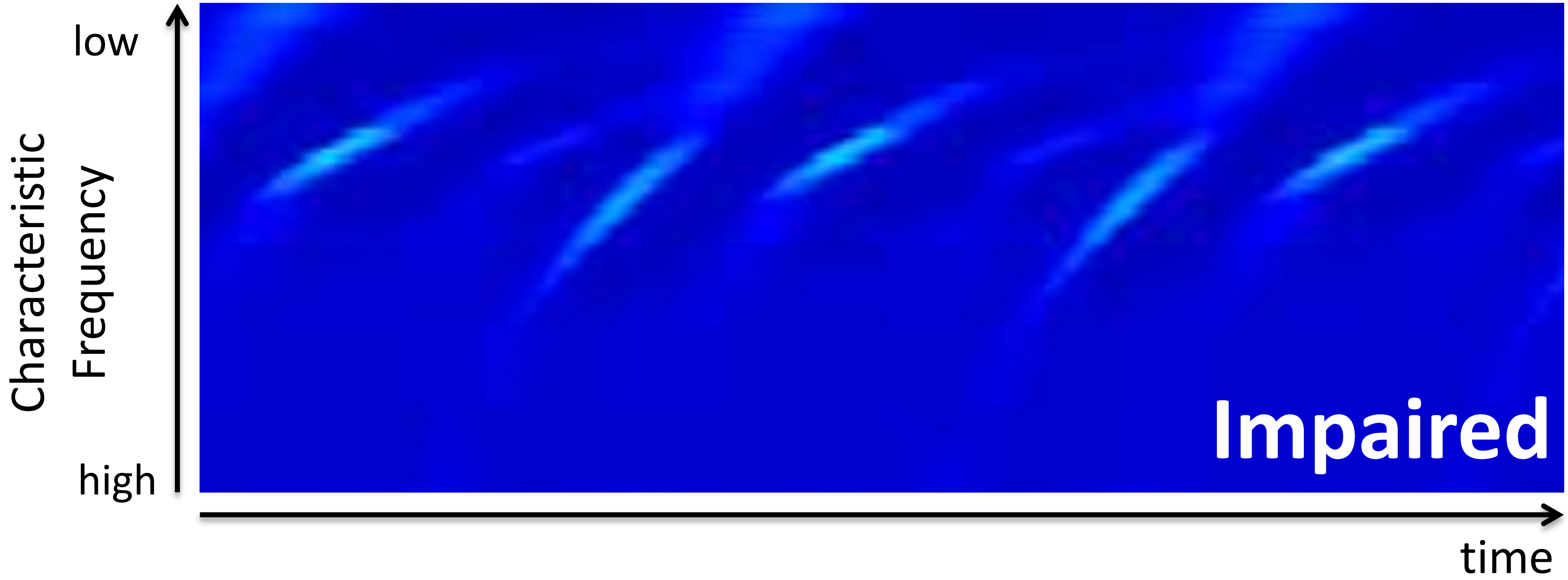
Phase Locking is Reduced Above 3kHz



Kale, Sushrut S. (2011) "Temporal coding in auditory-nerve fibers following noise-induced hearing loss." PhD thesis, Purdue University.

Neurogram

Instantaneous firing rate as a function of time for each CF



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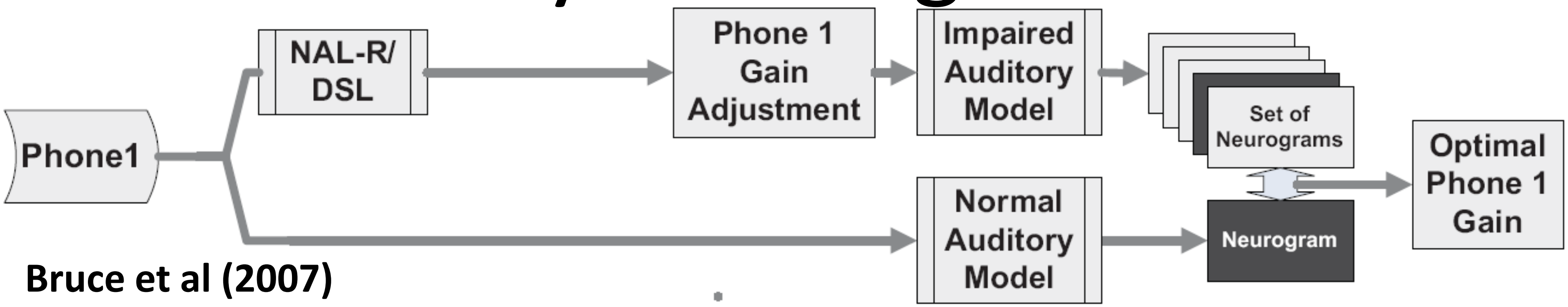
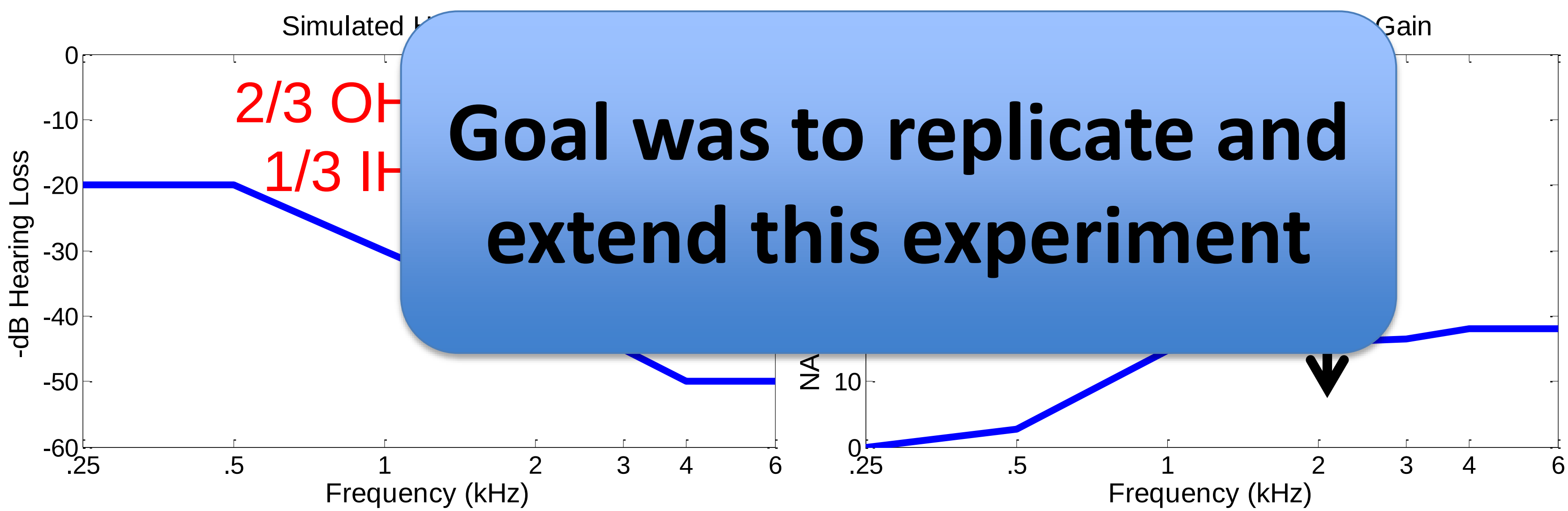
Study 1: Background



Bruce et al (2007)



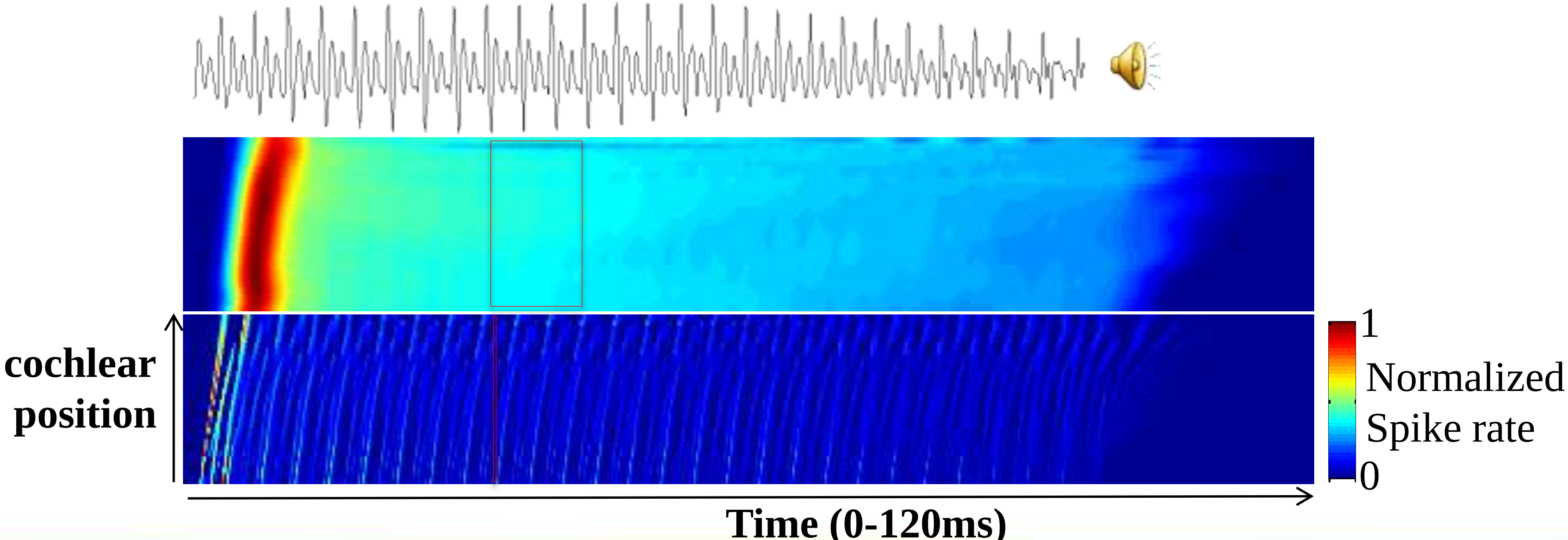
Goal was to replicate and extend this experiment

Bruce, I. C., Dinath, F. and Zeyl, T. J. (2007). "Insights into optimal phonemic compression from a computational model of the auditory periphery," in *Auditory Signal Processing in Hearing-Impaired Listeners, Int. Symposium on Audiological and Auditory Research (ISAAR)*

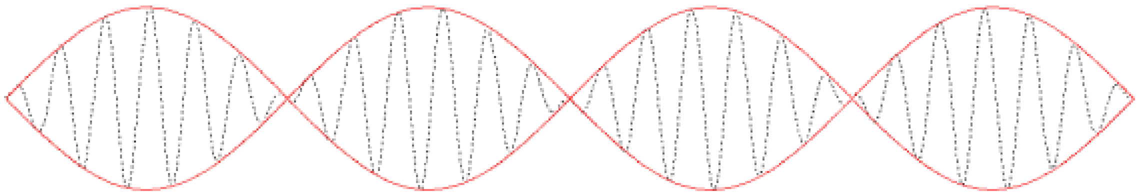
Optimal gain depends on what you consider "optimal"

- Bruce *et al* used two methods for determining optimal gain
  - Average Discharge Rate ("Envelope") = 8ms window
  - Spike Timing Information = 256μs window ("Temporal Fine Structure")

optimal = lowest mean absolute error



Temporal Fine Structure is important in complex acoustic situations



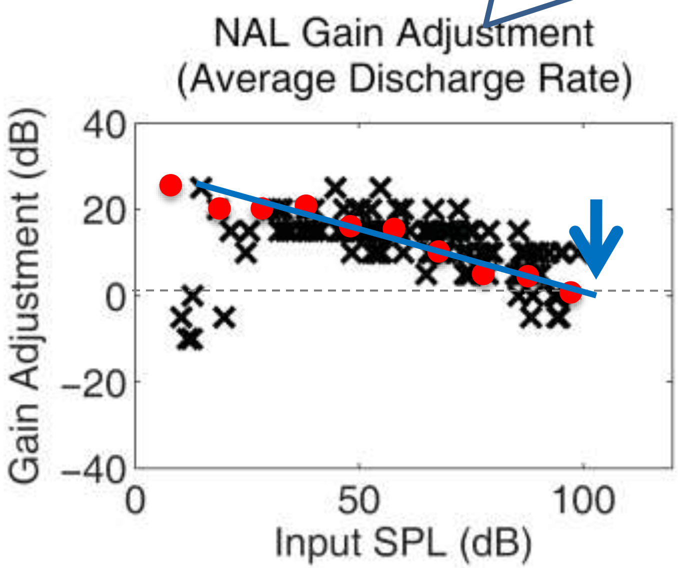
- Envelope information is sufficient for speech intelligibility in quiet (Shannon, 1995)
- TFS is important for pitch perception and localization (Smith *et al*, 2002)
  - Pitch and localization are especially important for **source segregation** (Bregman, 1990)
- Hearing impaired listeners have trouble using TFS cues (Lorenzi *et al*, 2006)

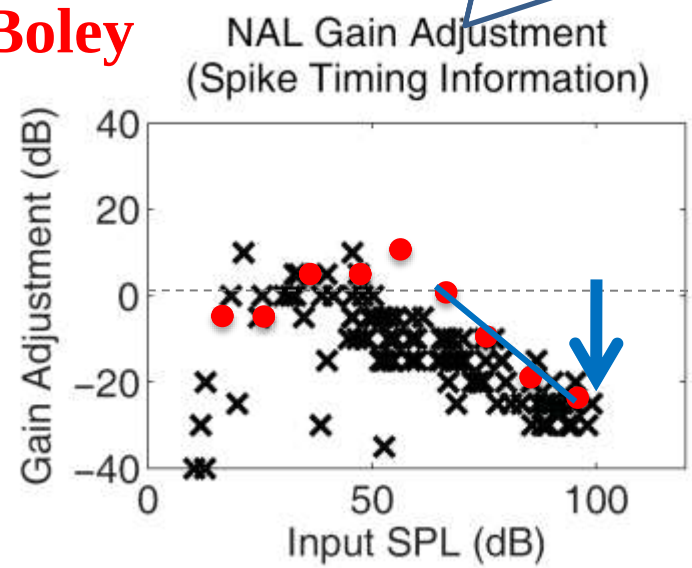
Optimal Gain (mixed damage)

Turn up the volume when listening in a quiet room

Turn down the volume when listening in a noisy environment

Boley





0dB= prescription

This is known as **compression**

(Modern hearing aids already do this)

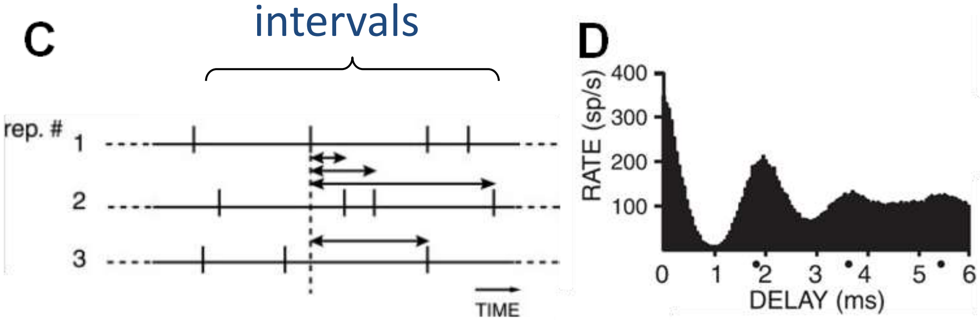
Prescribed gain appears to provide balance between optimizing “average discharge rate” & “spike timing information”

Study 1: Methods

- Single phone at various input SPLs
- Model 30 CFs (250Hz-8kHz)
- Extensions to Bruce's Study:
  - Model different ratios of OHC/IHC damage
    - Most of the threshold shift due to OHC damage
    - Most of the threshold shift due to IHC damage
  - Measure neural ENV & TFS (better time resolution)
    - Bruce's 8ms window isolated fluctuations < 80Hz
    - Bruce's 256µs window isolated fluctuations <2.5kHz

We can use spike correlations to tell us about envelope and fine structure

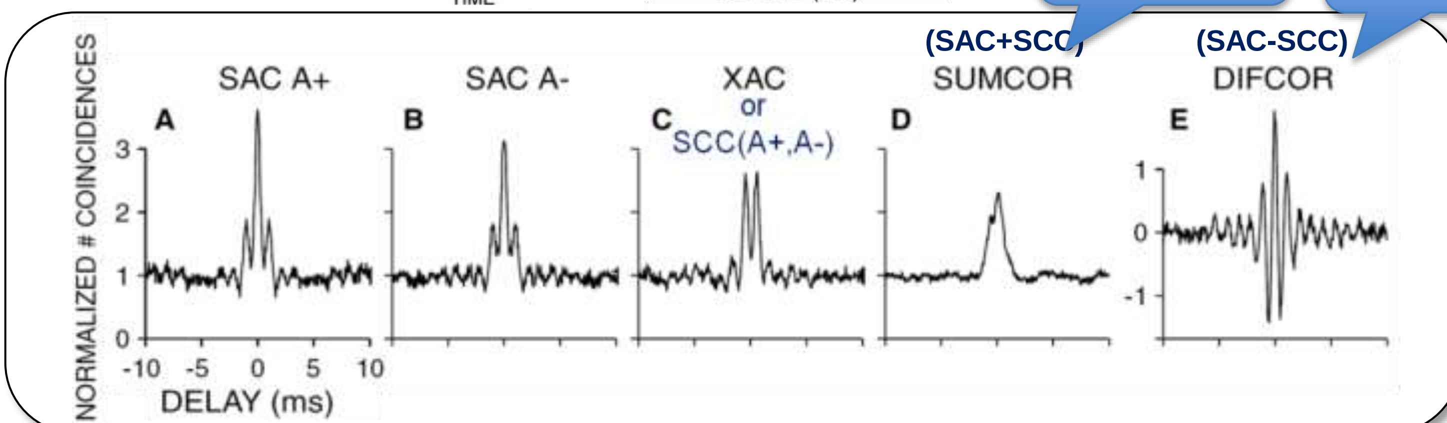
Measure inter-spike intervals



Shu… …ti… function
(a ty… …in… …n)

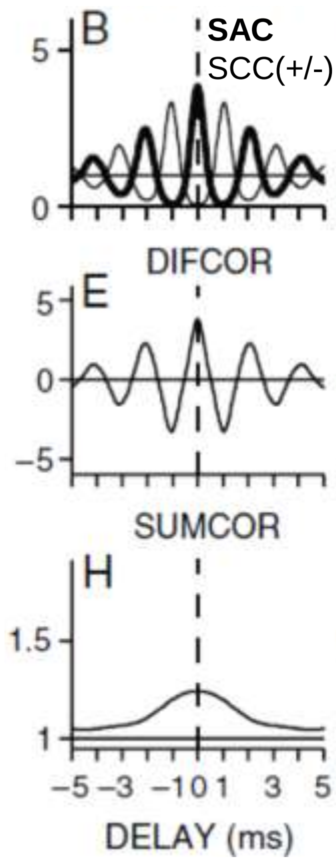
Neural Envelope

Neural TFS



Louage, D. H., van der Heijden, M., and Joris, P. X. (**2004**). "Temporal properties of responses to broadband noise in the auditory nerve," Journal of Neurophysiology, **91**, 2051–2065.
Joris, P. X., Louage, D. H., Cardoen, L., and van der Heijden, M. (**2006**). "Correlation index: a new metric to quantify temporal coding," Hearing Research, **216-217**, 19–30.

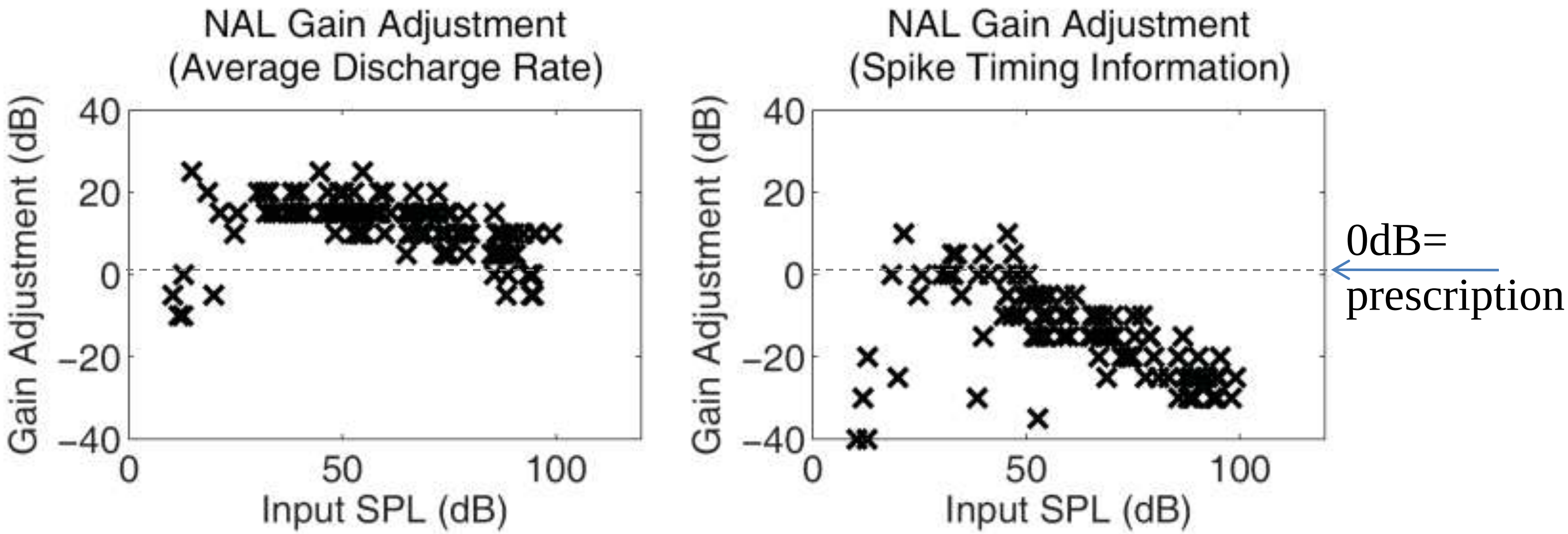
Aided (Impaired)	Normal	Cross-Condition



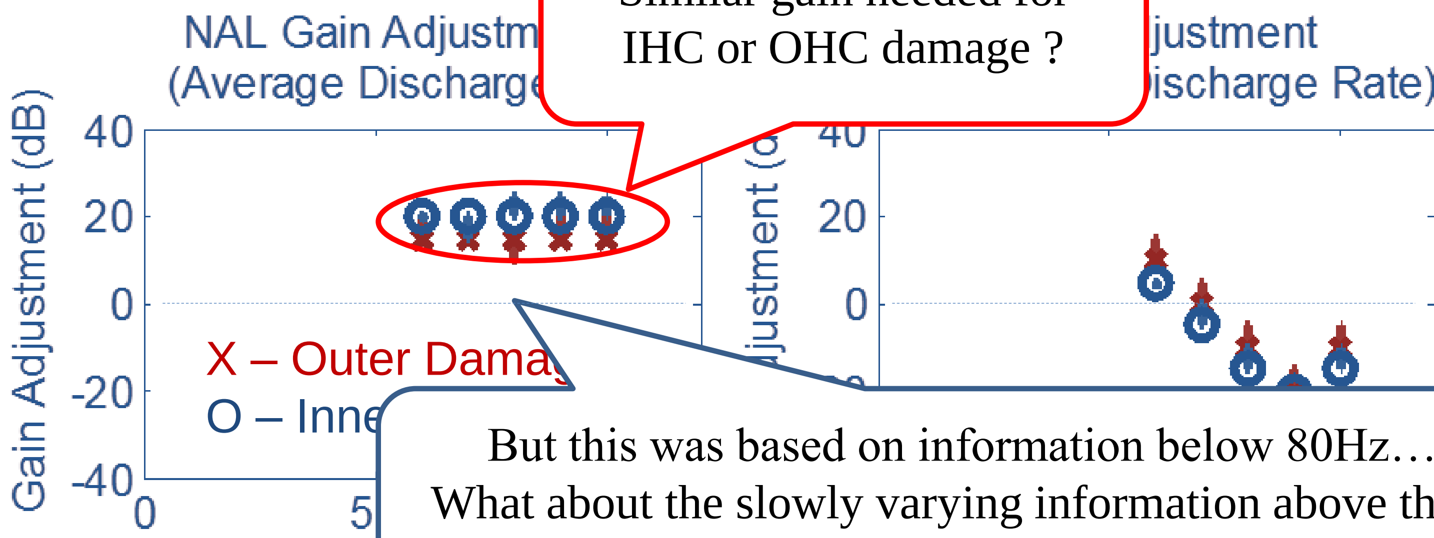
Heinz, M. G., and Swaminathan, J. (2009). “Quantifying envelope and fine-structure coding in auditory-nerve responses to chimaeric speech,” J Assoc Res Otolaryngol, 10, 407–23.

Study 1: Results

- Quick reminder of Bruce et al (2007):

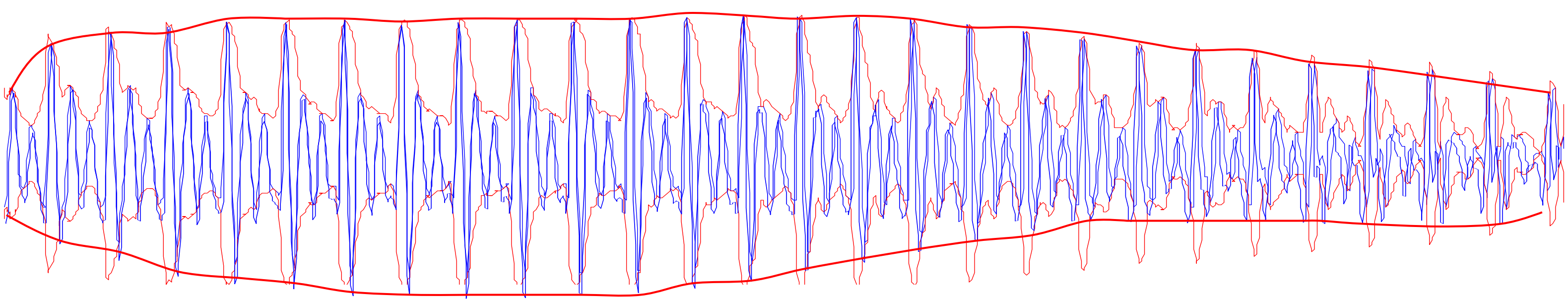


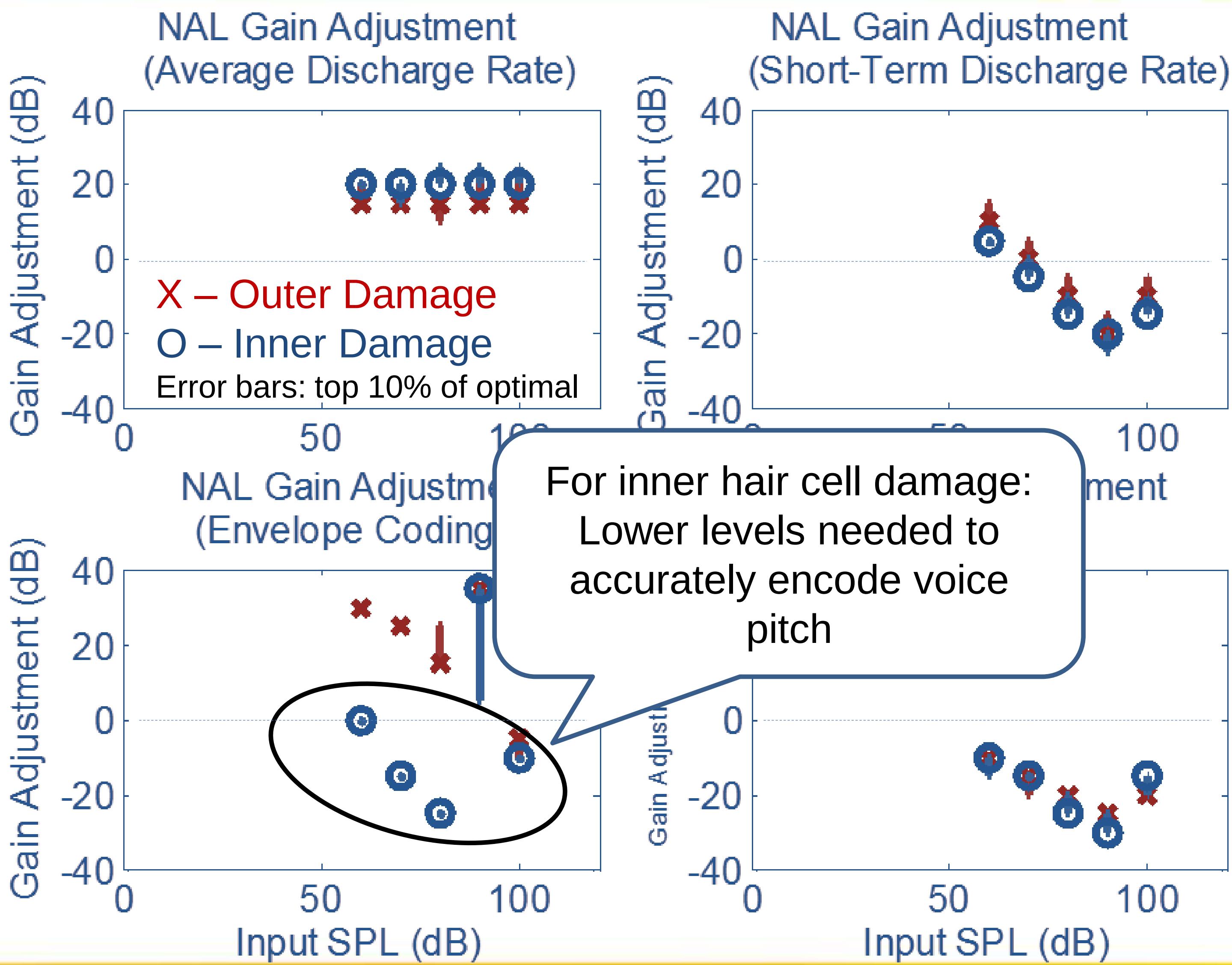
Outer / Inner Hair Cell Damage



Similar gain needed for IHC or OHC damage ?

But this was based on information below 80Hz…
What about the slowly varying information above that?
(e.g. voice pitch is in the region of 100-300Hz)




NAL Gain Adjustment (Average Discharge Rate)
NAL Gain Adjustment (Short-Term Discharge Rate)
NAL Gain Adjustment (Envelope Coding
ment
Gain Adjustment (dB)
Input SPL (dB)
X – Outer Damage
O – Inner Damage
Error bars: top 10% of optimal
For inner hair cell damage: Lower levels needed to accurately encode voice pitch

Study 1: Conclusions

- For people with primarily inner hair cell damage:
  - Decreased gain may enhance neural coding of pitch
- For all hearing impaired:
  - Prescriptive gain with compression may be optimal for noisy conditions
- But hearing aid users obviously have trouble in noise, so maybe we need more than just amplification…
  - **Rather than optimizing the average of individual fibers, let's look at relative coding across fibers**

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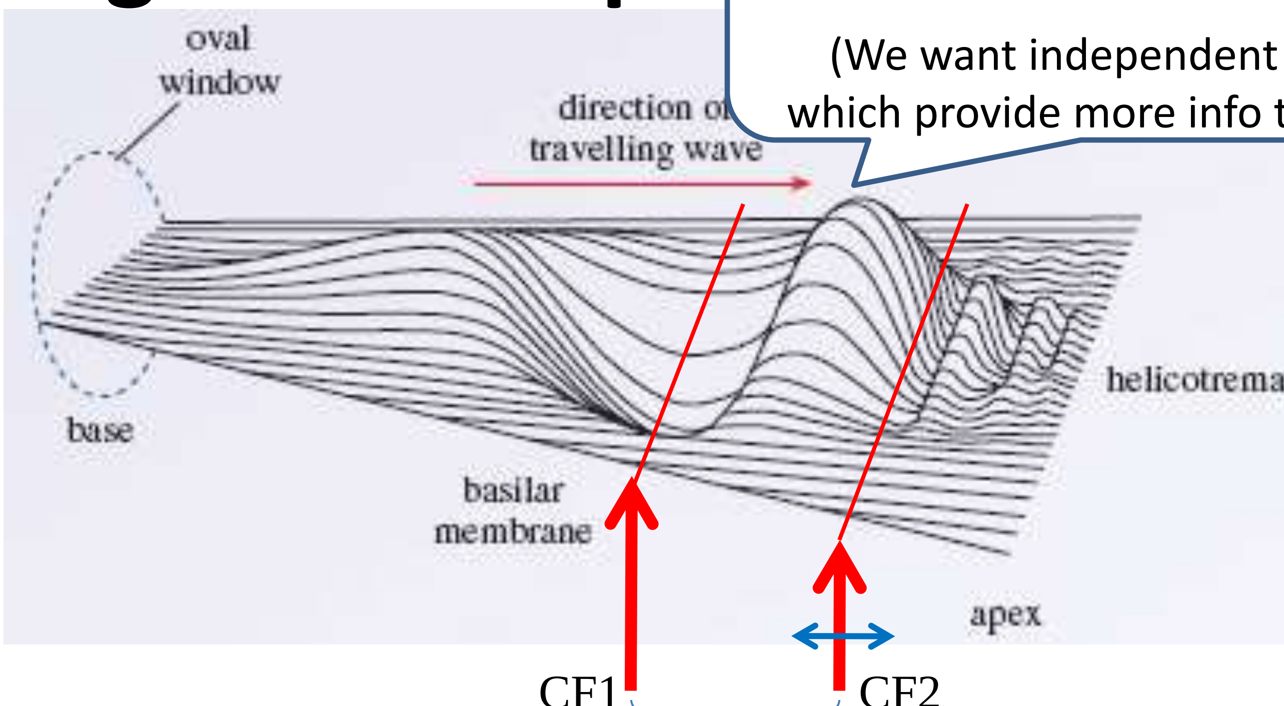
Study 2: Background

Traveling Wave & Spat

Note: we want **low** correlation and **high** delay

(We want independent channels, which provide more info to the brain)



Measure difference in temporal patterns
(e.g., correlation & delay)

Image from http://openlearn.open.ac.uk/mod/resource/view.php?id=263156

Pitch is especially important for understanding concurrent speech
(Assmann & Summerfield 1990; Meddis & Hewitt 1992; Scheffers 1983).

ding

..

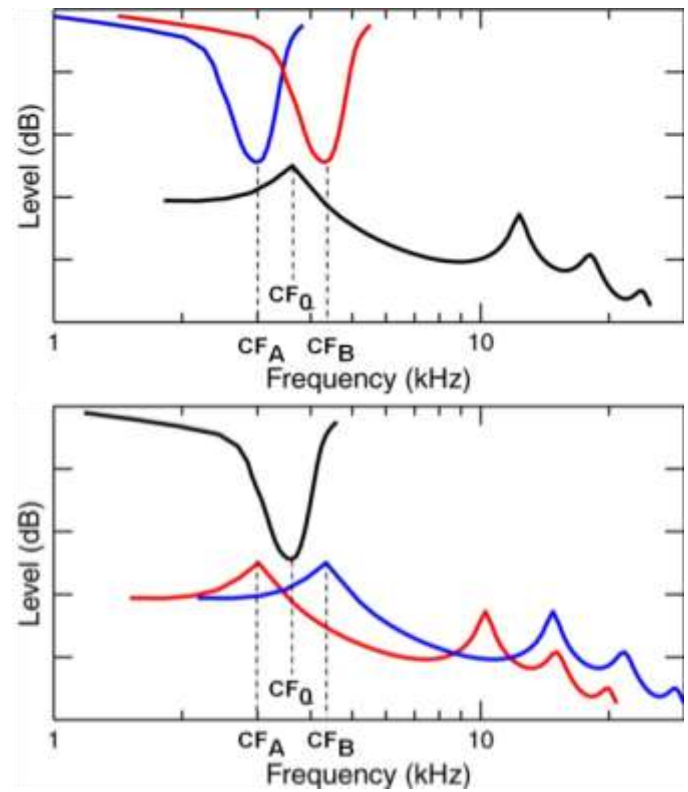
- **Spee**
  - Shamm), Deng and Geisler (1987); Heinz (2007)
- **Pitch**
  - Loeb et al (1983); de Cheveigne´ and Pressnitzer (2006); Cedolin and Delgutte (2007); Larsen et al (2008); Cedolin and Delgutte (2010)
- **Loudness**
  - Carney (1994); Heinz et al (2001)
- **Masking**
  - Carney et al (2002)
- **Localization**
  - Shamma (1989); Joris et al (2006)

Study 2: Methods

We simulate a *population* to evaluate relative timing of nearby fibers

- It is very difficult to measure the exact nerve fibers of interest *in vivo*

- Spectro-Temporal Manipulation Procedure (STMP):
  - Adjust sample rate (up/down)
  - Record spikes
  - Scale spike times (up/down)

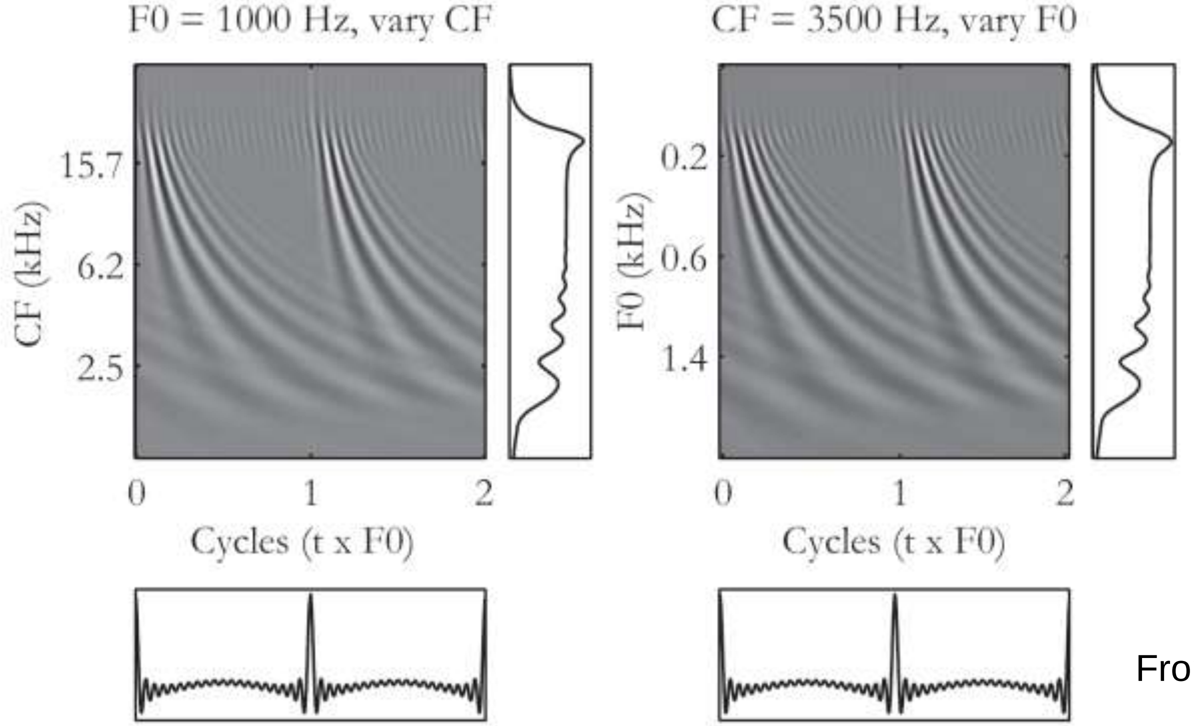


Heinz MG. 2005. Spectral coding based on cross-frequency coincidence detection of auditory-nerve responses. In *Assoc. for Res. in Otolaryngology.*

The STMP works because of

Cochlear Scaling Invariance:

response depends primarily on f/CF



From Larsen et al (2008)

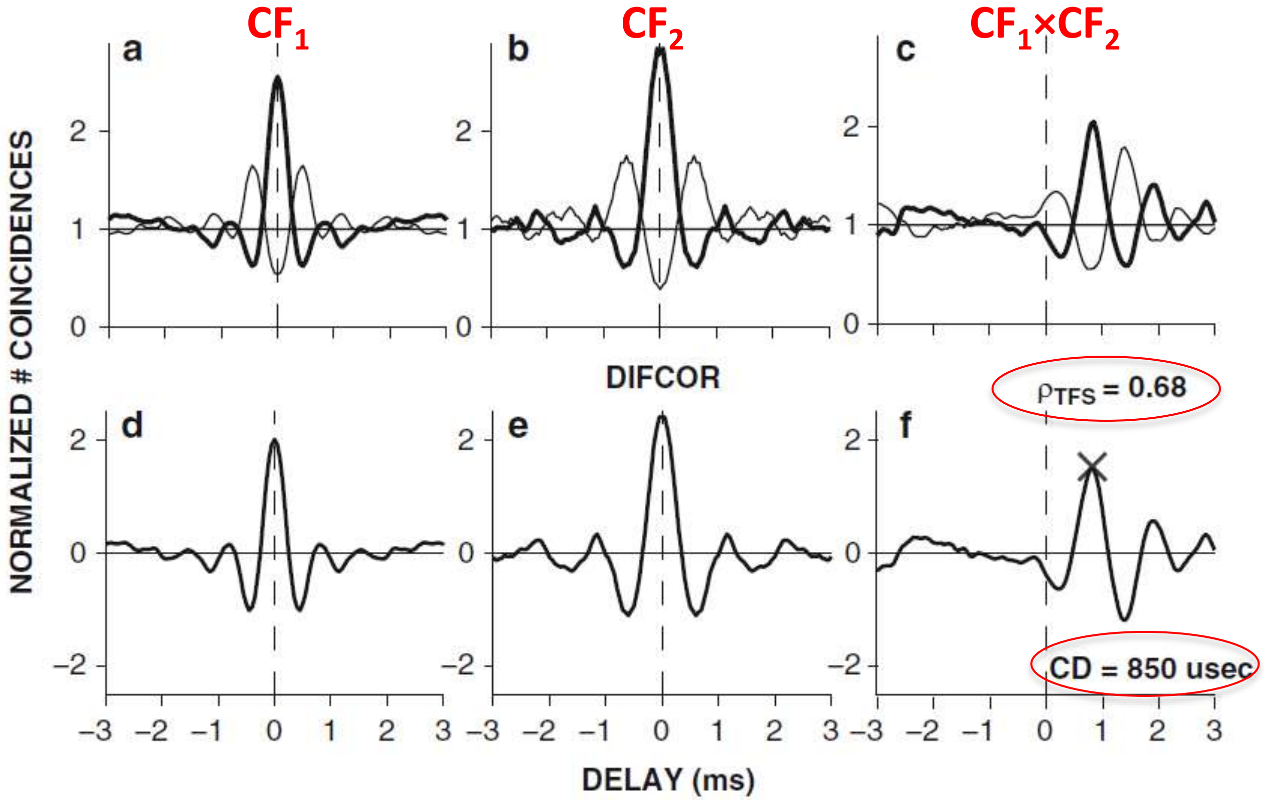
Zweig, G. (1976). “Basilar membrane motion,” Cold Spring Harbor Symposia on Quantitative Biology, Cold Spring Harbor Laboratory Press, 619–633.
Larsen E, Cedolin L, Delgutte B. 2008. Pitch representations in the auditory nerve: two concurrent complex tones. *J Neurophysiol 100:1301-19*

Study 2: Methods (continued)

- 2 Chinchillas (1 normal-hearing; 1 hearing-impaired)
- Noise-Induced Hearing Loss
  - Noise band at 2kHz (50Hz wide)
  - 115dB SPL for 4 hours (under anesthesia)
  - 6 weeks for hearing loss to stabilize
- Stimuli: broadband noise & speech sentence
  - 10-20dB above AN fiber threshold
  - Sample rate adjusted for STMP (range of 1 octave)

Cross-CF Correlation

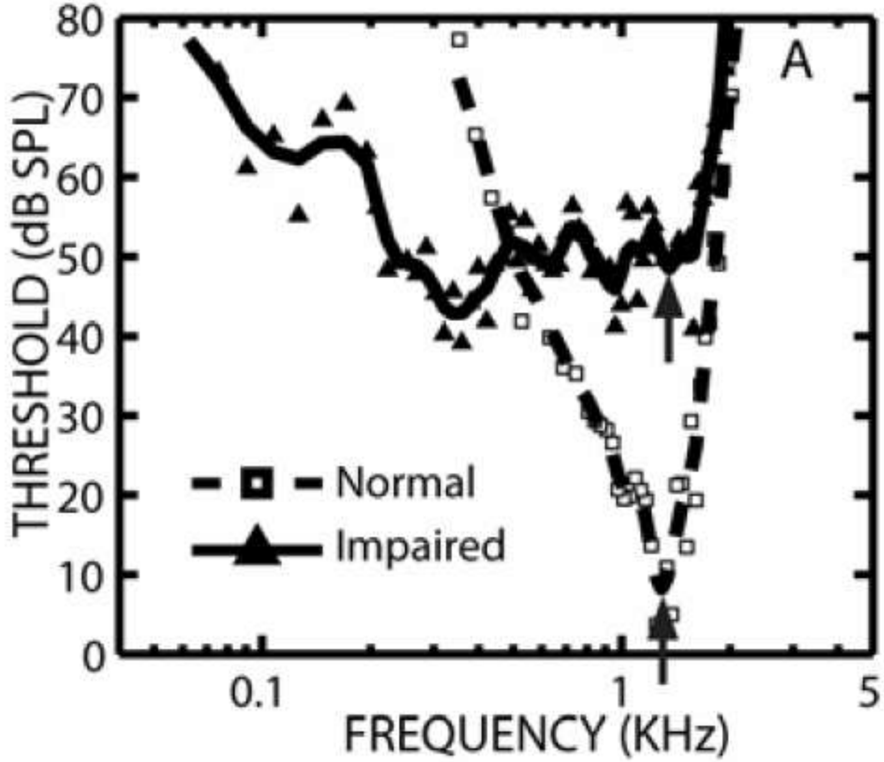
was used to calculate cross-CF correlation & delay



Heinz, M., J. Swaminathan, **J. Boley**, and S. Kale, "*Across-Fiber Coding of Temporal Fine-Structure: Effects of Noise-Induced Hearing Loss on Auditory Nerve Responses,*" *in Auditory Physiology, Perception and Models. Springer (New York), 2010.*

Study 2: Results

Impaired cochlea has worse tuning



2 representative AN fibers

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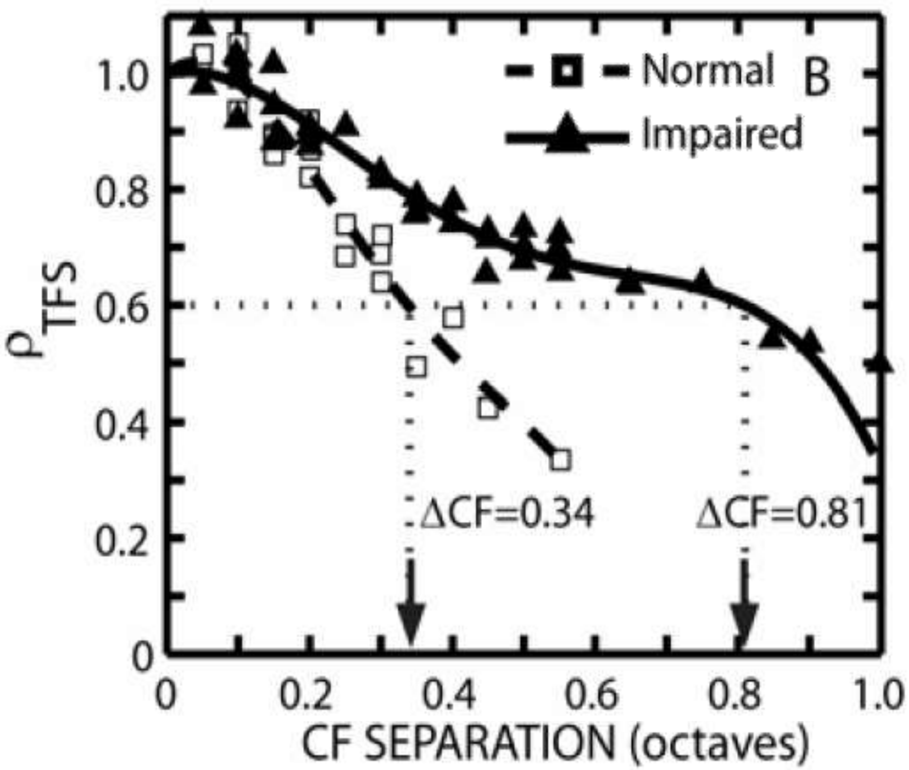
Correlation

Impaired cochlea has more correlated activity



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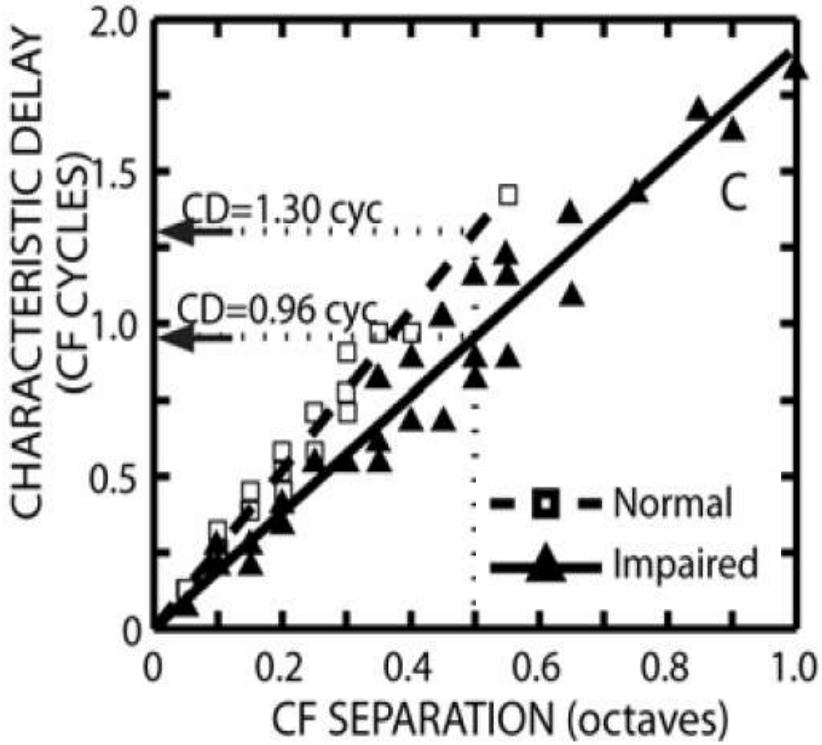
Traveling Wave Delay

Impaired cochlea has smaller delay



2 representative AN fibers

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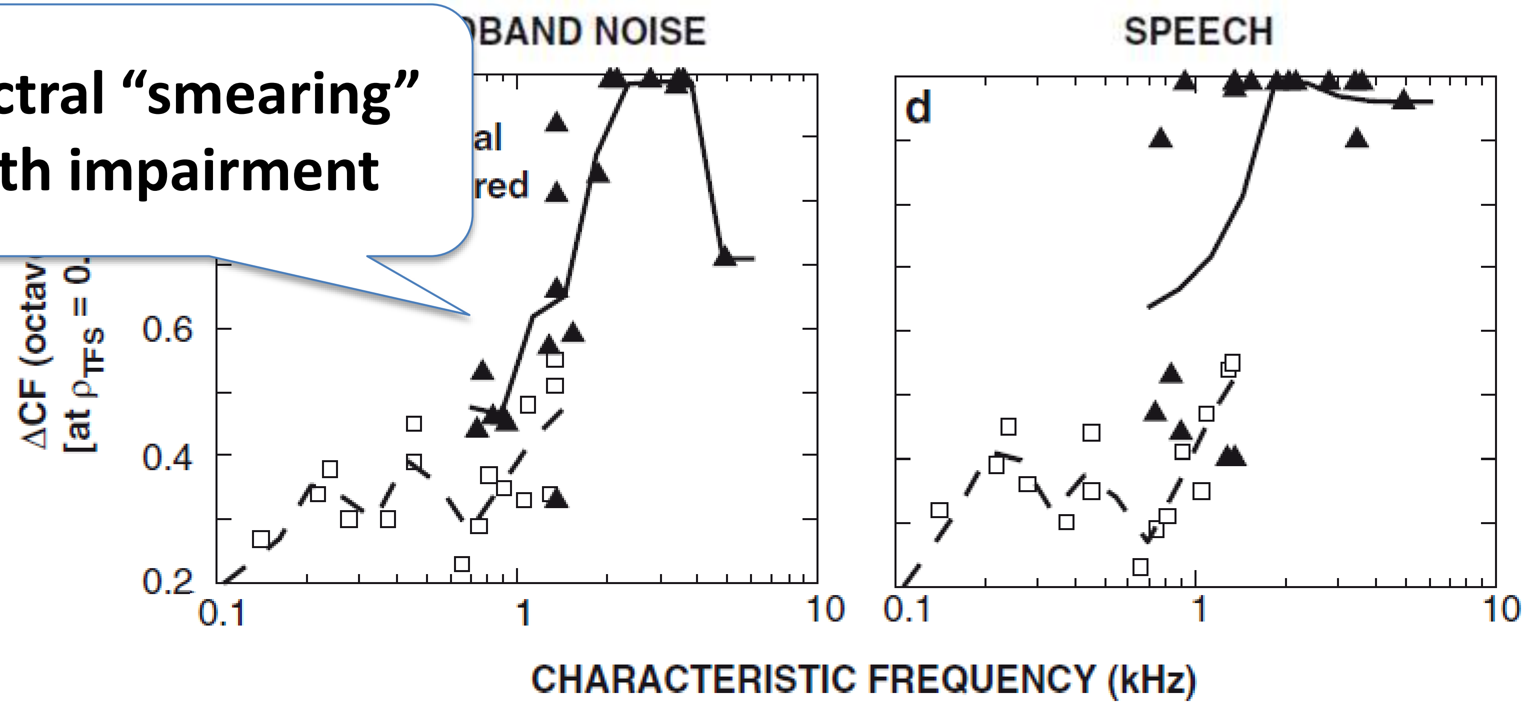
Impairment results in wider area of correlated activity

Current hearing aids do not correct for this

Spectral "smearing" with impairment



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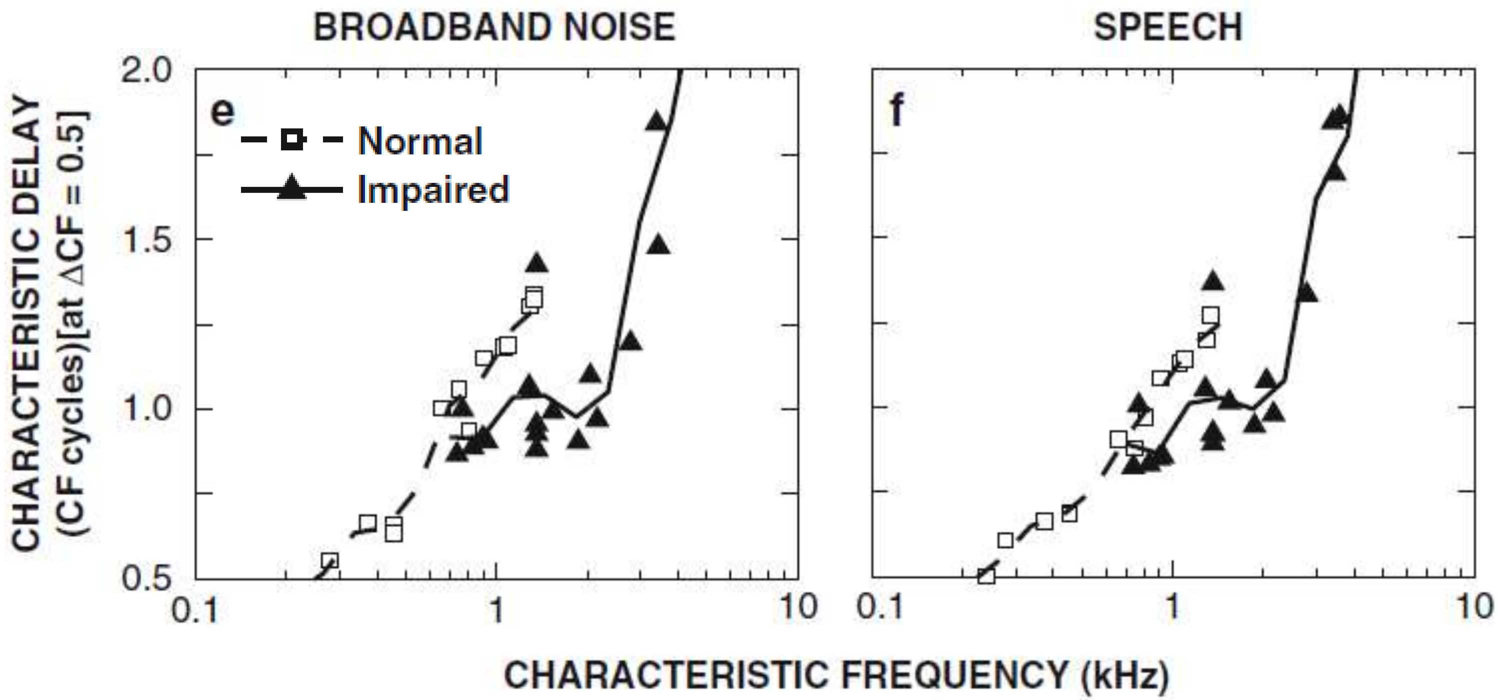
Impairment results in less delay between adjacent CFs

Current hearing aids do not correct for this



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Study 2: Conclusions / Discussion

- Across-CF coding is degraded with NIHL
  - Broad region of correlated activity
    - Consistent with broad auditory filters
    - Expected to reduce number of independent channels
  - Reduced traveling-wave delay
    - More coincident representation of temporal features across CF
    - Potentially degraded spatiotemporal cues important for perception
    - May also impact localization if binaural cochlear timing disparities are important*

* Joris, P. X., de Sande, B. Van, Louage, D. H., and van der Heijden, M. (2006). "Binaural and cochlear disparities," Proc Natl Acad Sci U S A, 103, 12917–12922.

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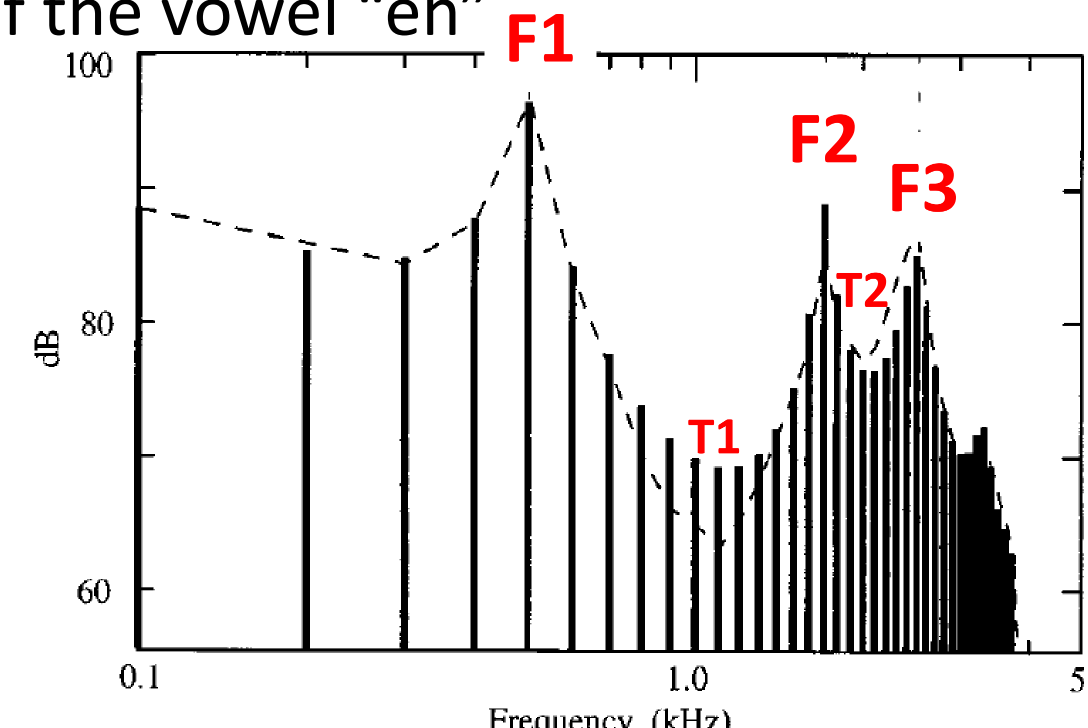
Study 3: Background

Spectrum of the vowel “eh”



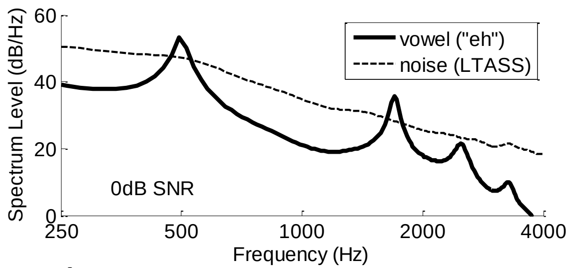
Miller, R. L., Schilling, J. R., Franck, K. R., and Young, E. D. (**1997**). “Effects of acoustic trauma on the representation of the vowel ‘eh’ in cat auditory nerve fibers,” Journal of Acoustical Society of America, **101**, 3602–3616.

Study 3: Background

- Miller et al (1997) showed that, with hearing loss…
  - AN fibers with CFs *near vowel formants* phase-lock to individual harmonics (rather than formants)
- Schilling et al (1998) showed that, with hearing loss…
  - AN fibers with CFs *between formants* respond more to formants than normal (“spread of synchrony”)
  - Spectral contrast enhancement can limit the spread of synchrony for F1, but not higher formants

Study 3: Methods

- 9 chinchillas with normal-hearing
- 8 chinchillas were over-exposed to noise
  - 500Hz, octave-wide noise; 116dB SPL for 2 hours
- Vowel “eh” presented at 67% of each AN fiber’s dynamic range; Formant of interest (F1 or F2) was centered on CF
- Speech-shaped noise was added at 2 levels:
  - Ec
  - Ec
    - te response was the same as in quie

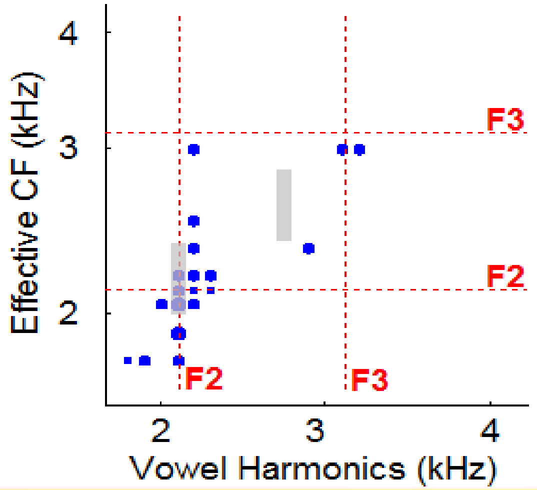


Predicted responses from:
209 normal-hearing CFs
242 hearing-impaired CFs

- The STMP was used to study CFs near F1 and F2

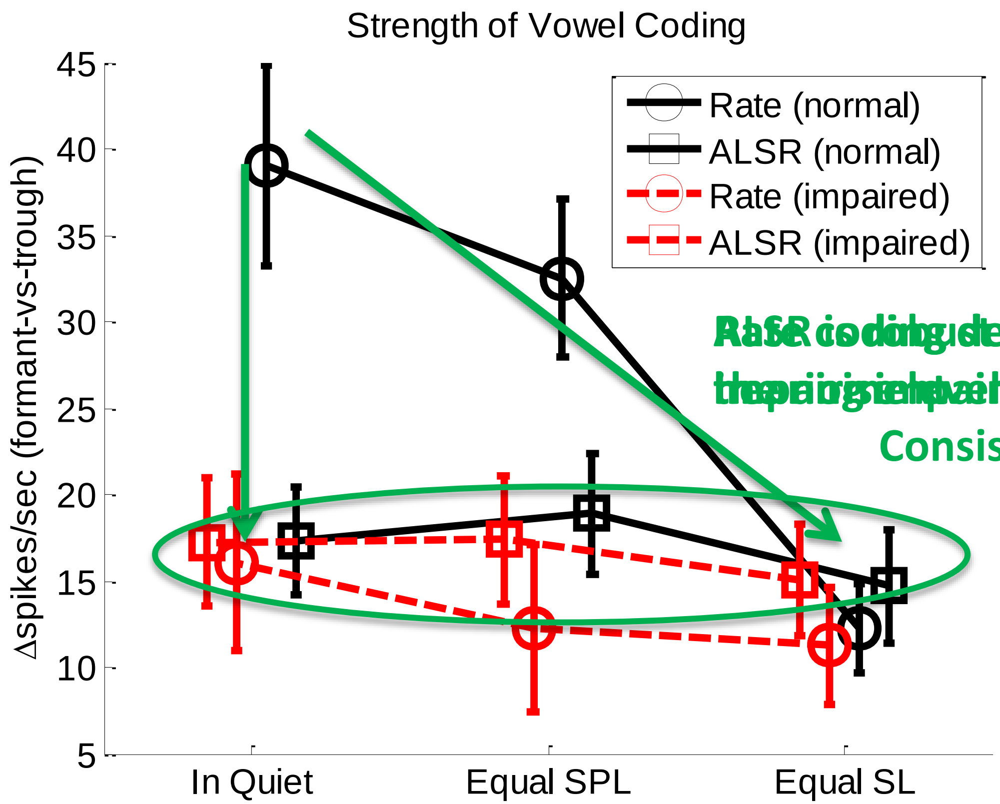
Study 3: Methods (part deux)

- Rate Coding was quantified by comparing the rate at each formant to the rate in the spectral trough
(e.g., rate for a CF at F1 relative to rate for a CF between F1 and F2)
- Average Localized Synchronized Rate (ALSR) was quantified by comparing the synchronized rate near each formant to the synchronized rate in the trough
- Spatiotemporal coding was quantified as in the previous study (cross-CF correlation & delay)



Study 3: Results

ALSR is more robust than rate coding



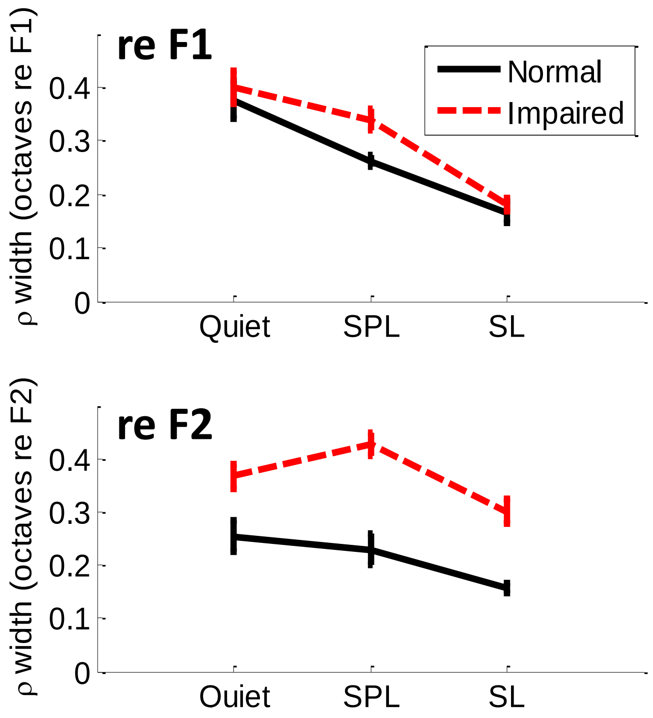
Rate coding degrades with hearing impairment

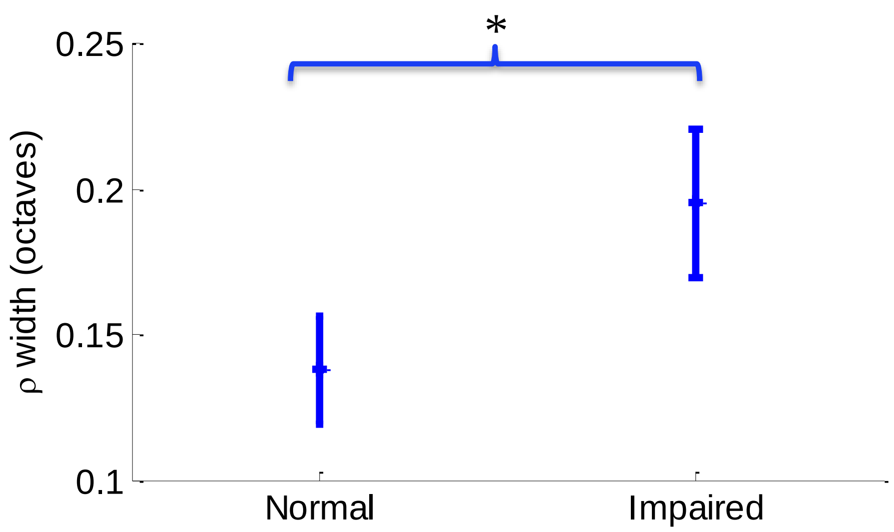
ALSR is robust to noise & the noise level is increased

Consistent with previous studies

Study 3: Results

Across-CF Correlation Increases with Impairment

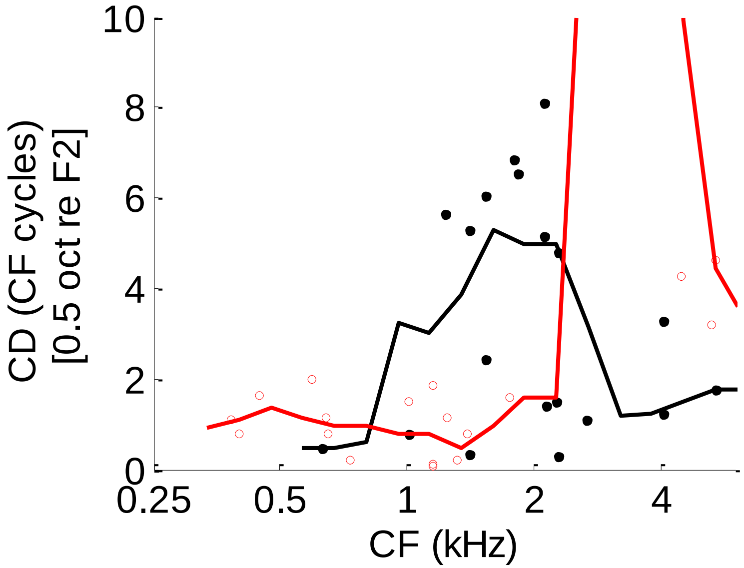


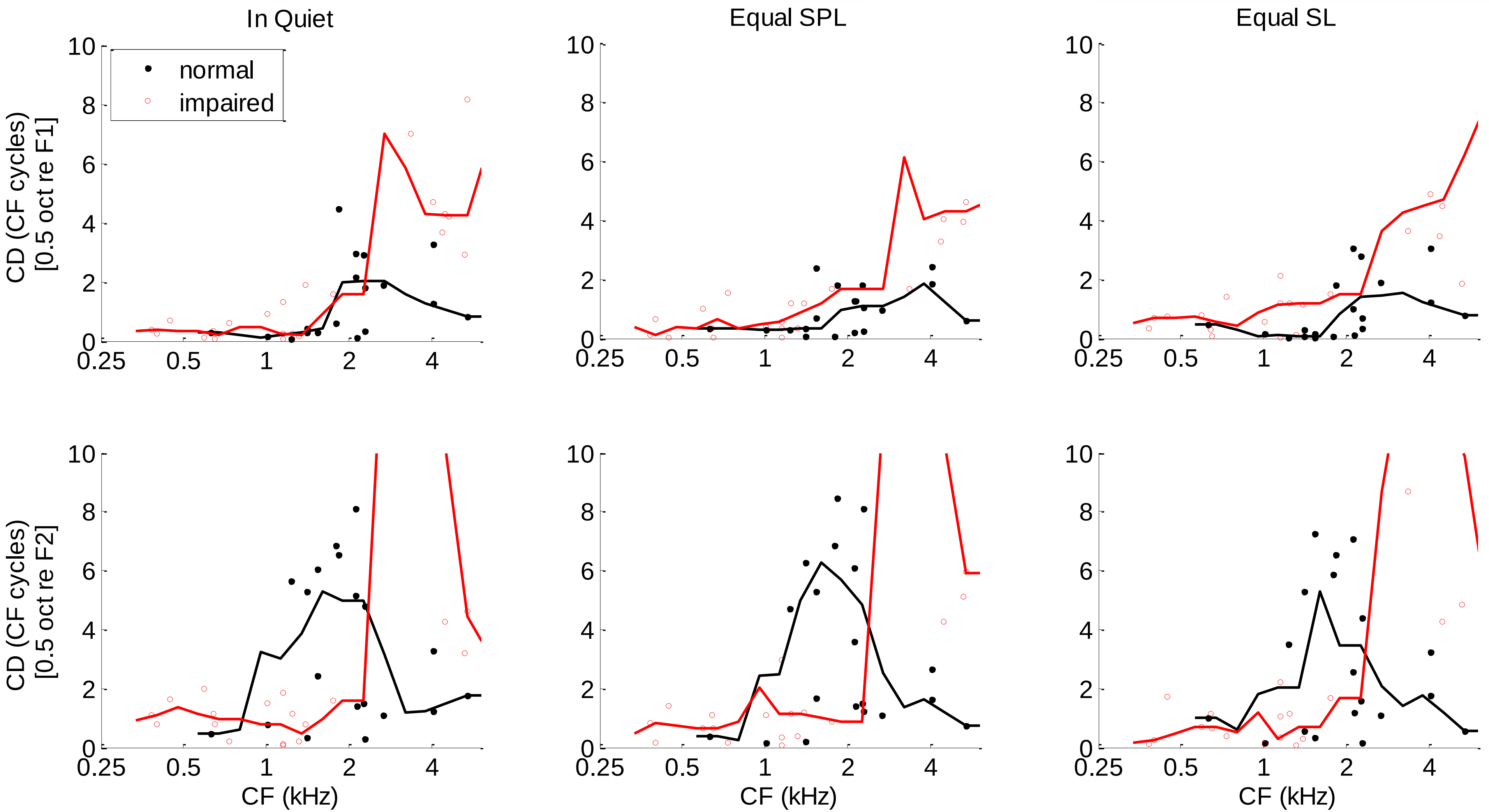


Study 3: Results

Across-CF Delay is reduced with impairment, but robust to noise

- Near F2, $CD_{normal} > CD_{impaired}$ (Wilcoxon Rank Sum; $p<0.05$)
- No effect of noise level




In Quiet
Equal SPL
Equal SL
normal
impaired
CD (CF cycles) [0.5 oct re F1]
CD (CF cycles) [0.5 oct re F2]
CF (kHz)
0.25
0.5
1
2
4
0
2
4
6
8
10

Study 3: Conclusions

- Spatiotemporal coding is robust to noise, but degraded with impairment
  - Particularly near second formant, where more nonlinearity is expected??

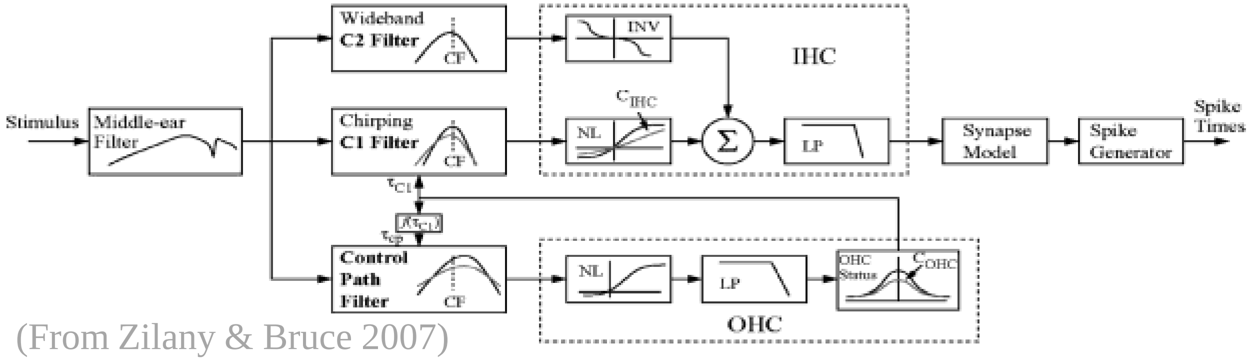
Topics

0. Brief Review of Neural Coding
1. Physiology-Based Hearing Aid Design

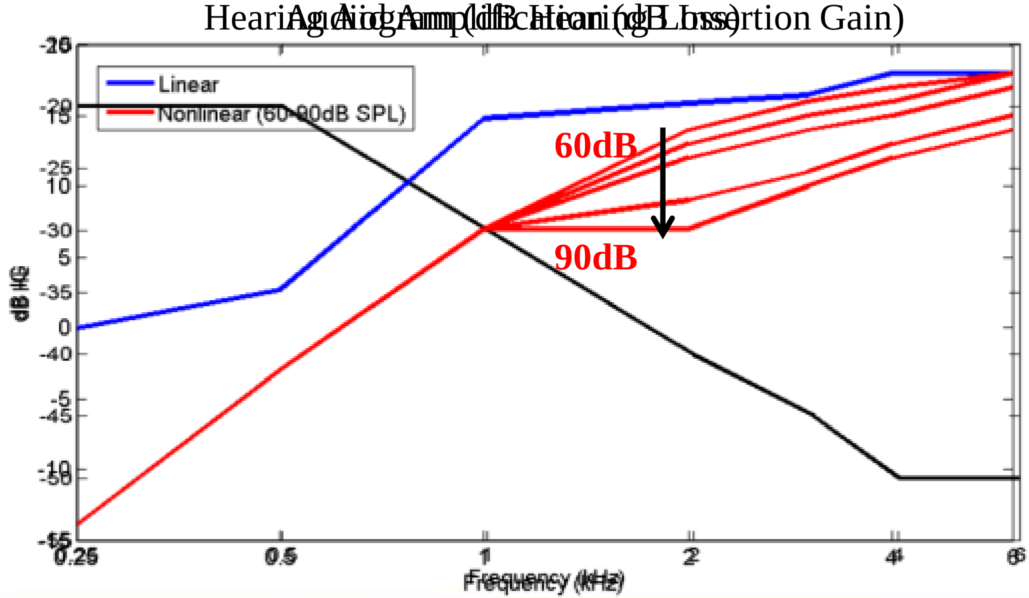
<u>Spatiotemporal Coding:</u>

2. Effects of Hearing Impairment
3. Impaired Coding of Vowels in Noise
4. Impaired Coding of ***Aided*** Vowels in Noise  
5. Limitations of Spatiotemporal Pattern Correction

Study 4: Background (Modeling Study)

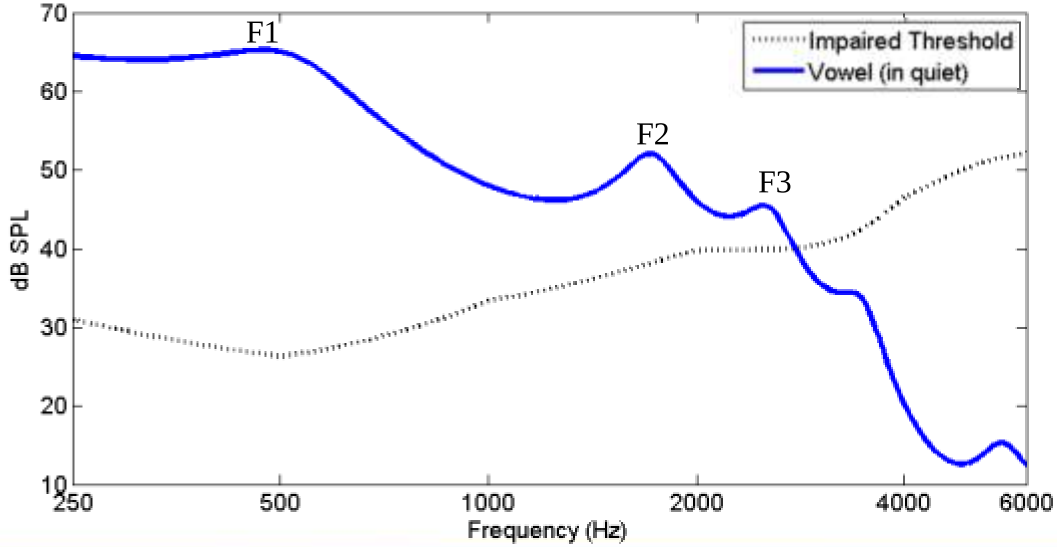


(From Zilany & Bruce 2007)

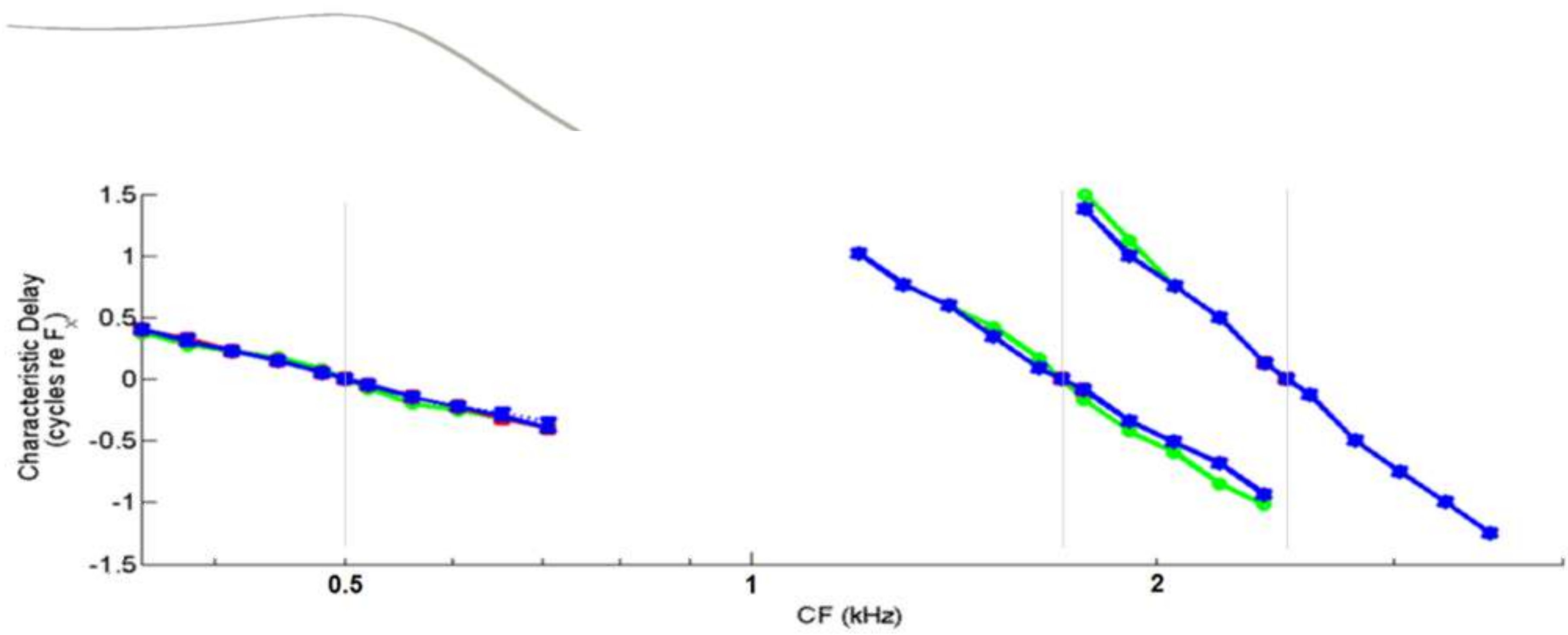


Stimulus: Synthesized Vowel “Eh”

- Vowel at 65dB SPL
- White noise added to achieve various SNRs (at each formant frequency)

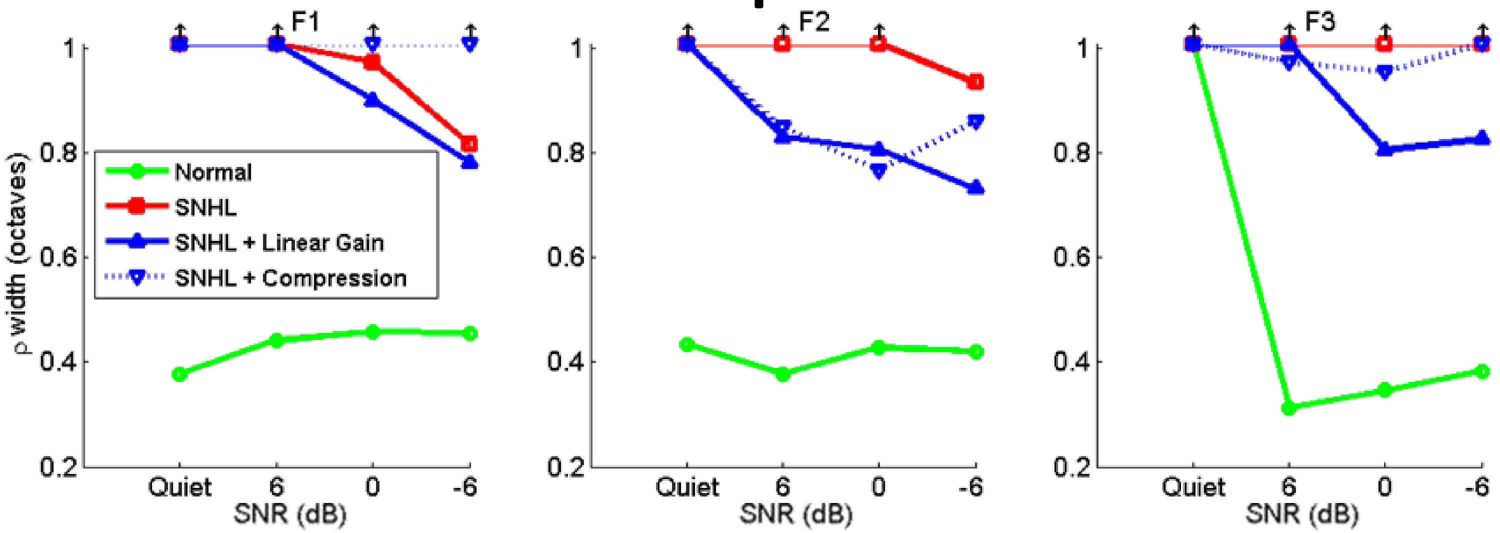


Spatiotemporal Coding was quantified around first 3 formants



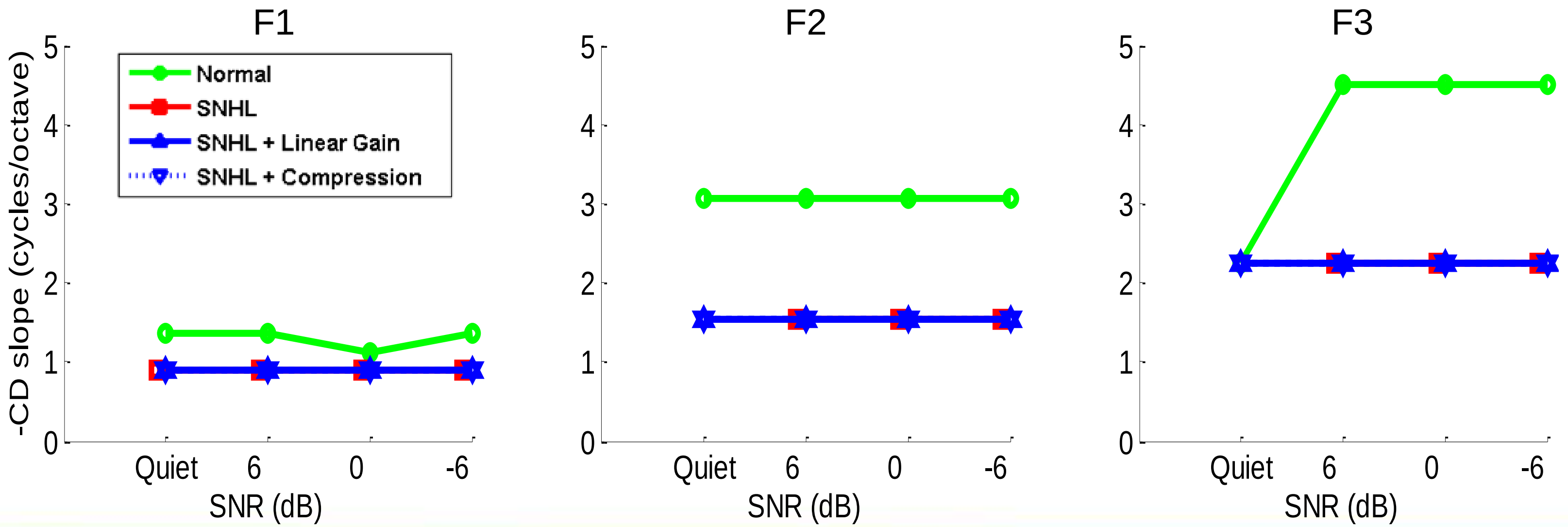
Modeling suggests that …

The **width of correlated activity** is **not** returned to normal after amplification



Modeling suggests that …

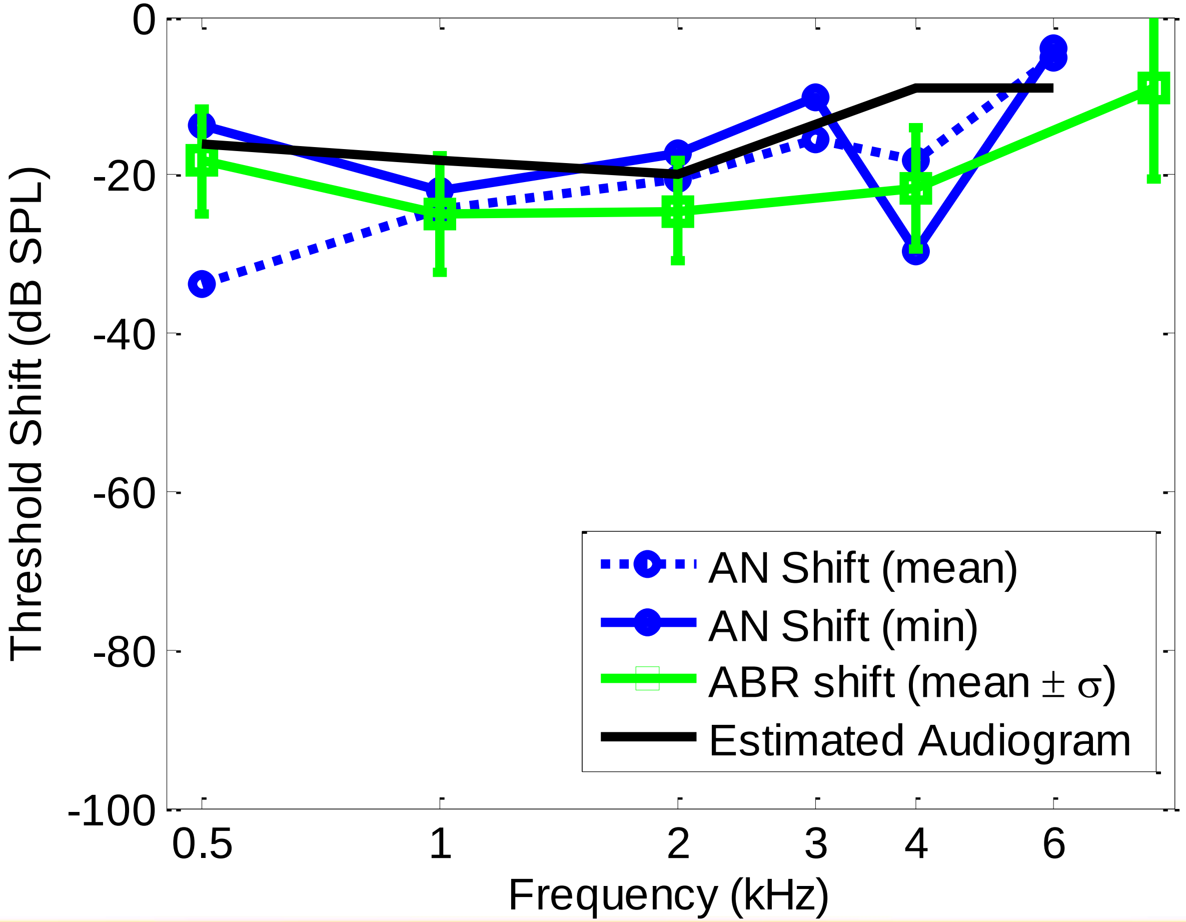
The **slope of the delay function** is **not** returned to normal after amplification



Study 4: Methods

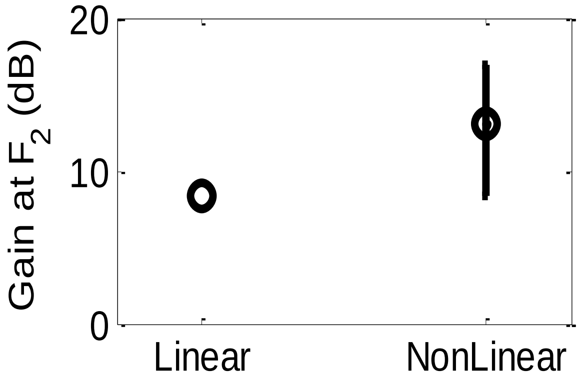
- 4 Chinchillas
  - over-exposed to noise (as in previous study)
- Stimuli: vowel in noise (as in previous study)
- Hearing aids implemented in Matlab, to provide gain
  - Stimuli presented through stereotaxic ear bar (as in previous study)
  - Hearing loss estimated from previous experiments

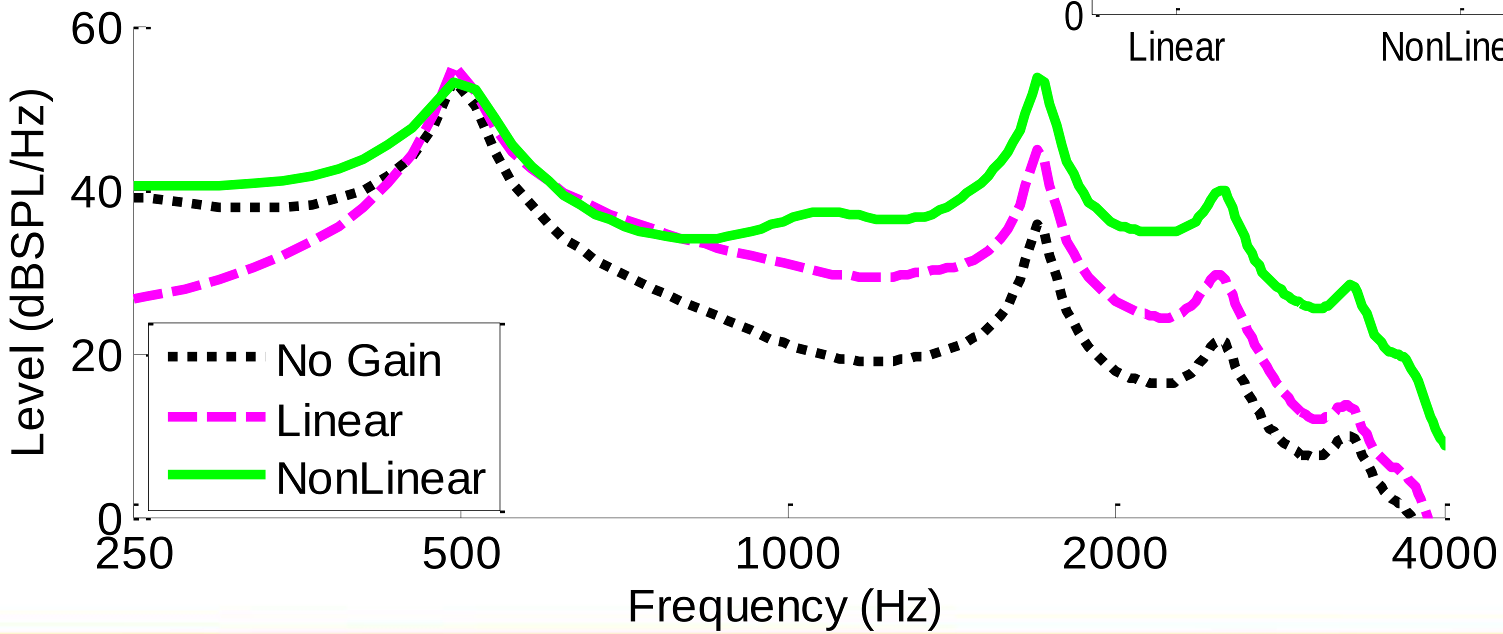
Estimated Hearing Loss



Hearing Aid Gain

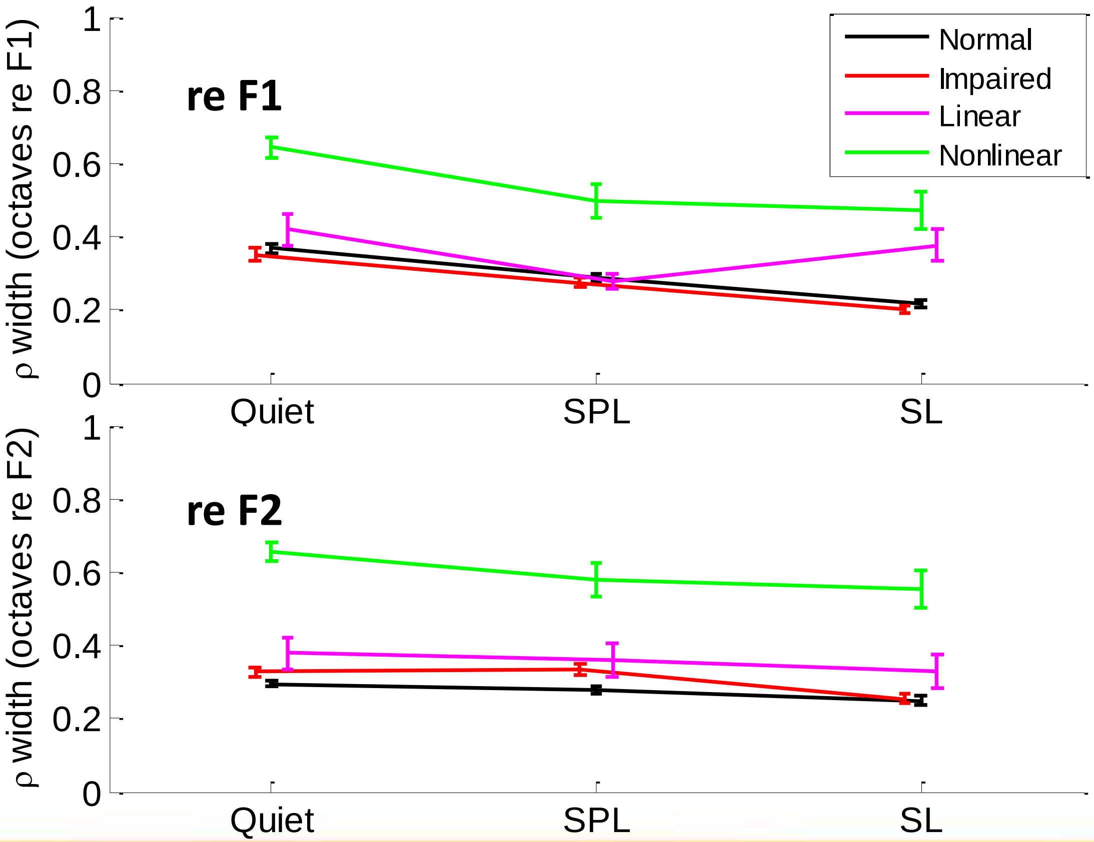
- Linear Gain: NAL-R prescription
- NonLinear Gain: DSL [i/o]
  - F1 & F2 in different channels





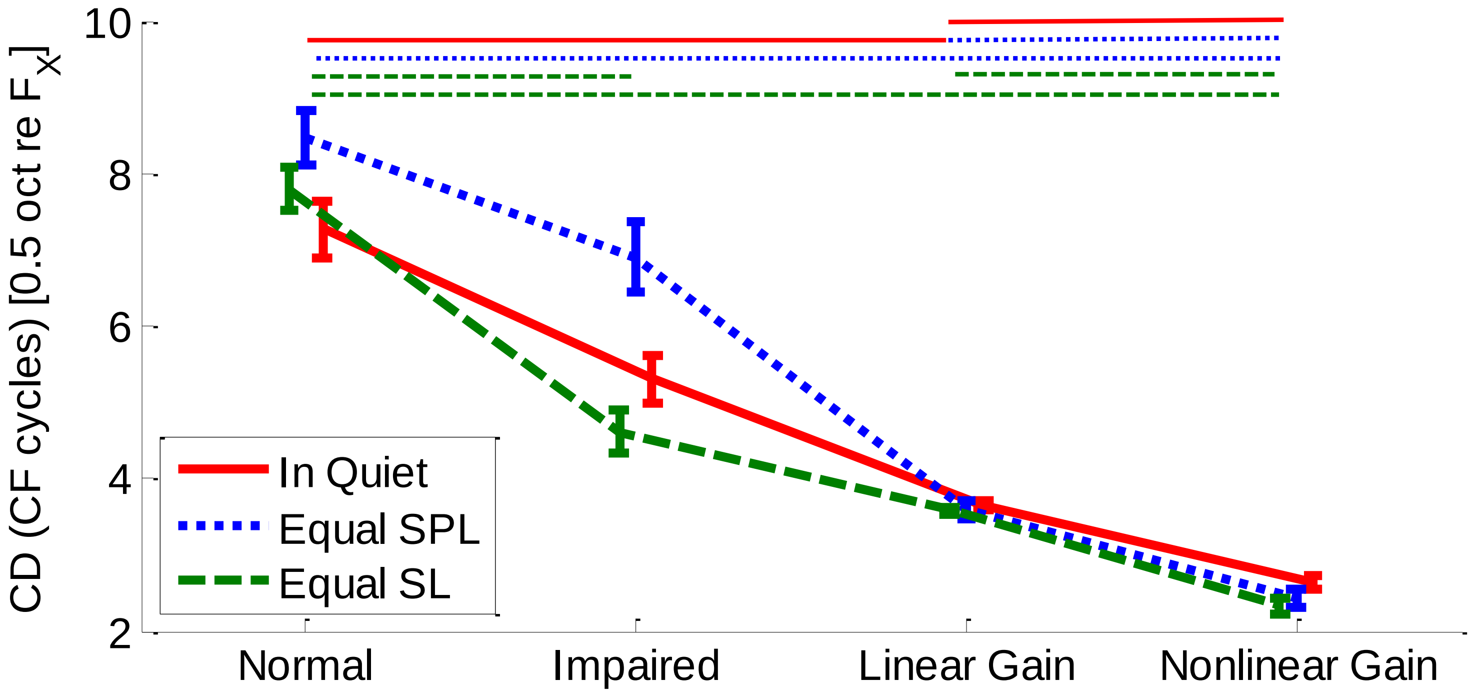
Study 4: Results

Hearing Aid Gain Does Not Decrease Across-CF Correlation



Study 4: Results

Hearing Aid Gain Does Not Increase Across-CF Delay



Study 4: Conclusions

- Hearing aids do not improve spatiotemporal coding
  - They may potentially degrade ST coding, as the increased sound levels result in wider auditory filters
  - They may not be beneficial for any percept that relies on spatiotemporal coding
    - e.g., Speech intelligibility with multiple talkers remains poor (Summers and Leek, 1998; Rossi-Katz and Arehart, 2005)

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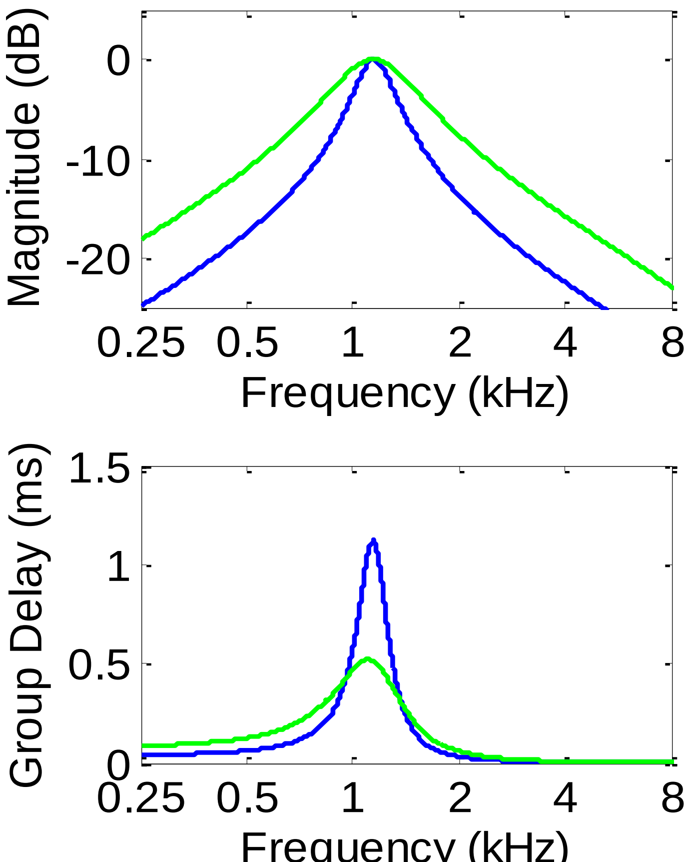
Study 5: Background

- Hearing impairment:
  - Broad auditory filters
  - Less delay
- Carney *et al (2006)* proposed to add back in missing delay
  - The resulting neural patterns were not analyzed to confirm the desired effect



Shi, L.-F., Carney, L. H., and Doherty, K. A. (**2006**). "Correction of the peripheral spatiotemporal response pattern: a potential new signal-processing strategy," **49**, 848–855.

Study 5: Methods

- Stimulus was the vowel “eh” at 65dB SPL
  - filtered to add varying amounts of frequency-dependent delay
- Measure the across-CF delay
  - Measured delay should increase as we add more delay to the stimulus

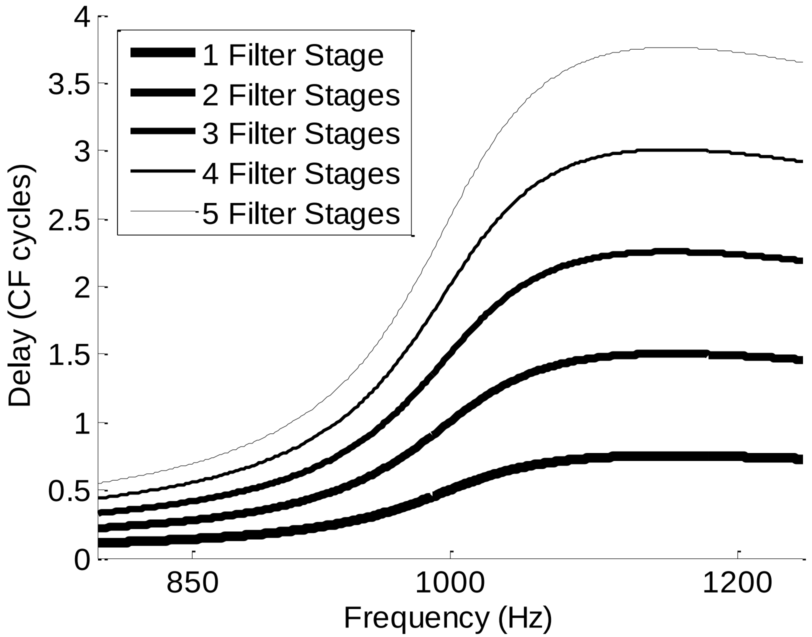
All-Pass Filter Design

$$H(z) = \frac{r_0 + r_1(1 + r_0 r_2)z^{-1} + r_2 z^{-2}}{v_2 + v_1(1 + v_0 v_2)z^{-1} + v_0 z^{-2}}$$

$$v_0 = r_0 = \frac{D_{max} - 2}{D_{max} + 2}$$

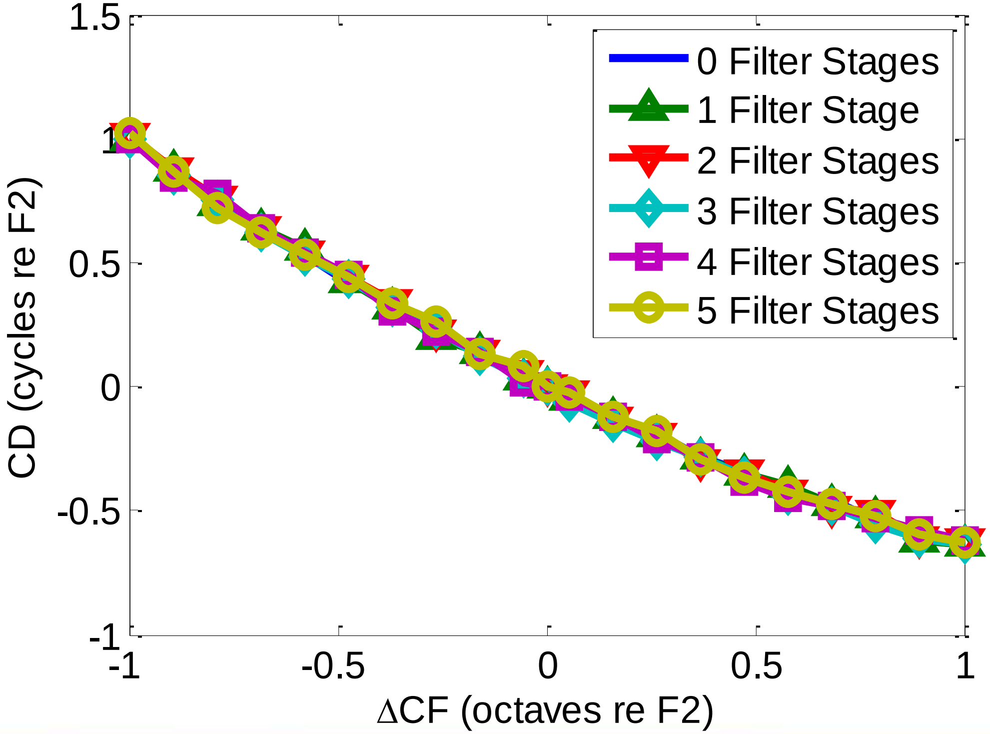
$$v_1 = r_1 = -\cos\frac{2\pi f}{F_S}$$

$$v_2 = r_2 = 1$$



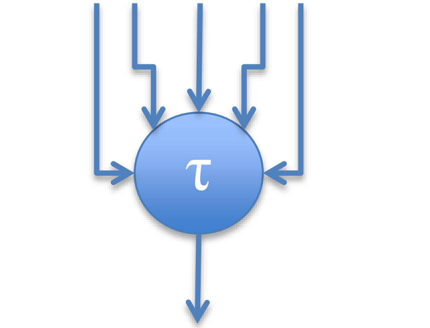
Study 5: Results

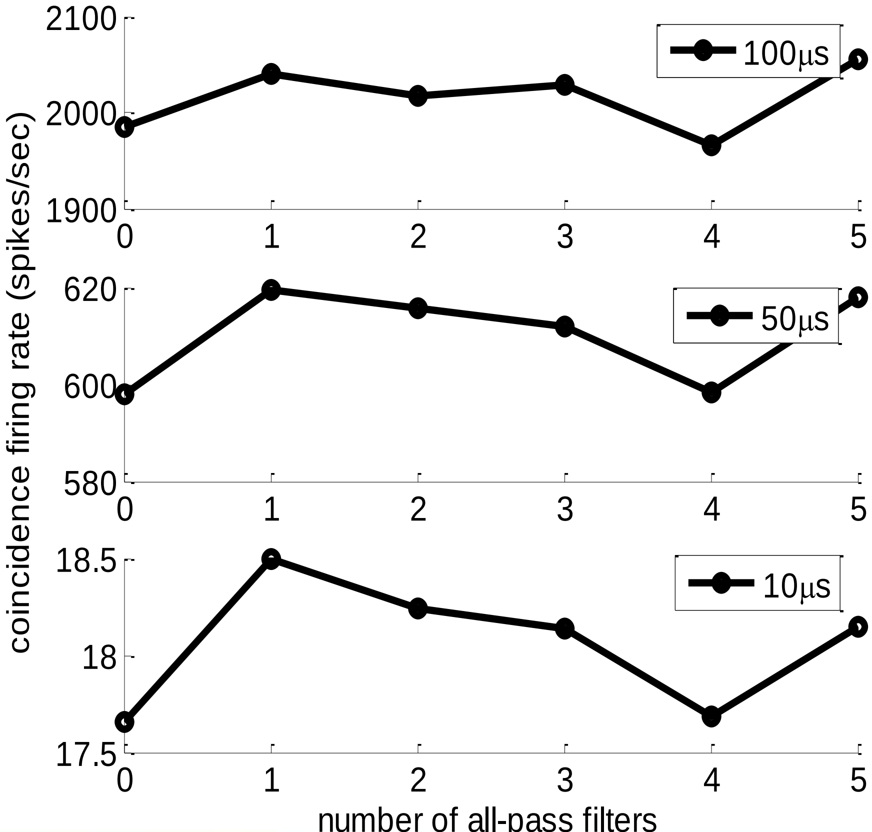
Delays in the stimulus do not affect the spatiotemporal pattern



Confirmation: Across-CF coincidence does not decrease with additional delay

10 input CFs
(1kHz ± 0.25 octaves)





Krips, R., and Furst, M. (**2009**). "Stochastic properties of coincidence-detector neural cells," Neural computation.

Study 5: Conclusions

- Spatiotemporal pattern correction does not alter the across-CF timing pattern as expected
  - This represents a ***fundamental limitation*** to the approach of spatiotemporal pattern correction.
  - An ideal algorithm would alter the time delay (phase) for one CF more than for another CF, but this is not possible by adding delay to the acoustic signal.
    - This concept is similar to the inability to separately control cochlear regions with gain adjustment (Giguère and Smoorenburg, 1999; Heinz, 2010)

Giguère, C., and Smoorenburg, G. (**1999**). “Computational modeling of outer hair cell damage: Implications for hearing aid signal processing,” Models of Hearing.
Heinz, M. G. (2010). “Computational Modeling of Sensorineural Hearing Loss,” In Computational Models of the Auditory System, Springer-Verlag.

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Summary

1. Hearing aids appear to balance the needs for both envelope and fine structure information

   … The optimal gain for a given ear may depend on the ratio of IHC/OHC dysfunction (and perhaps the degree of neural degeneration)

2. Hearing impairment
   - increases across-CF correlation
   - decreases across-CF delay (faster traveling-wave)

Summary

3. Hearing impairment degrades spatiotemporal vowel coding, particularly near the second formant
4. Modern hearing aid prescriptions do not improve spatiotemporal coding
5. The CF-dependent delay cannot be corrected by adding frequency-dependent delays to the stimulus

Discussion

- Using a combination of computational modeling & neurophysiological experiments, we have shown…
  - How knowledge of the underlying physiology can inform the design of prostheses like hearing aids
  - That computational models are useful for reducing the number of animals needed to gather data (e.g., no animal experiments needed in the last study)

chinchillin'

Publications

Published

Heinz, M., Swaminathan, J., **Boley, J.**, and Kale, S. (2010). “Across-Fiber Coding of Temporal Fine-Structure: Effects of Noise-Induced Hearing Loss on Auditory-Nerve Responses,” In E. A. Lopez-Poveda, R. Meddis, and A. R. Palmer (Eds.), The Neurophysiological Bases of Auditory Perception, Springer, New York, pp. 621–630.

In Prep

Boley, J., Heinz, M. “Spatiotemporal Coding of Vowels In Noise: Effects of Impairment and Subsequent Amplification”. To be submitted to Journal of the Acoustical Society of America

Boley, J., Heinz, M. “Limitations of Spatiotemporal Pattern Correction”. To be submitted to Ear & Hearing

?