The Effects of Hearing Loss on Binaural Function

Steve Colburn

Boston University

colburn@bu.edu

•Outline

What are the major advantages of two ears?

How do the left and right signals differ?
How do we use this information physiologically?

How well can we exploit our two ears for important tasks?

- Localization of sound sources
- Attending to source of interest in complex situations

Effects of hearing impairment in binaural processing ... Interaural parameter sensitivity and speech with speech maskers.
(a study by Nathan Spencer in my lab).

What limits performance with impairments/aids/implants?

What are the major advantages of two ears?

Redundancy

Localization of sources

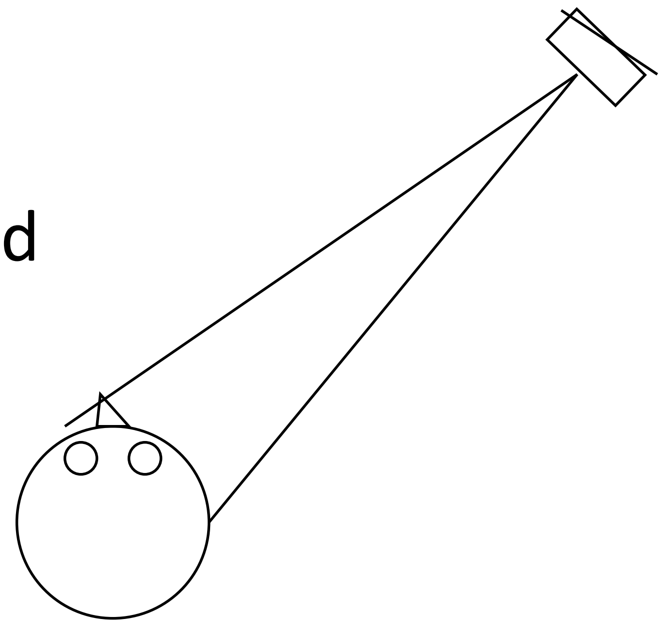
Identifying room characteristics
(size, shape, wall reflectivity, and ???)

The Cocktail Party Effect …
Renoir's “Luncheon of the Boating Party”

Different signals at the two ears

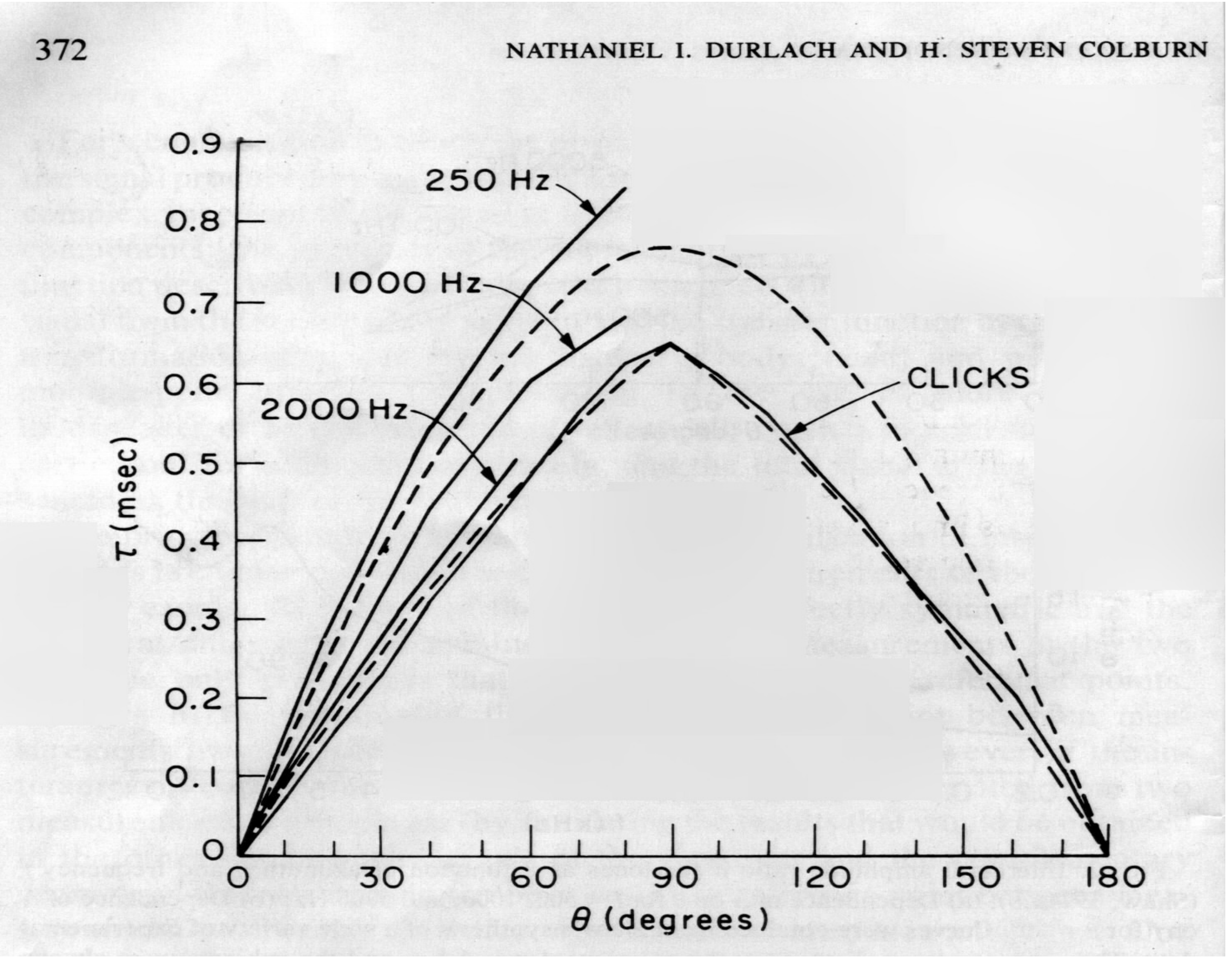
- **Localization Cues**:

- ITD: far ear delayed
- ILD: far ear attenuated
- Spectral Shapes



Interaural Time Delay (ITD)

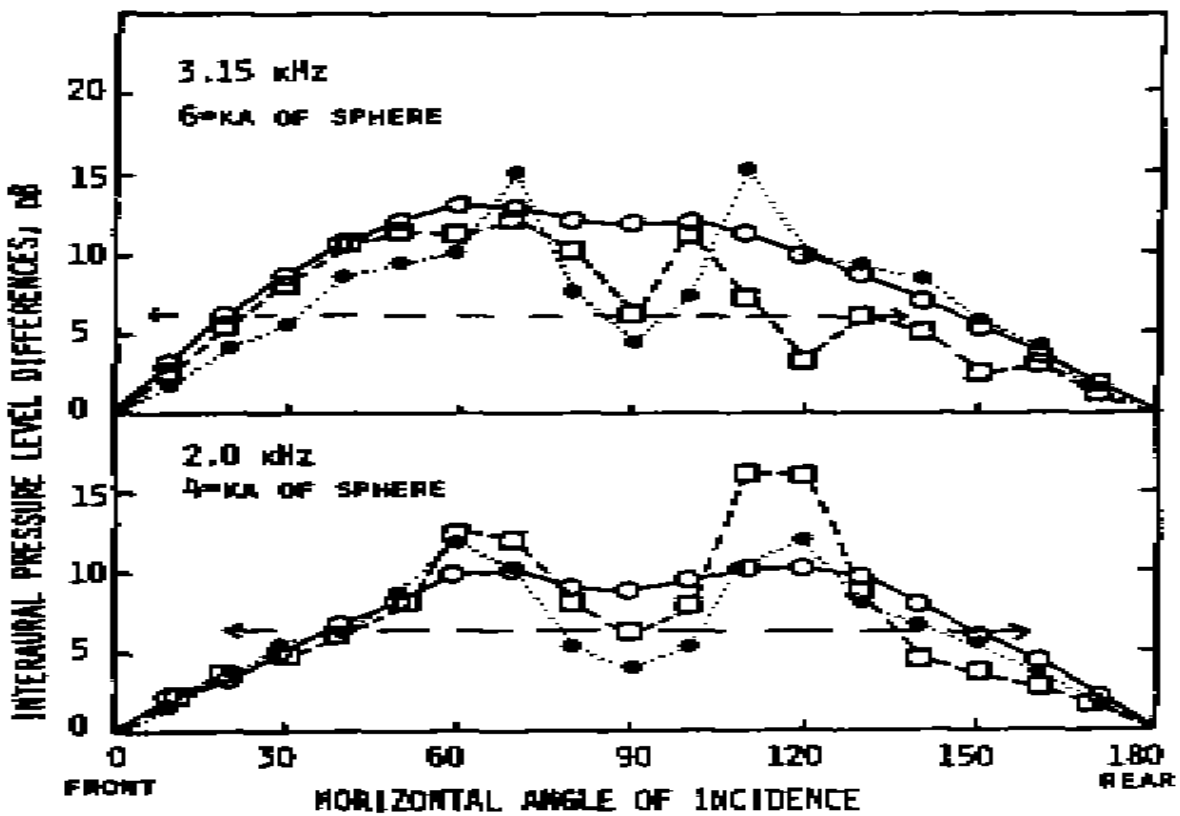
•versus azimuth θ



•Durlach and Colburn, 1978

•Interaural Level Difference (ILD)

- ILD versus azimuth for two frequencies
- Measurements and sphere calculations



Spectral Shape Information as a localization cue

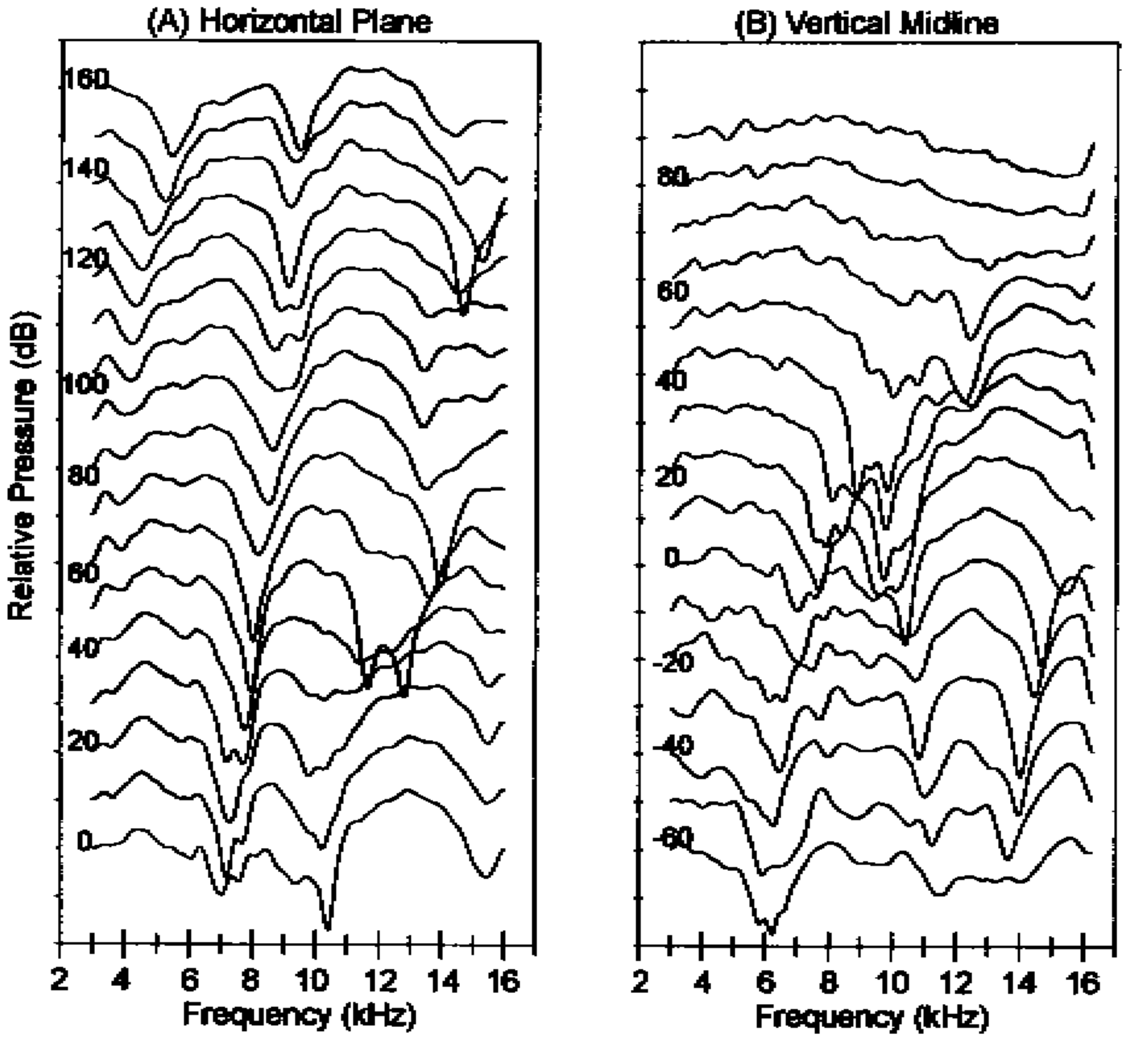
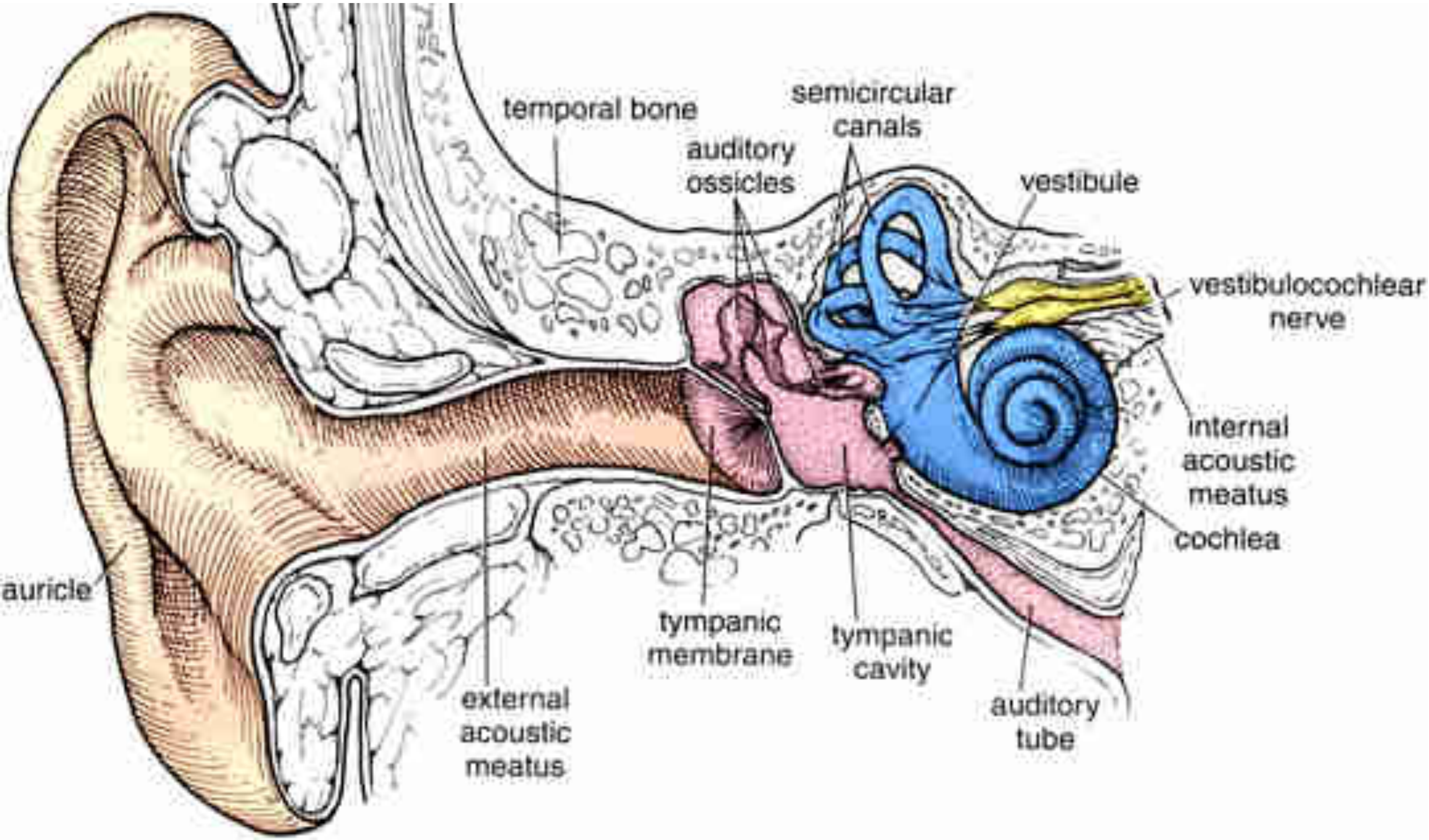


FIG. 2. Directional transfer functions (DTFs). These DTFs were recorded from the right ear of one subject. (A; left) DTFs for sound source locations in the horizonal plane (i.e., 0° elevation) at various azimuths. (B; right) DTFs for locations in the vertical midline plane (i.e., 0° azimuth) at various elevations. The number next to each DTF indicates the azimuth or elevation. The DTFs are separated vertically by 10-dB intervals. [From Middlebrooks, 1992; reprinted with permission]

Outer Ear (beige), Middle Ear (pink), Inner Ear (Blue, cochlea)



Physiological Mechanisms

- Consider stimulus coding and binaural processing in physiological structures.

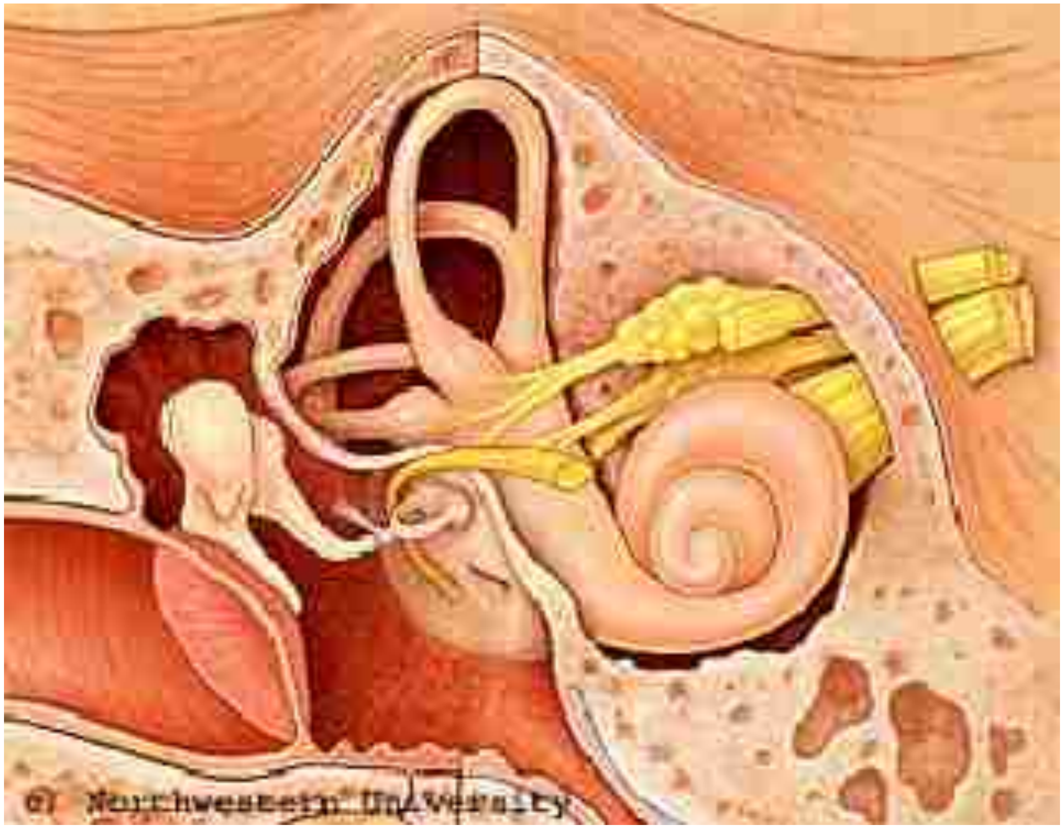
- Quick review of peripheral physiology
  - Auditory Nerve Responses and Timing Information
  - Superior Olivary Nuclei compare left and right responses with sensitivity to ITD or ILD

Middle Ear bones

Vestibular and
Auditory Nerves

Semicircular
Canals

Cochlear
spiral



Stapedius muscle attaches to third bone (stapes) and contracts to decrease transmission

May respond in anticipation of loud sounds

Recordings from three individual auditory nerve fibers with NO ACOUSTIC STIMULUS

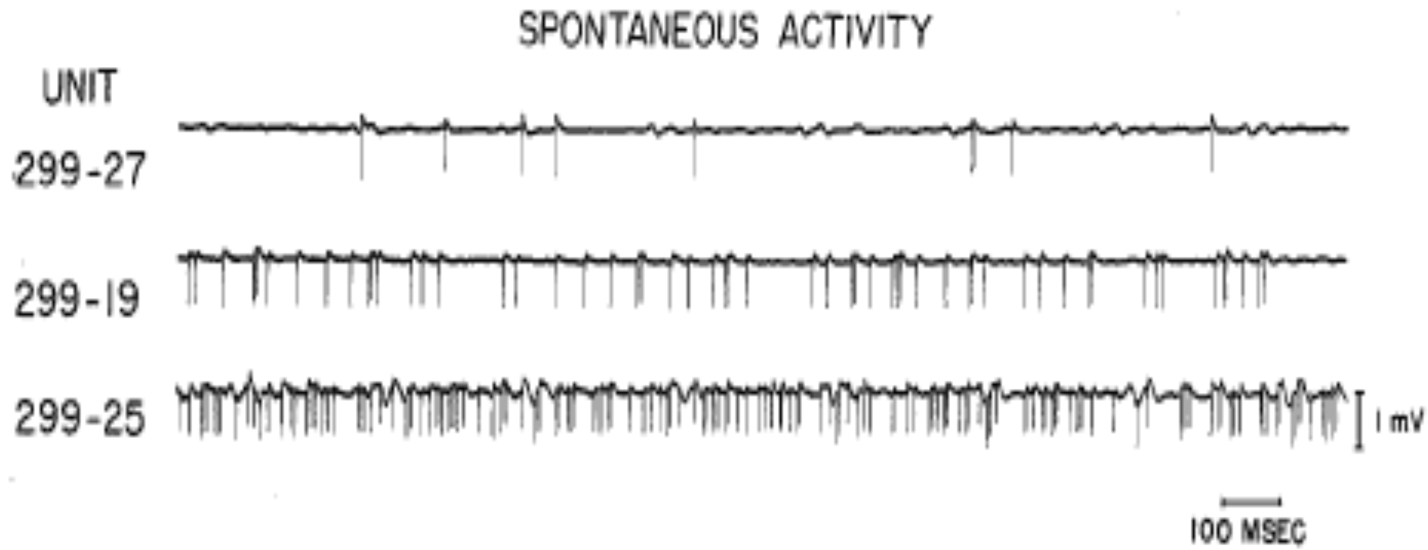
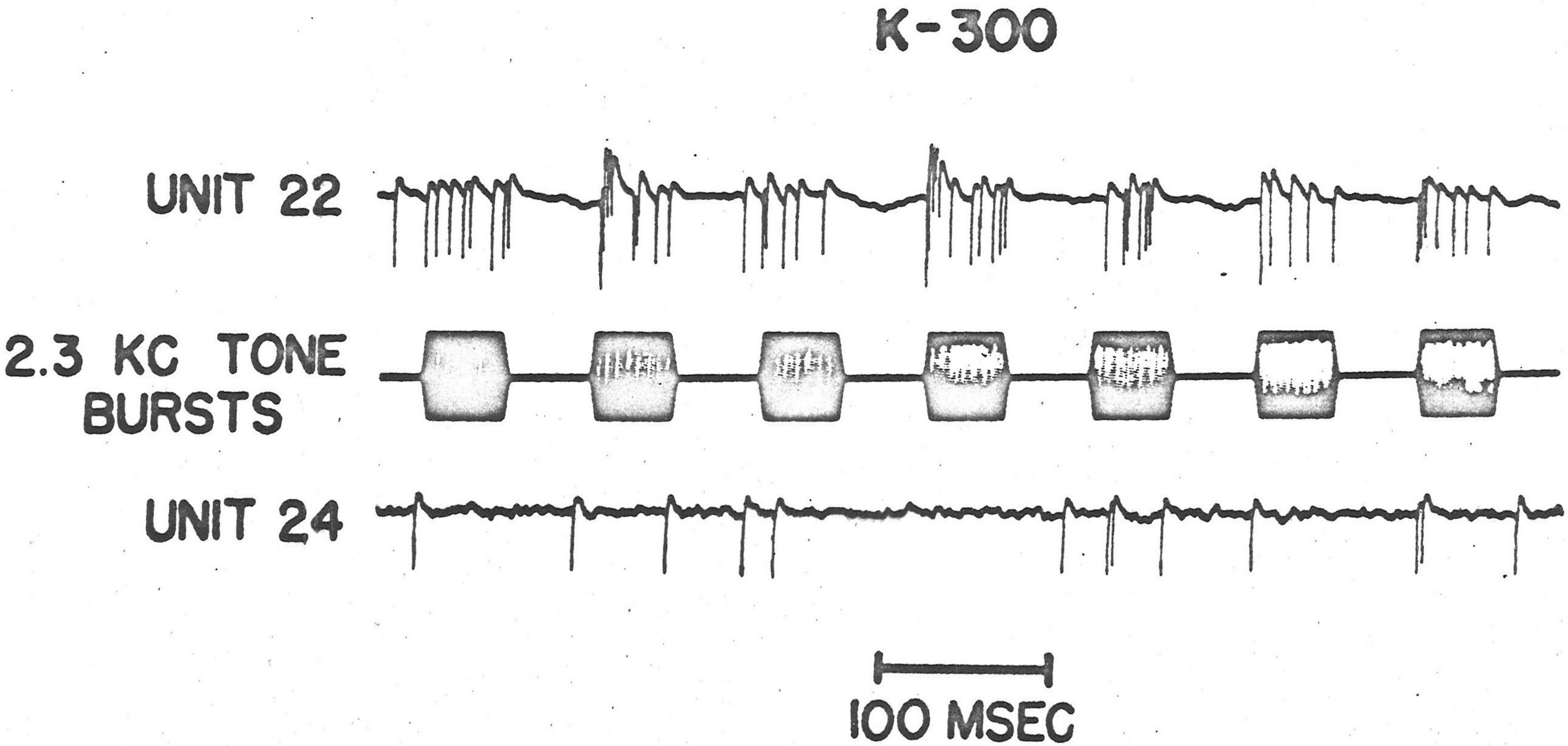


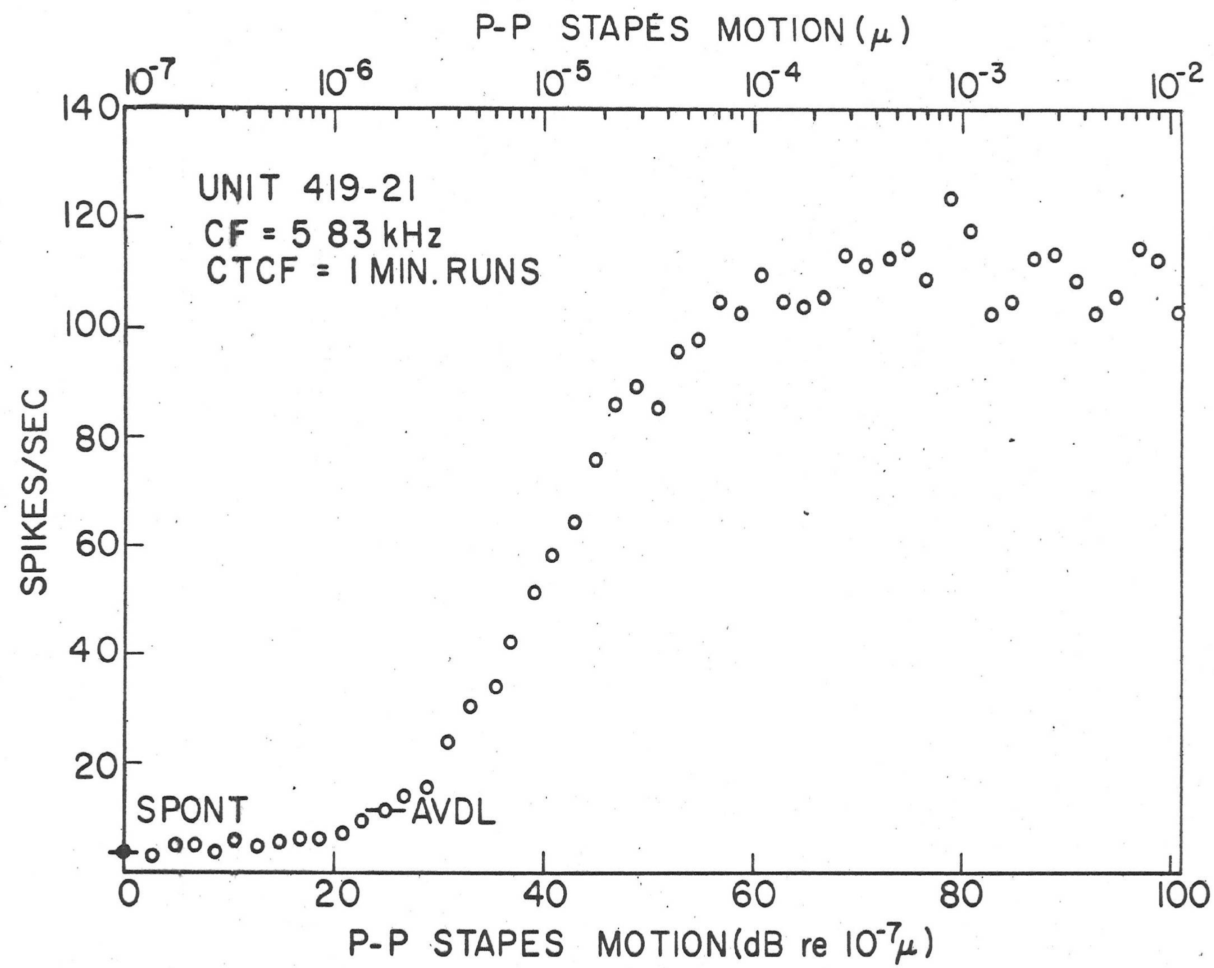
Figure 8.1 Spike trains of activity in 3 units from the same animal.
The 3 units were selected because their tuning curves were nearly identical. The CF for the units were 10.06 kc, 11.6 kc, and 10.95 kc respectively; the rates of spontaneous discharges for the 3 units were 4.3, 38.3, and 72.0 spikes/sec, respectively. Less than an hour elapsed between the recording from Unit 299-25 and that from Unit 299-27.

•Primary Auditory Nerve Patterns (Kiang, 1965)

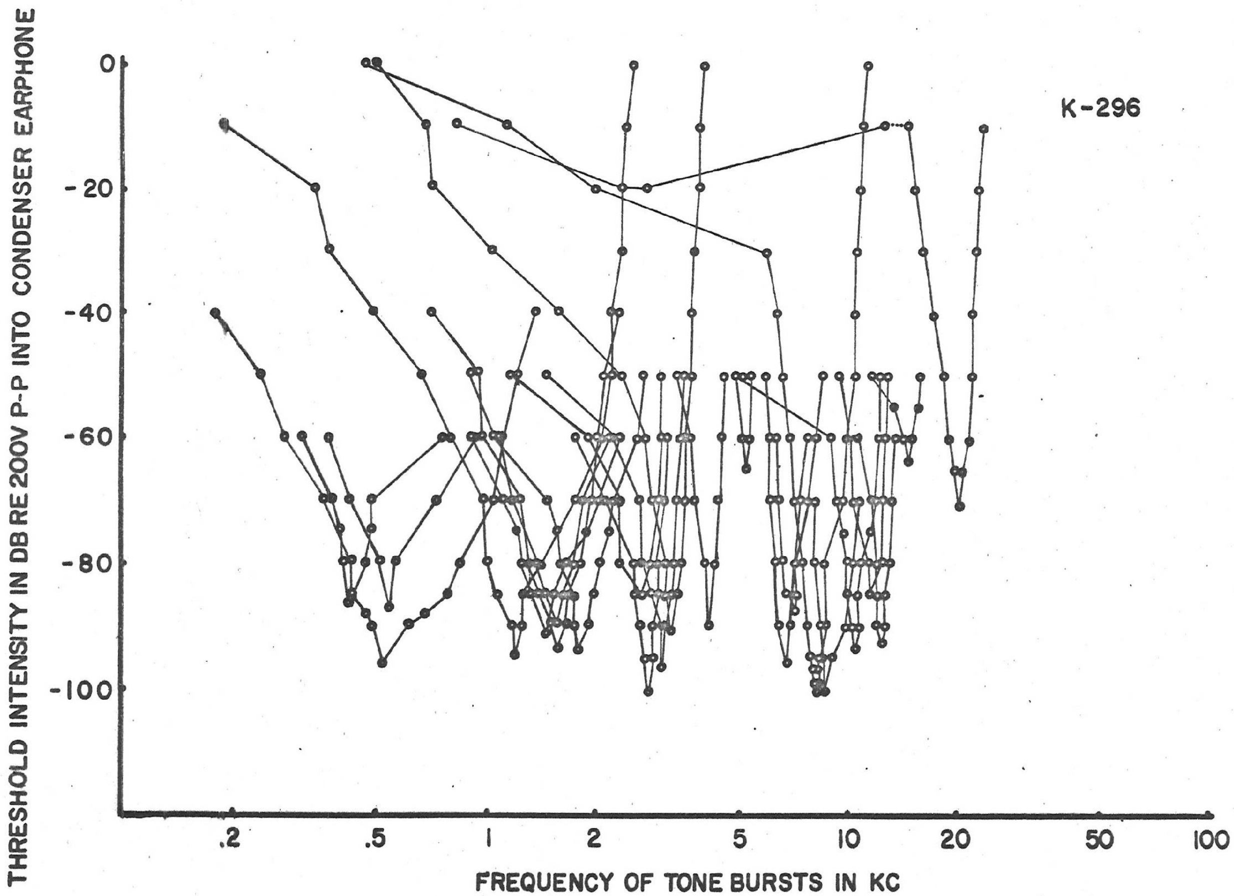


•Note the stochastic nature of the response

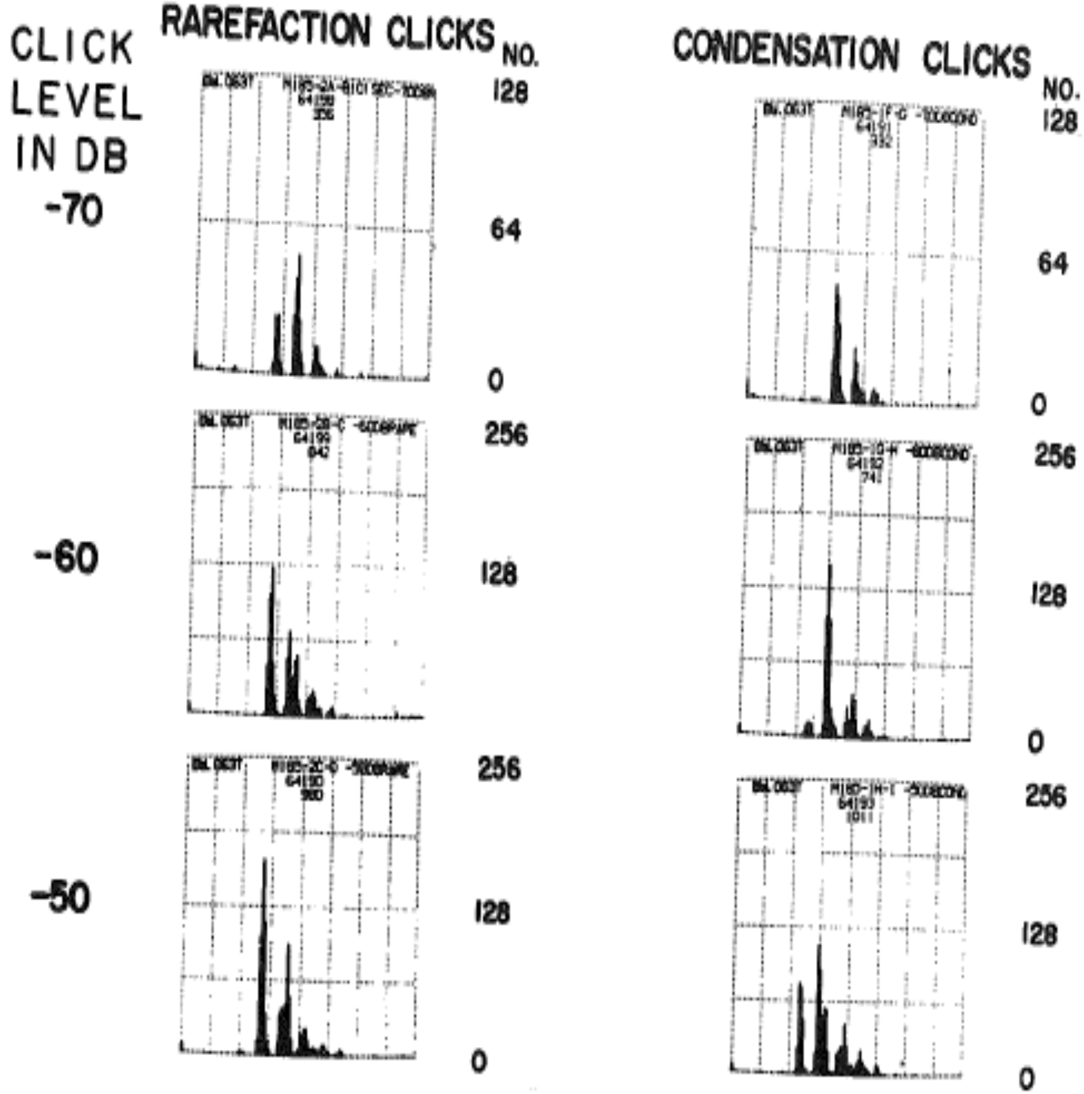
Rate-intensity function for auditory nerve fiber



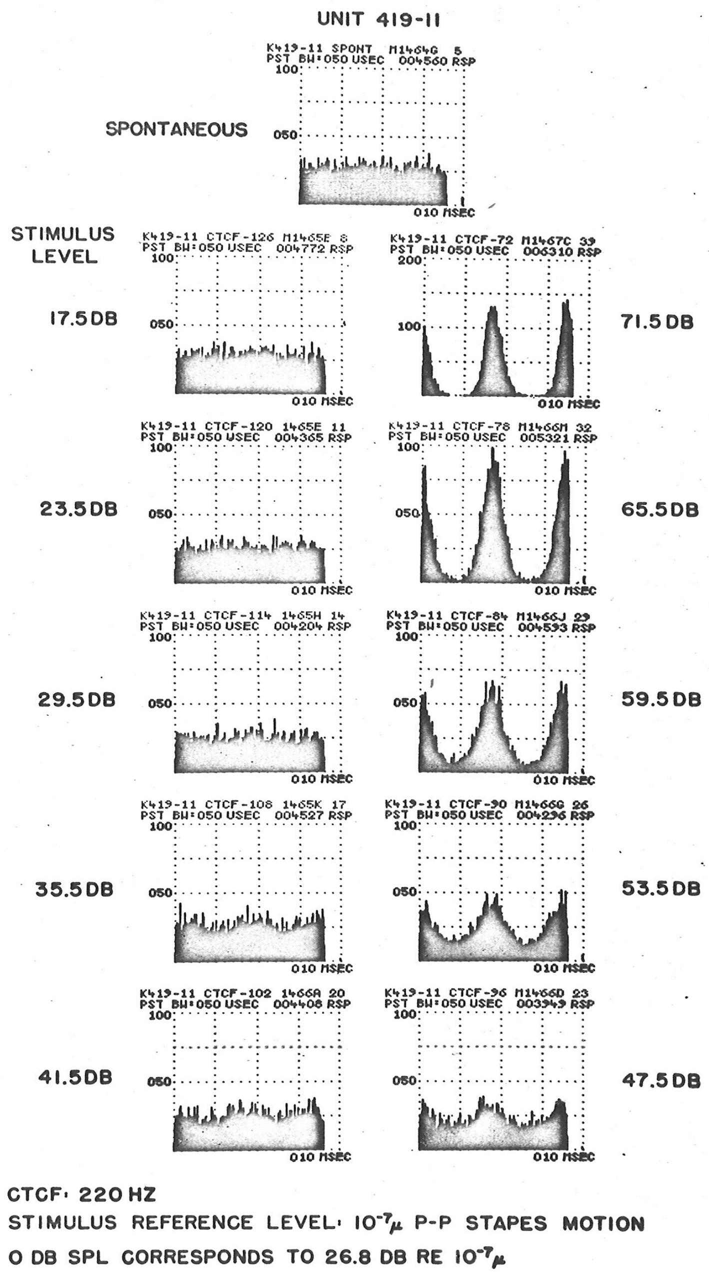
Auditory Nerve Tuning Curves: Level required for detectable response



PST HISTOGRAMS



Synchronization to tone cycles



Histograms of responses to tones at various levels

Note that histograms here cover two periods of the tonal stimulus

•Jeffress model of ITD processing

•How do process this timing information to compare right and left timings

•Jeffress postulated Coincidence Detector Network in 1948.

•Internal delays that are different for each cell in an array

•Fixed time delay on input patterns would excite compensating delay cell most strongly

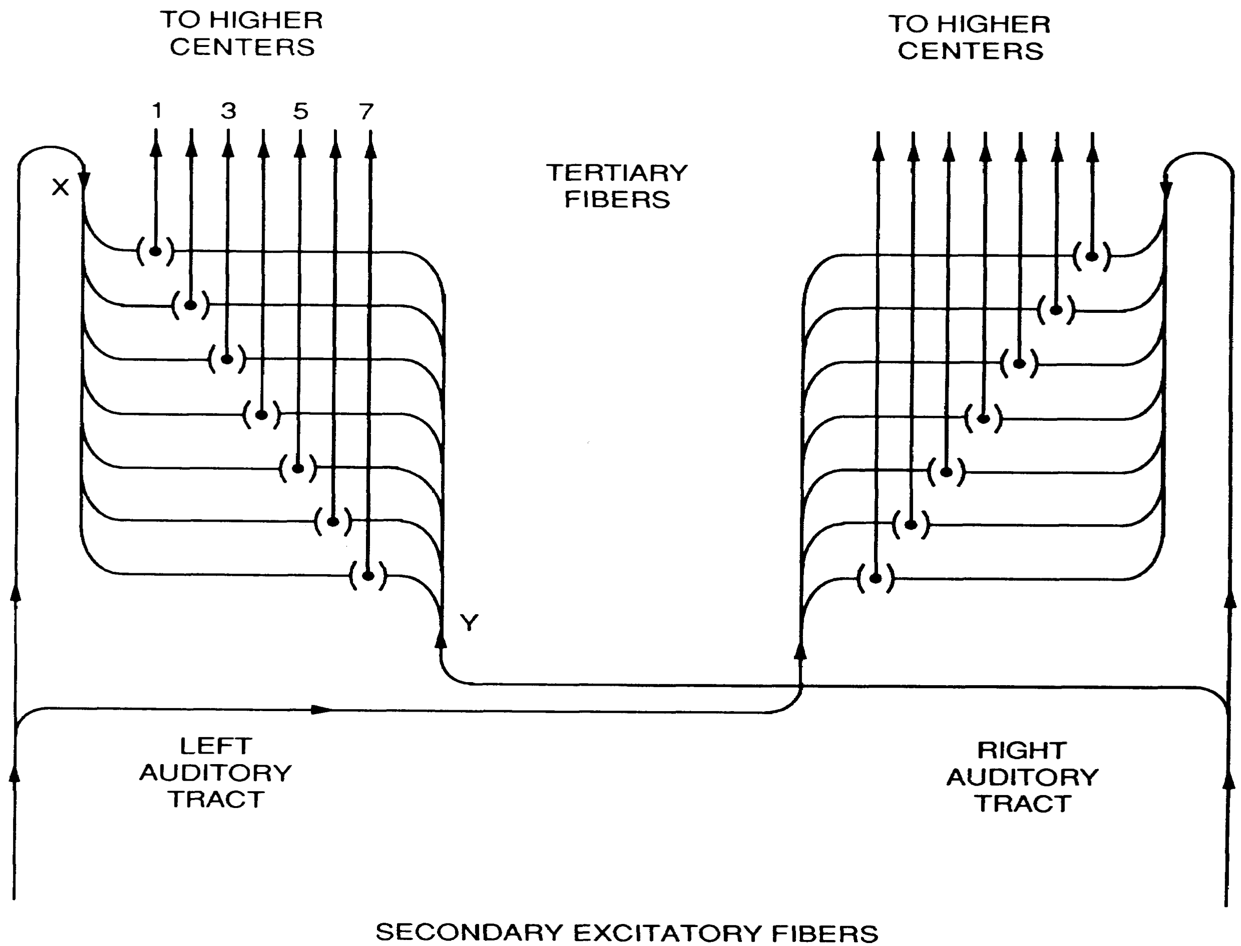


FIGURE 8.2. Neural network proposed by Jeffress for localization of low-frequency tones. The tertiary neurons act as coincidence detectors: a tertiary neuron is more likely to respond when firing from left and right secondary fibers reach the cell body at times that are closer to simultaneity. Interaural time differences in the firings of the input fibers are thus converted to differences in the spatial excitation pattern of the output fibers. (Reproduced from Jeffress 1948 with permission.)

- **Coincidence Network of Jeffress (1948)**

ITD-sensitive neuron in MSO

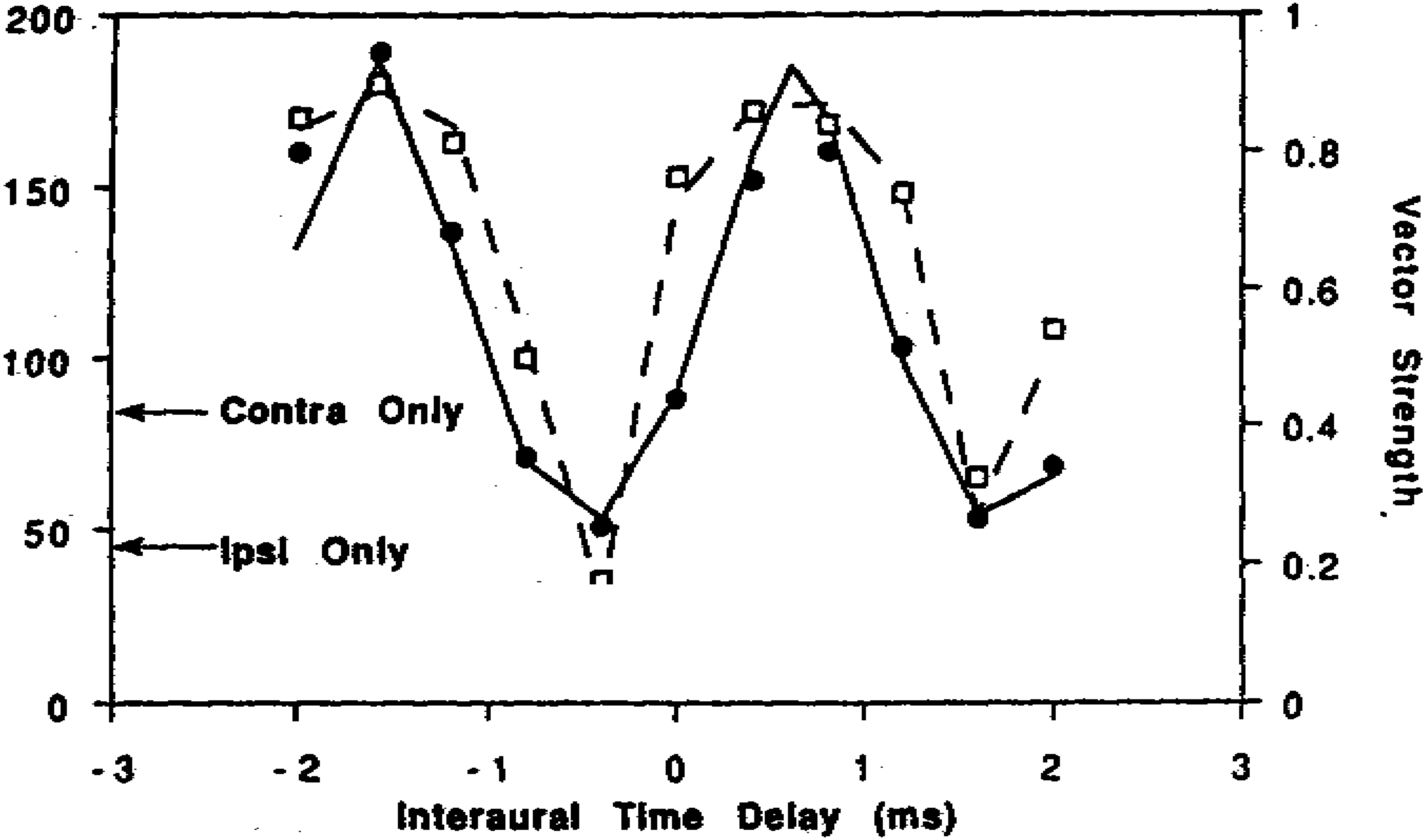


Fig. 2. Discharge rate and vector strength for model cell 1 and for unit 67–82–5 from Goldberg and Brown (1969). These quantities are

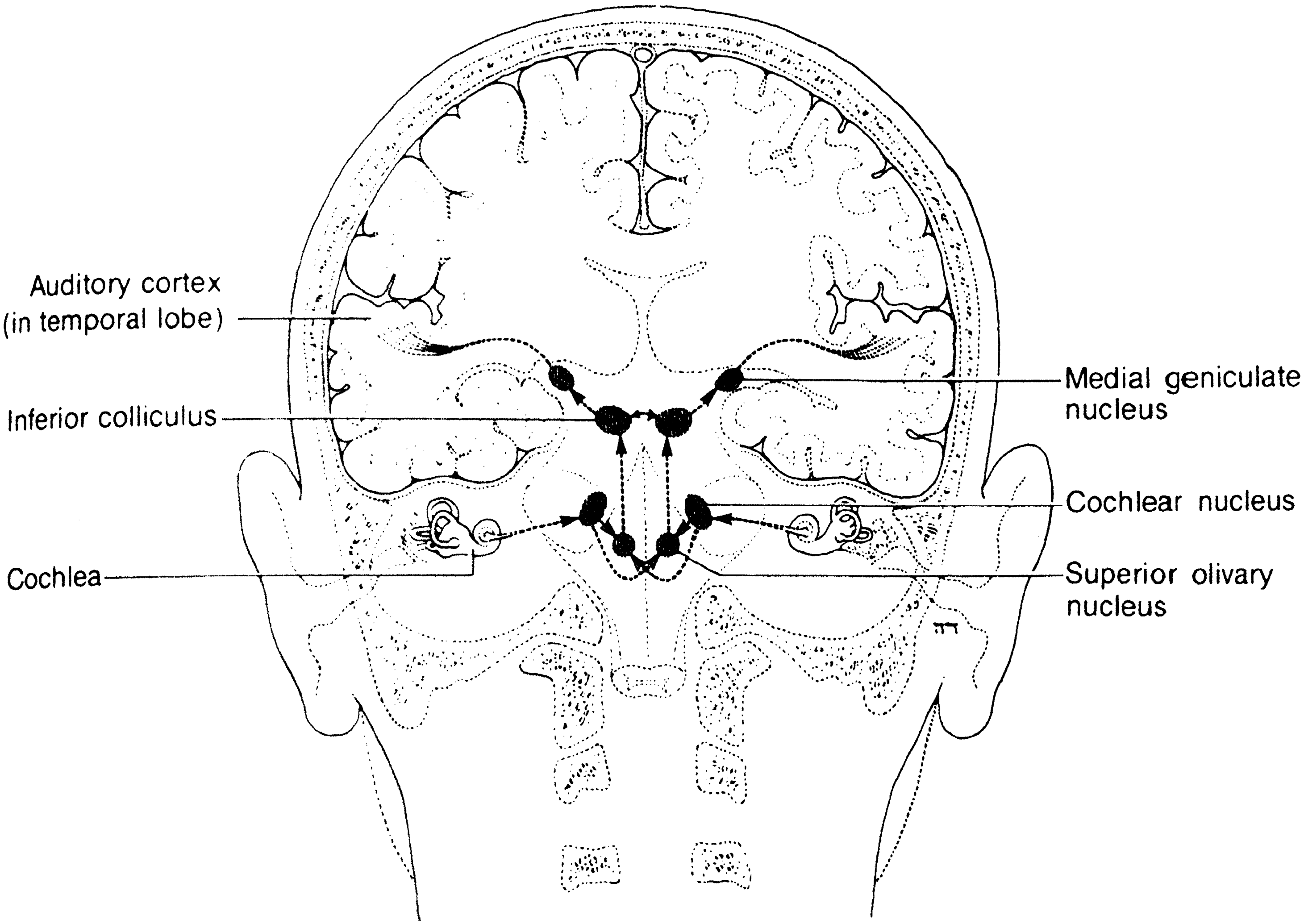
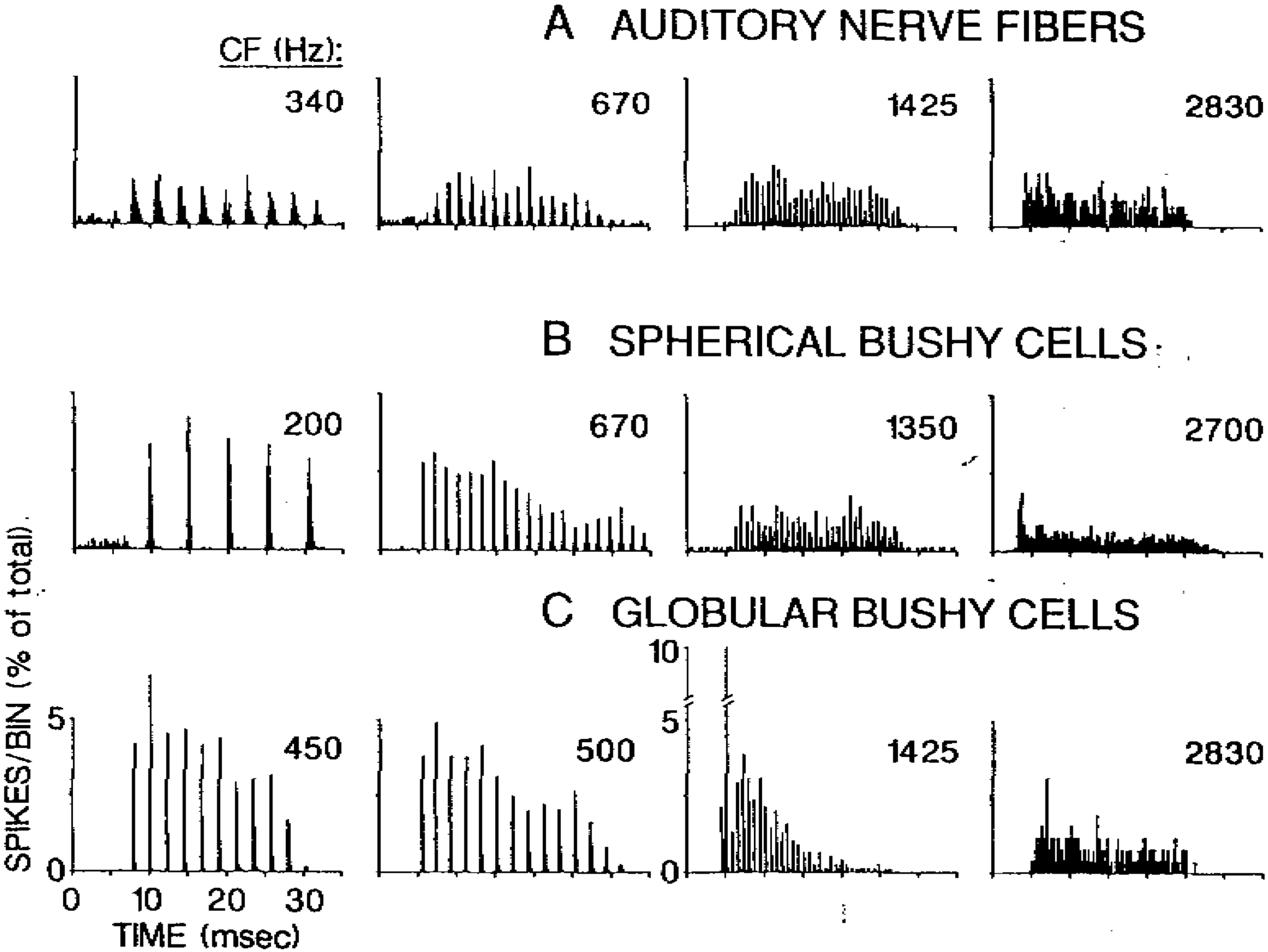


Figure 8.19
Diagram of the auditory pathways. This diagram is greatly sin plified, as numerous connections between the structures are not shown. (Adapted fron Wever, 1949.)



A AUDITORY NERVE FIBERS
CF (Hz):
340
670
1425
2830
B SPHERICAL BUSHY CELLS
200
670
1350
2700
C GLOBULAR BUSHY CELLS
450
500
1425
2830
SPIKES/BIN (% of total)
0
5
10
0
10
20
30
TIME (msec)

•Mechanisms of ITD Processing

- Coding of time structure to neural pattern
  - Primary auditory nerve coding
- Maintenance/sharpening of temporal structure
  - Sharpening in cochlear nucleus (Bushy Cells of CN)
- Sensitivity to delays of left and right inputs
  - Single neuron processing in MSO
- Preservation to higher neural levels
  - Maintenance of “spatial code” for ITD

Binaural Display: (f,τ)-plane

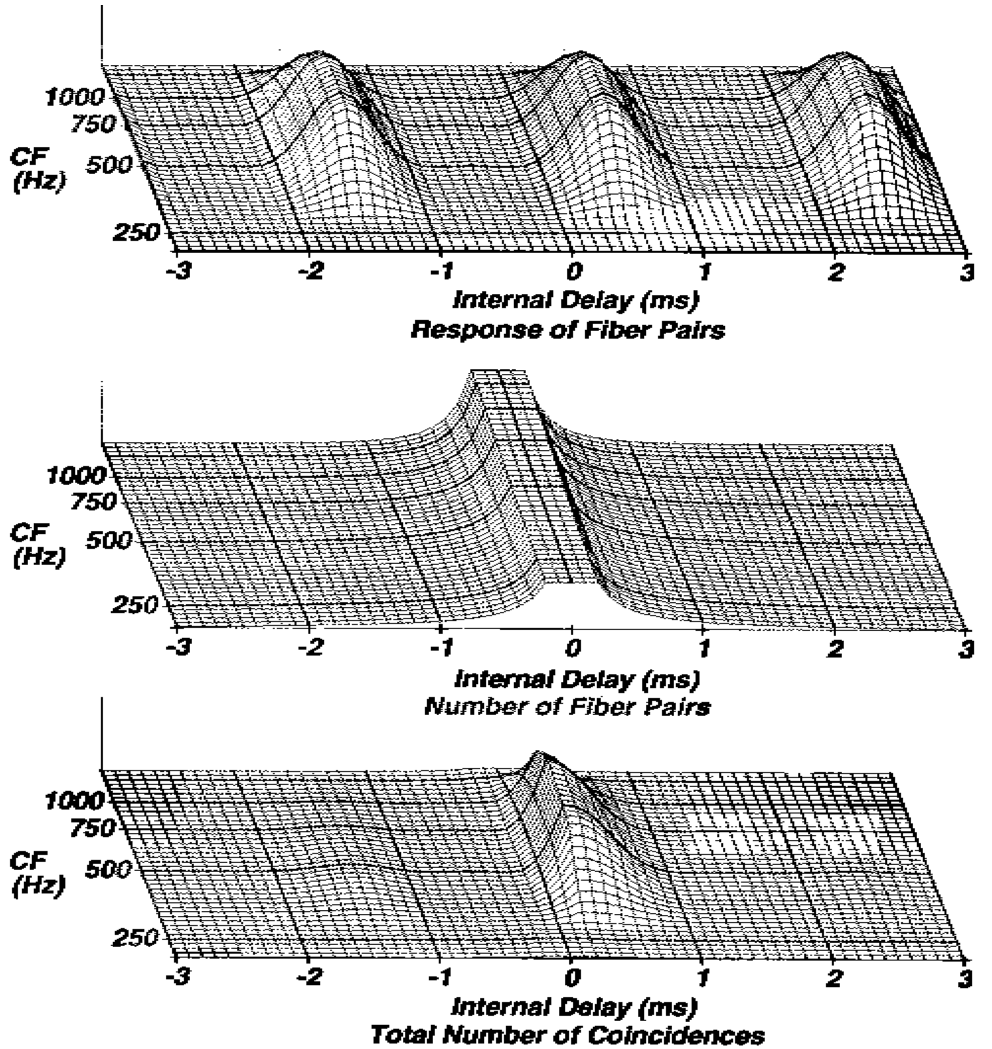


FIG. 4. Response of an ensemble of binaural coincidence-counting units to a 500-Hz pure tone with a 0.5-ms ITD. Upper panel: The relative number of coincidences per fiber pair as a function of internal delay τ (ms) and CF of the auditory-nerve fibers (Hz). Central panel: The assumed density of internal delays as a function of CF. Lower panel: The average total number of coincidences as a function of internal delay and CF, which is the product of the upper and central panel.

Narrowband Cross-correlation function for each f

Internal delay limiting function

Resulting distribution of activity
ITD from ridge

From Stern and Trahiotis, 1997

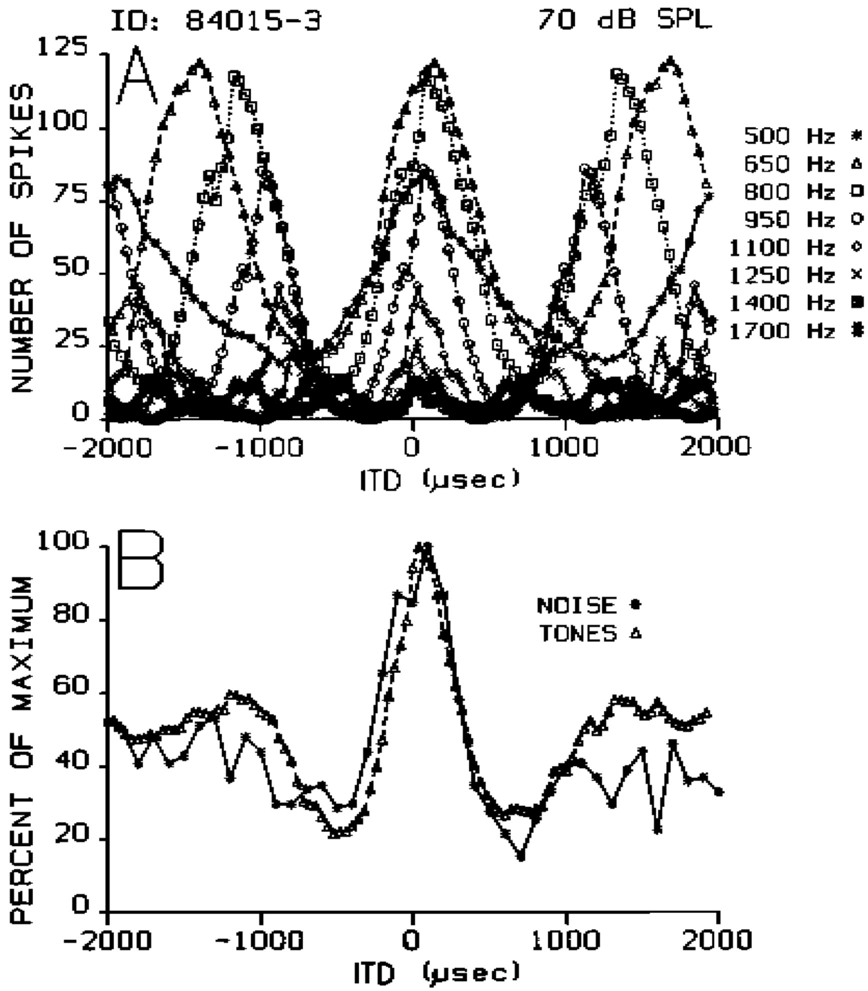
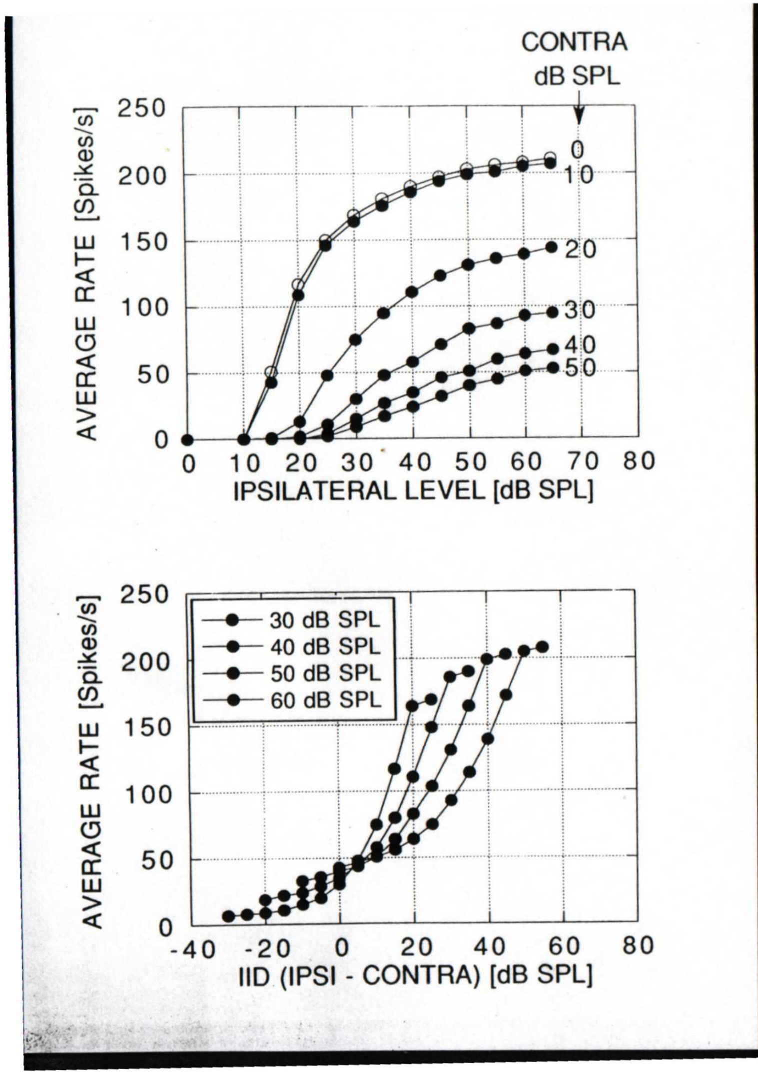


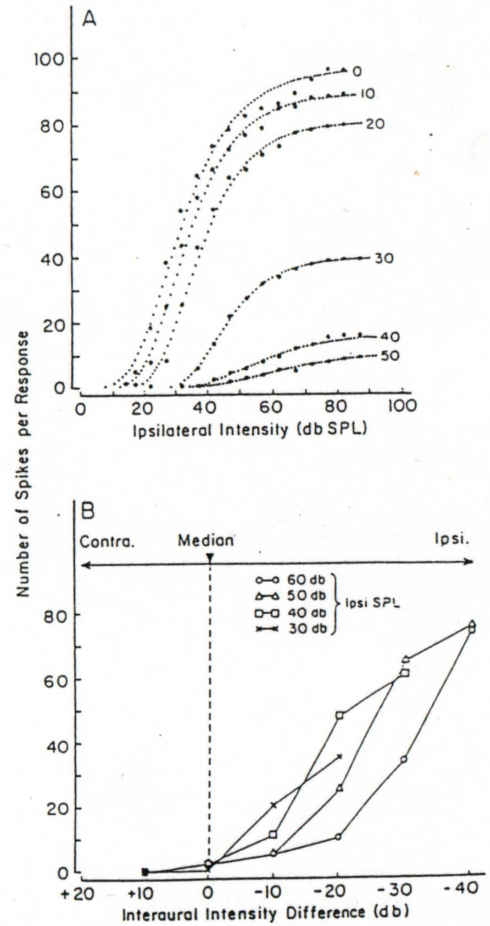
FIG. 6. (A) Interaural time delay curves for an MSO cell to eight different stimulation frequencies, all plotted on a common time scale. (B) ITD curves for the same cell in response to broadband noise stimulation (asterisk) or derived from the tonal responses in A by computation of the composite curve (Δ). (From Yin and Chan, 1990.) Reprinted with permission.

•Interaural level (ILD) representation

- LSO neurons (ILD and onset-ITD sensitive)
- Excitatory input from ipsilateral side
- Inhibitory input from contralateral side
- Array of ILD processors versus frequency

•LSO Neuron and ILD sensitivity





Boudreau and Tsuchitani, 1970

•Diranieh and Colburn, 1994

•(MODEL)

•ILD,f array of LSO neurons

•LSO neurons are each ILD sensitive

•LSO neurons are tuned in frequency (like auditory nerve fibers and MSO cells)

•Provide information about ILD for each frequency band

•May be particularly important in reverberant environments (Hartmann, 1999)

Interaural Difference (ITD or ILD) Resolution for Human Subjects

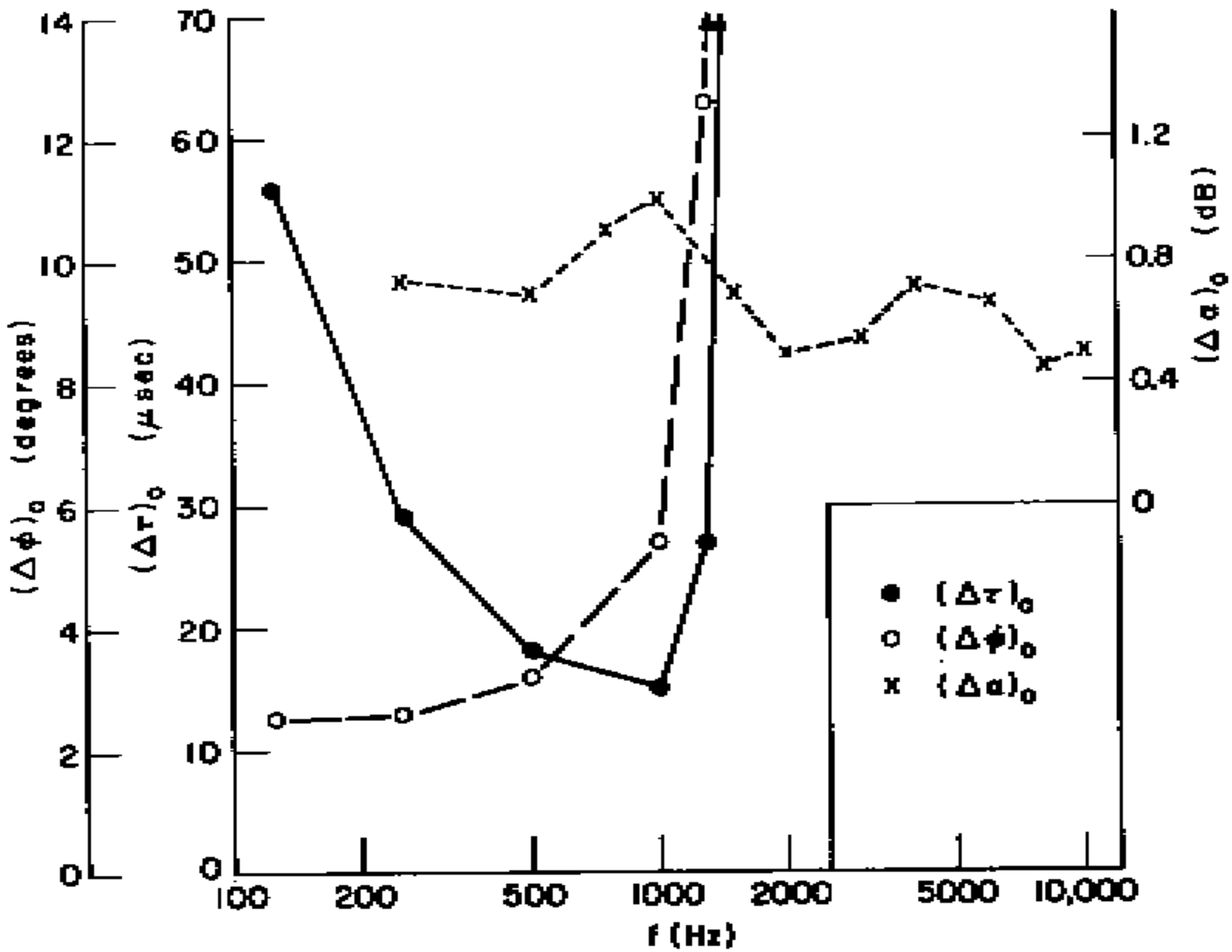
- How small a time delay between the ears is reliably detectable by a human listener?

- Called a Just-Noticeable Difference in ITD or ILD

- Best listeners can do better than 10 μs –– on the order of ten millionths of a second!

- Best listeners for ILD do about 0.5 decibels

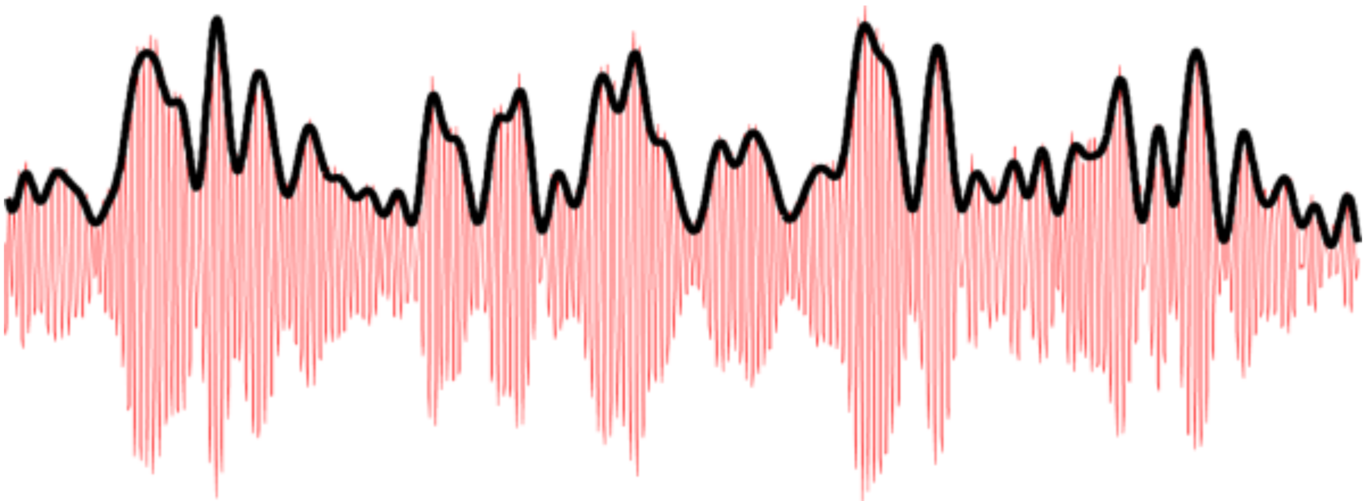
Interaural Difference Sensitivity versus frequency



Envelope carries ITD at HF

- Temporal synchronization to timing falls off at high frequencies …
- Minimal sensitivity to fine structure ITD above about 1500 Hz in humans
- But high frequencies carry interaural timing information in synchronization to the envelopes. This is a factor in binaural performance but it is complicated.

Envelope on noise band provides timing cues



Neural synchronization to the envelope (black curve with frequencies related to bandwidth)

No synchronization to the fine structure (i.e., to the carrier) at high frequencies

How do we handle the cocktail party?

- Combined stimuli mixed together in each frequency band
- We want to use the internal distributions over frequency and interaural parameters … may be based on interaural time and level or may involve processed, position-based information
- These displays change over time as different stimuli from different directions dominate.
- This is a complex challenge!

Sorting it all out

- The information has to be there.
- We need to ignore distracting sources
  - Evidence that musicians can do this better
  - Practice makes us better in any case
  - Called informational masking versus "energetic"
- We need to exploit the interaural differences as well as the dynamic temporal variations
- We need to use our knowledge of the signals

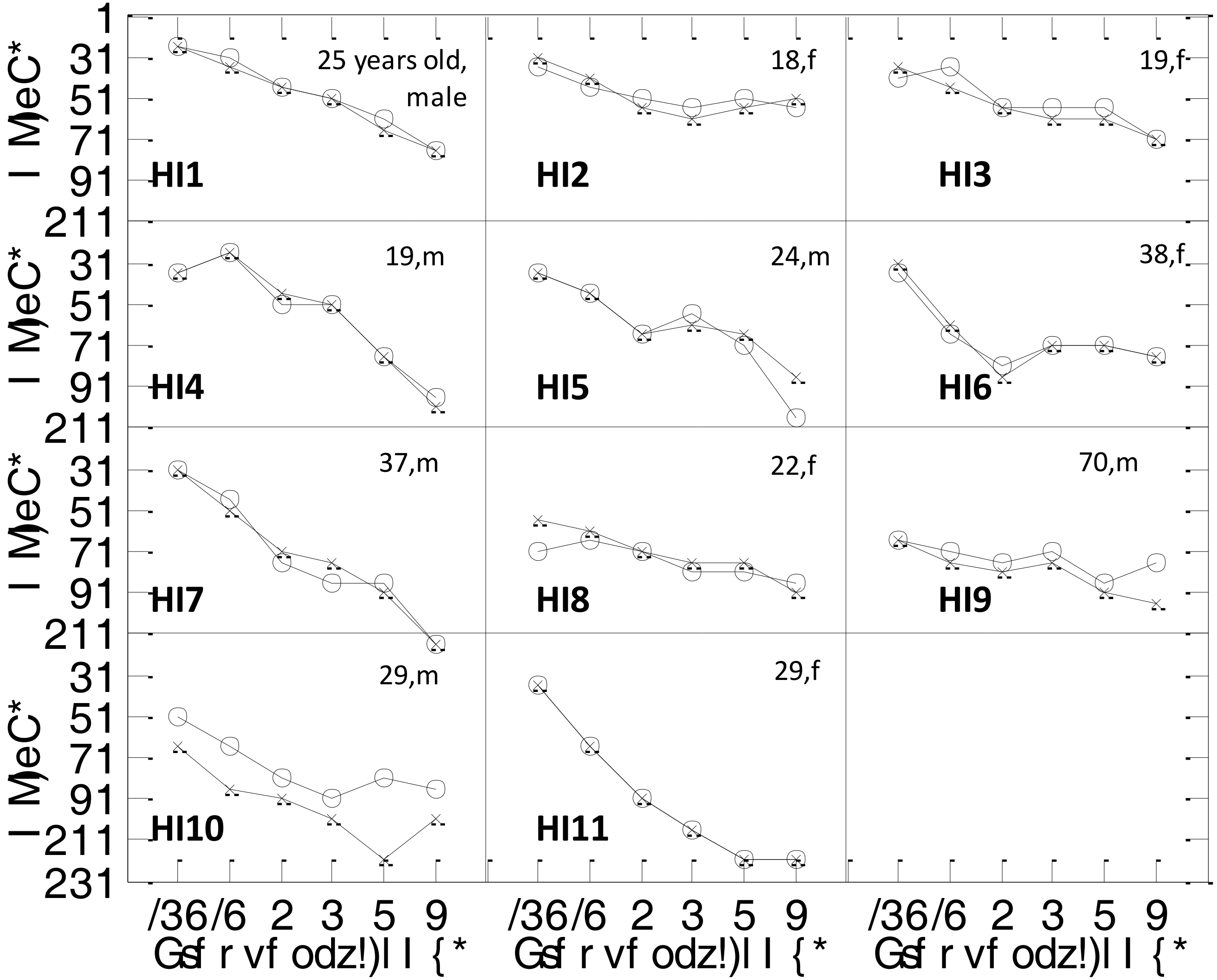
Interaural Sensitivity with Hearing Loss (Nathan Spencer Experiments)

- Primary interest was effects of hearing impairments on binaural processing.
- Measured interaural discrimination as well as spatial release in speech-on-speech masking.
- Hypothesized that interaural discrimination ability [just-noticeable differences (JNDs) in interaural time, level, and correlation] would co-vary with spatial separation benefits.

Nathan Spencer Subjects

- Ten young normal-hearing subjects,
  aged 20-29
- Ten young hearing-impaired subjects.
  - HI1-HI8, HI10, HI11; aged 19-38
- One older hearing-impaired subject
  - HI9 aged 70

Hearing Impaired audiograms



Audiograms symmetric in all cases except for in HI10, an author in this work.

Interaural difference sensitivity tasks

- Stimuli 1/3 octave, narrow-band noises, centered at either low frequency (500 Hz) or high frequency (2 kHz or 4 kHz).

- Measured just-noticeable differences (JNDs), relative to diotic reference (waveforms same in both ears)

  - Interaural time difference (ITD) discrimination
  - Interaural level difference (ILD) discrimination
  - Interaural correlation difference (ICC) discrimination

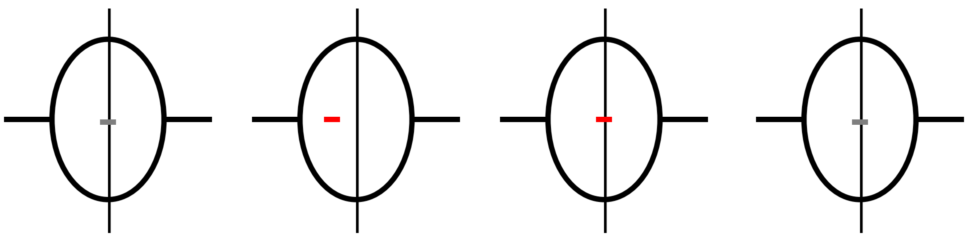
Measuring interaural difference sensitivity thresholds

- Acquired adaptive tracks to (Levitt, 1971) 70.7% correct
- Kept measuring performance in all tasks, over multiple days
- Calculated thresholds and error bars based on last twelve adaptive tracks

ITD sensitivity measurements

- Presented four intervals

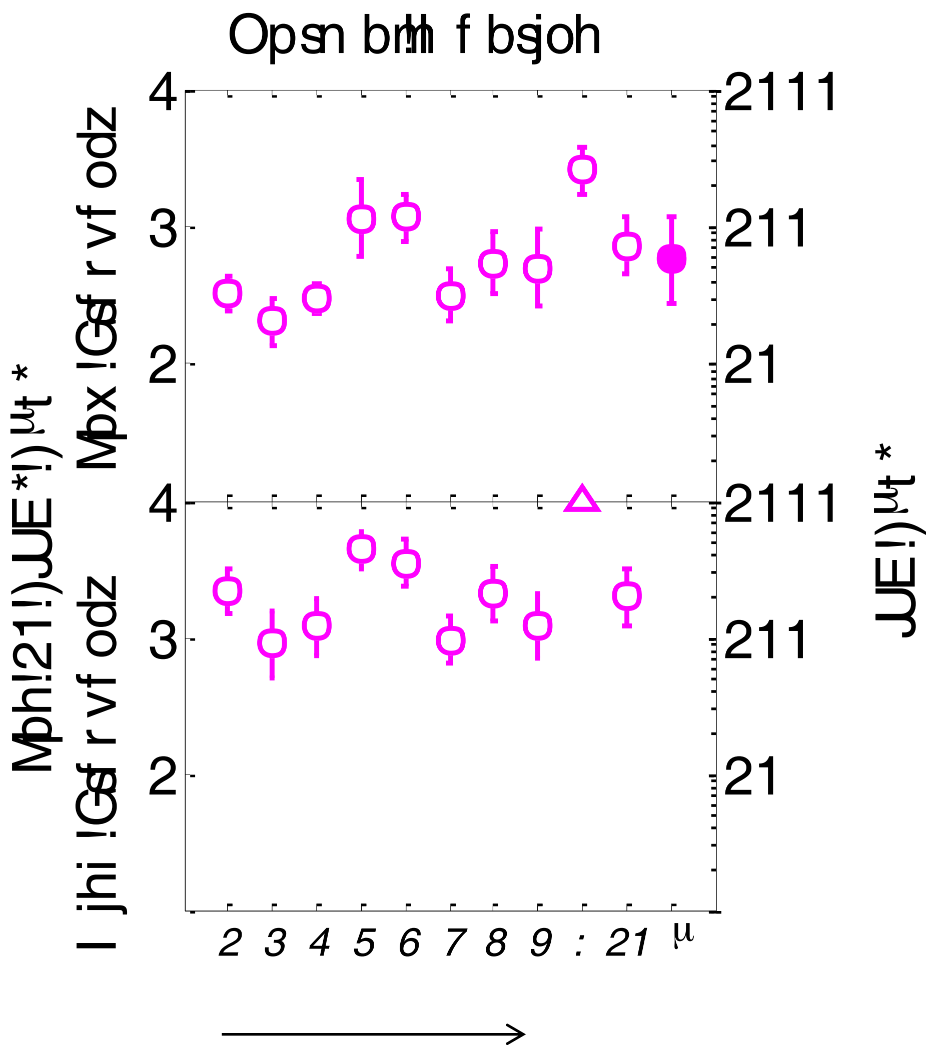
- In interval 2 or interval 3, waveform was delayed in one ear, relative to other… creating an off-center image in only one interval

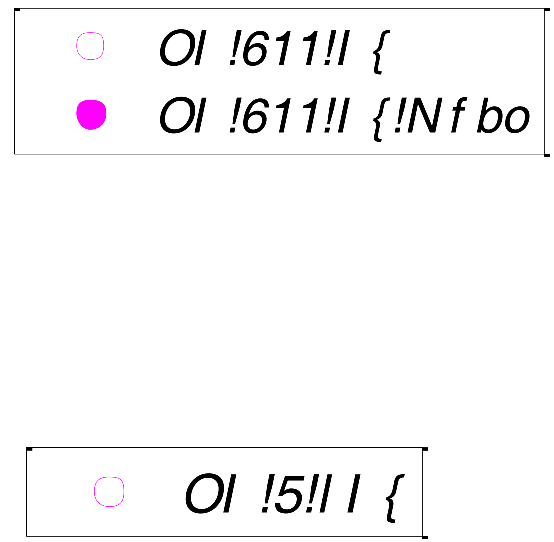


- Subject asked to identify which interval (2 or 3) was different

- Provided with feedback

Normal Hearing ITD thresholds

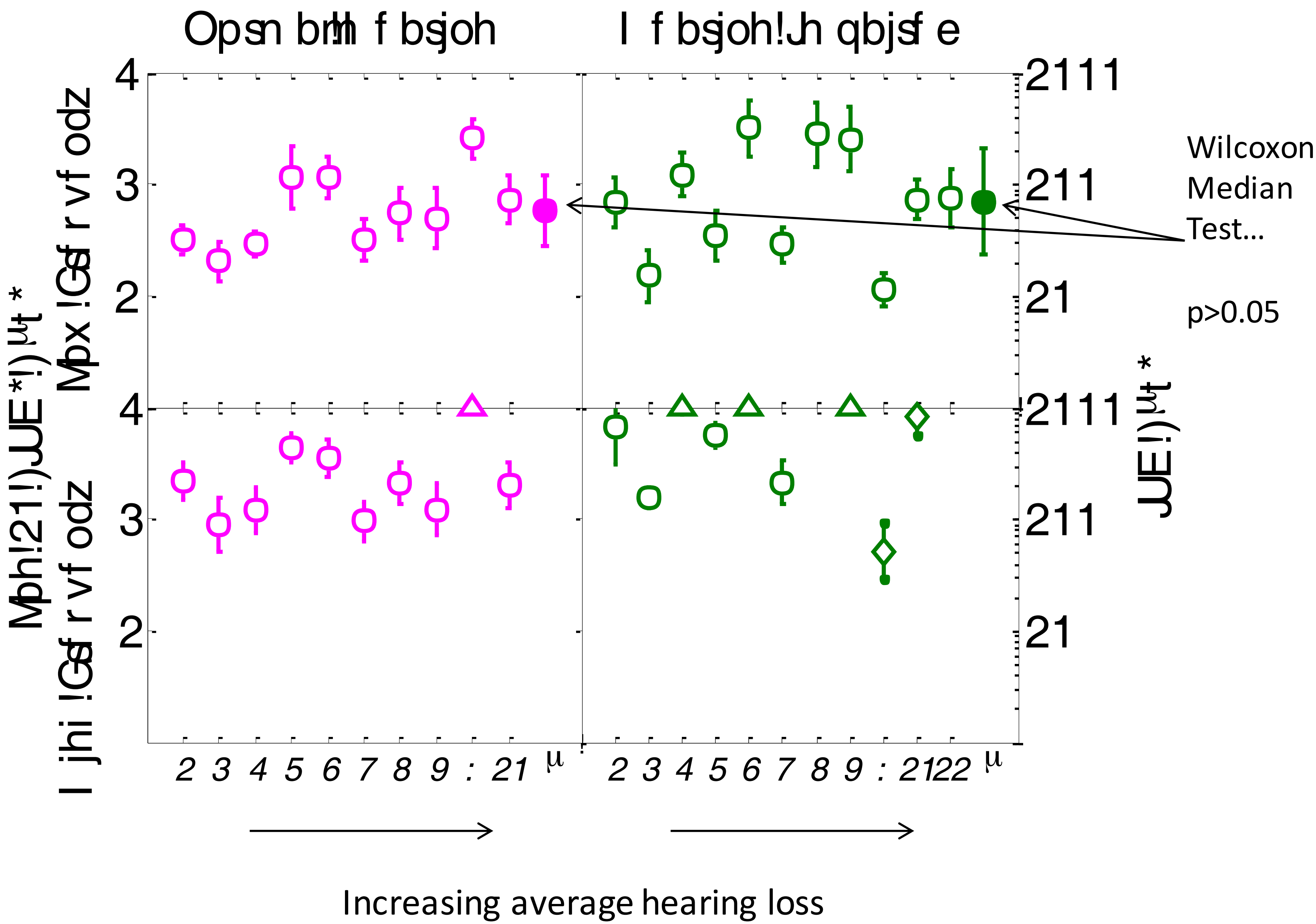




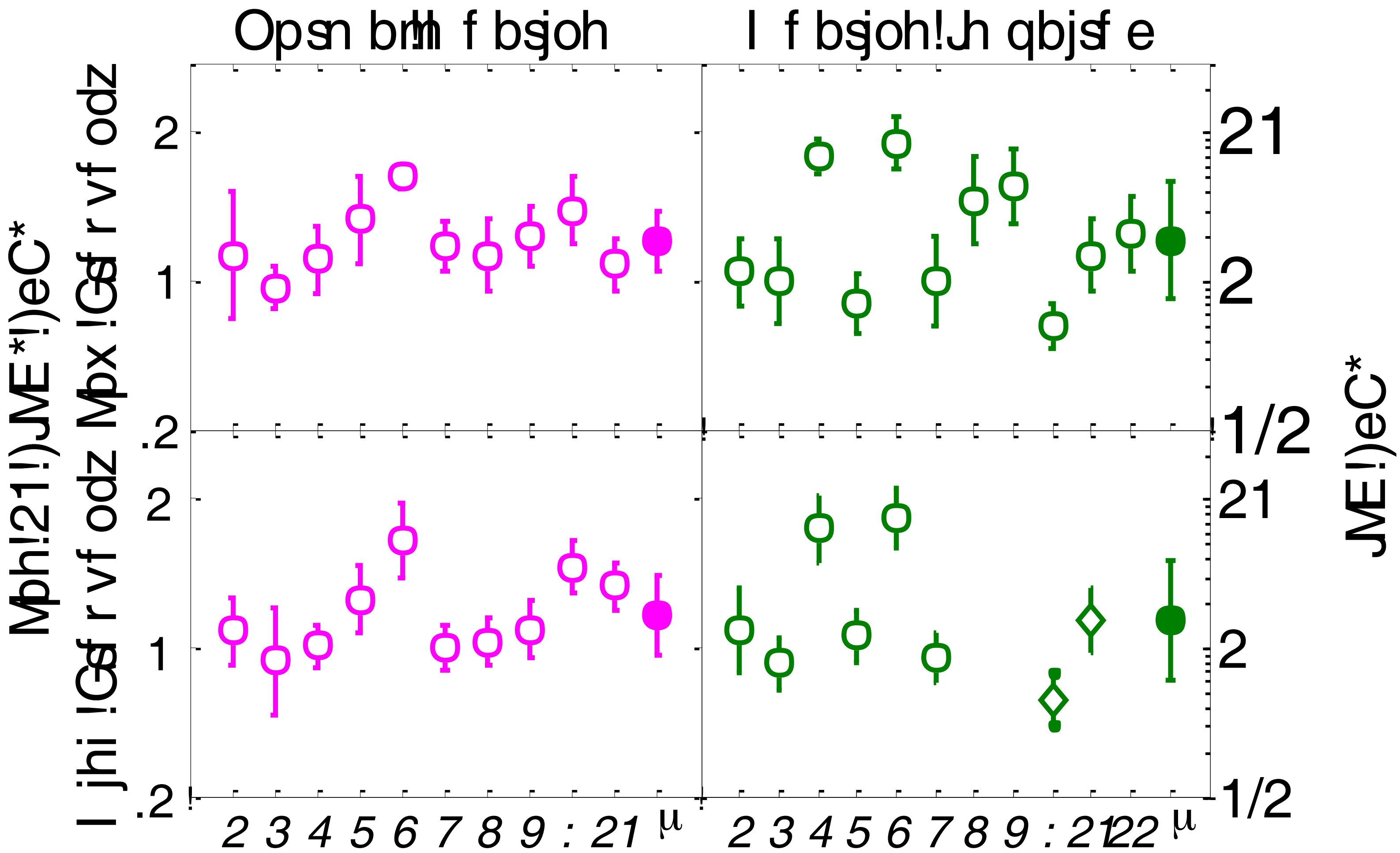
(Based on envelope timing)

Increasing average hearing loss (< 10 dB difference cumulative)

Hearing Impaired ITD thresholds (right)



ILD Thresholds (Note log scale)



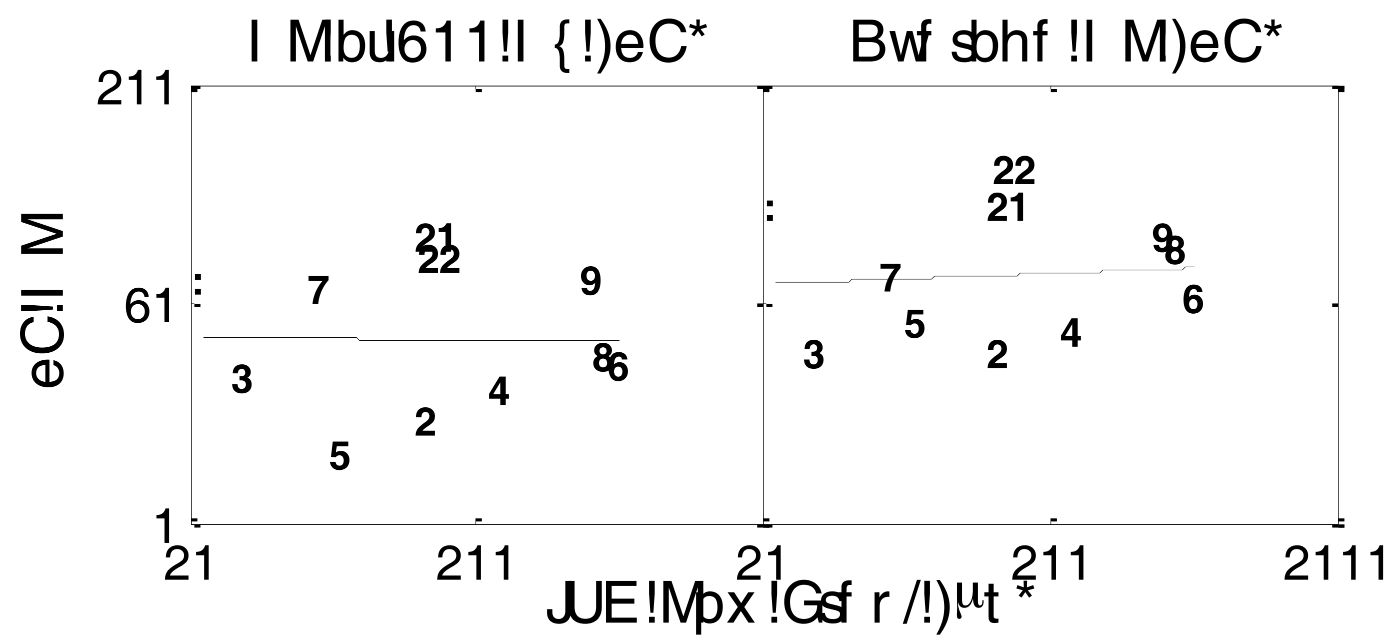
Wilcoxon
Median
Test…

$p>0.05$

Wilcoxon
Median
Test…

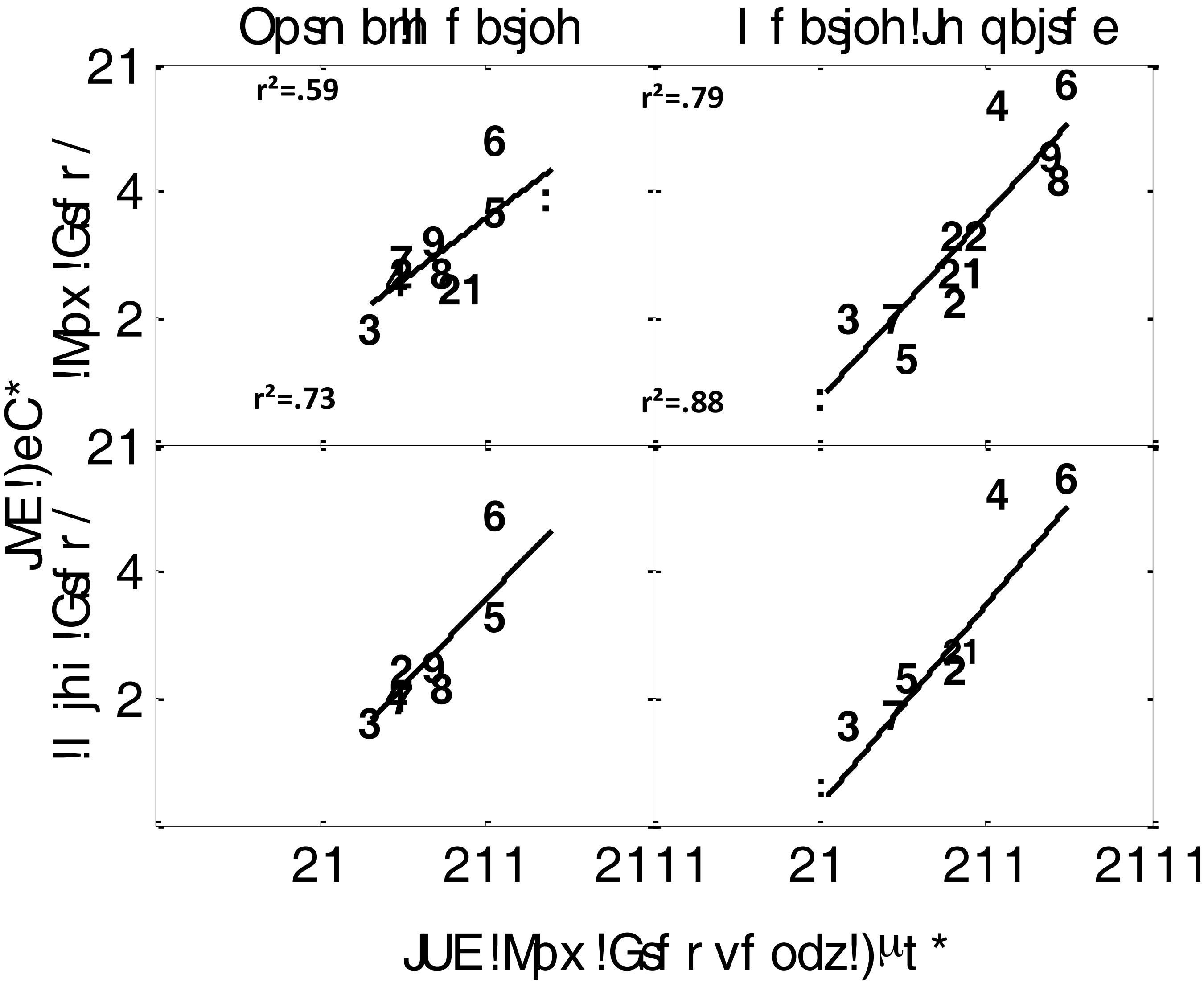
$p>0.05$

Hearing loss as a function of interaural difference sensitivity thresholds for HI

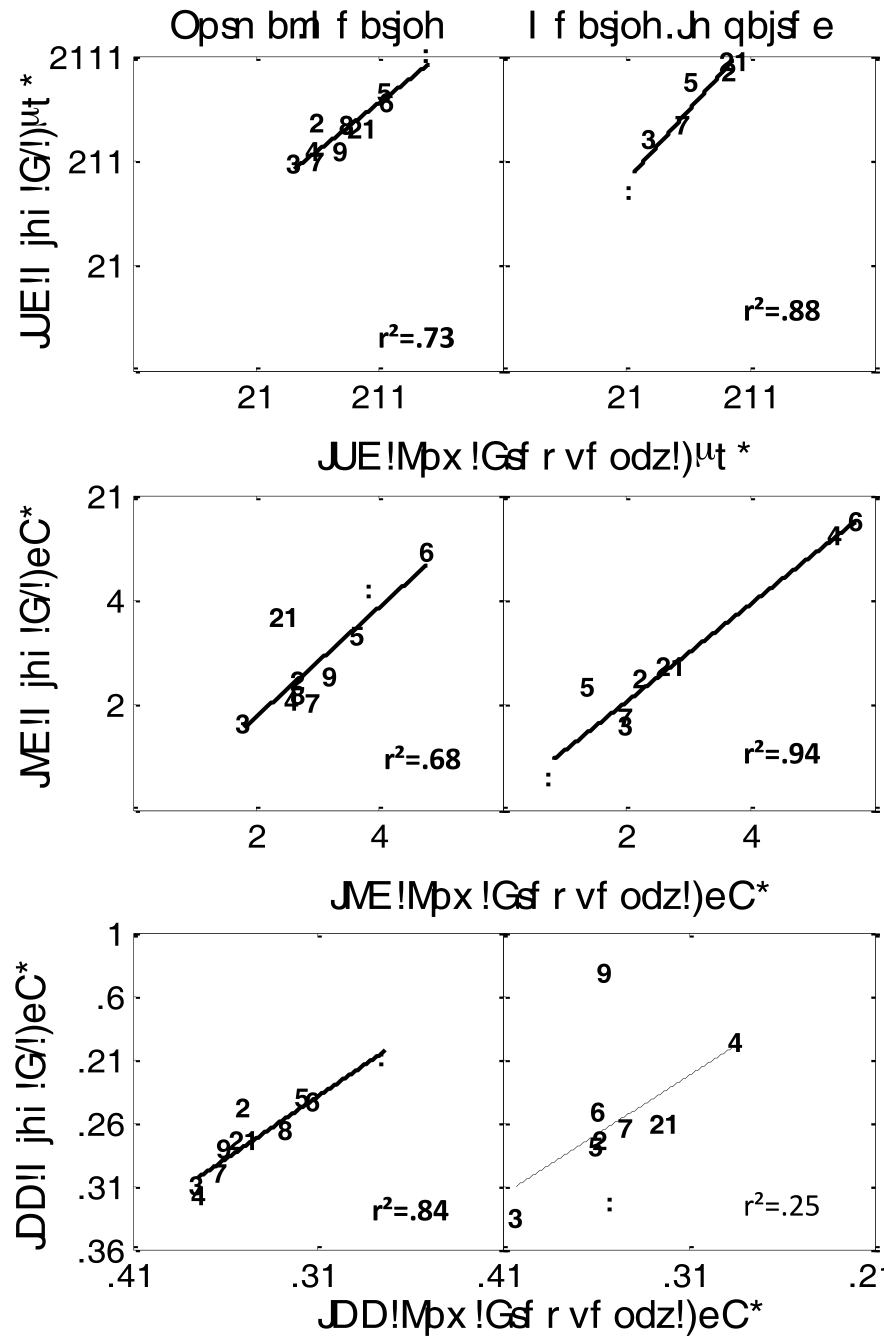


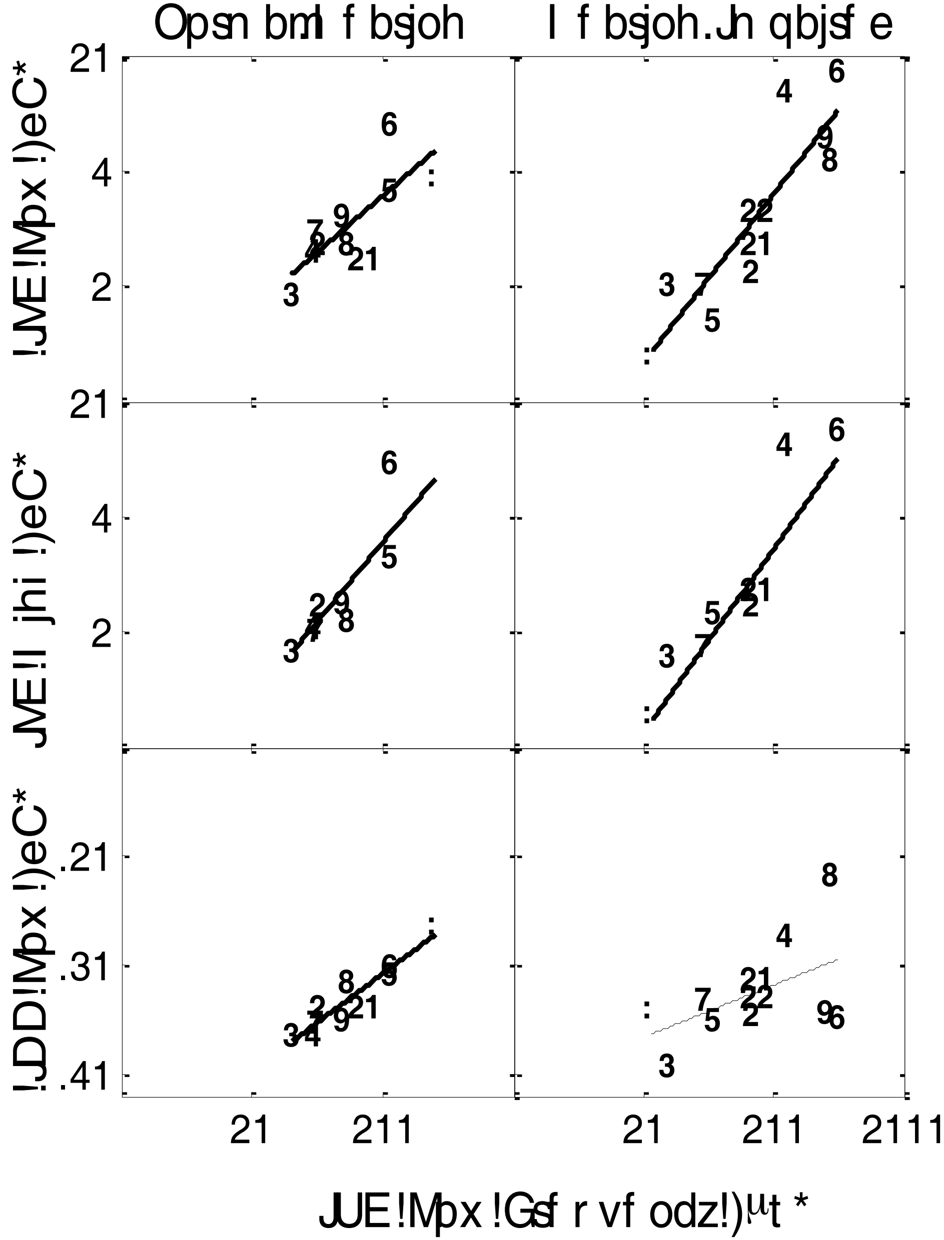
- Lack of correlation found for HI group in ITD at 500 Hz
- No correlations found for either of the subject groups, for any interaural difference sensitivity task

ILD threshold as a function of ITD threshold



ID JND measurements were generally correlated between low and high frequencies, considered across subjects




Opsn bml f bsjoh
I f bsjoh.Jn qbjsf e
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!JDD!Mpx !)eC*
JUE!Mpx !Gsf r vf odz!)µt *
21
4
2
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.31
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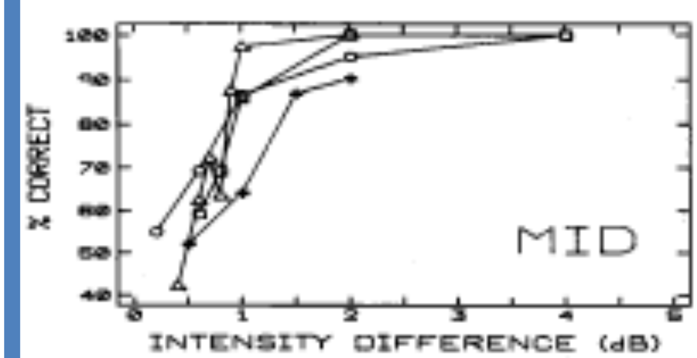
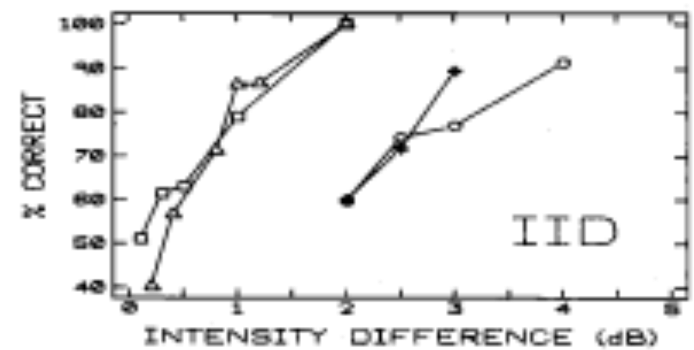
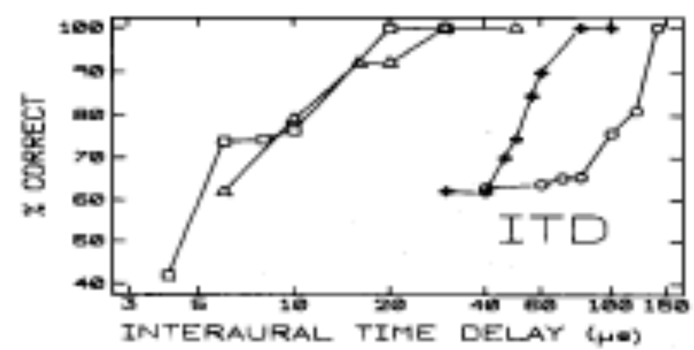
21
211
2111

Previous studies: individual differences in inter-aural difference sensitivity, not in monaural level sensitivity



MONAURAL
discrimination





INTERAURAL
discrimination

- Four, highly trained Normal-Hearing listeners at 500 Hz (Koehnke et al. 1986)…

Interaural Discrimination Conclusions

- Large inter-subject variability
- Interaural difference sensitivity thresholds did not correlate with hearing loss
- ITD and ILD thresholds highly correlated among both NH and HI subject groups
- Consistent with my seeing “remarkable subjects” who were excellent in binaural tasks with severe hearing loss

Now turn to the Cocktail Party Problem

Understanding speech in competition with other speech can be challenging.

The famous psychologist George A. Miller once wrote:

"It is said that the best place to hide a leaf is in the forest, and presumably the best place to hide a voice is among other voices" (p. 118).

Miller, G.A. (1947) "The masking of speech," Psychol. Bulletin, 44, 105-129

•E.Colin Cherry’s 1953 summary:

- “How do we recognize what one person is saying when others are speaking at the same time (the **‘cocktail party problem'**)?”

- Factors:
  - Voices from different directions
  - Lip-reading, gestures, and the like
  - Different speaking voices, pitches, speeds, …
  - Accents differing
  - Transition-probabilities (subject matter, voice dynamics, syntax, …)

Obtaining SRTs

- Used procedures developed by Carr (2010) (now Carr Levy)
- Adaptive algorithm used to determine the target/masker (T/M) ratio (dB) for 50% correct
  - Masker levels fixed
    - Normal hearing

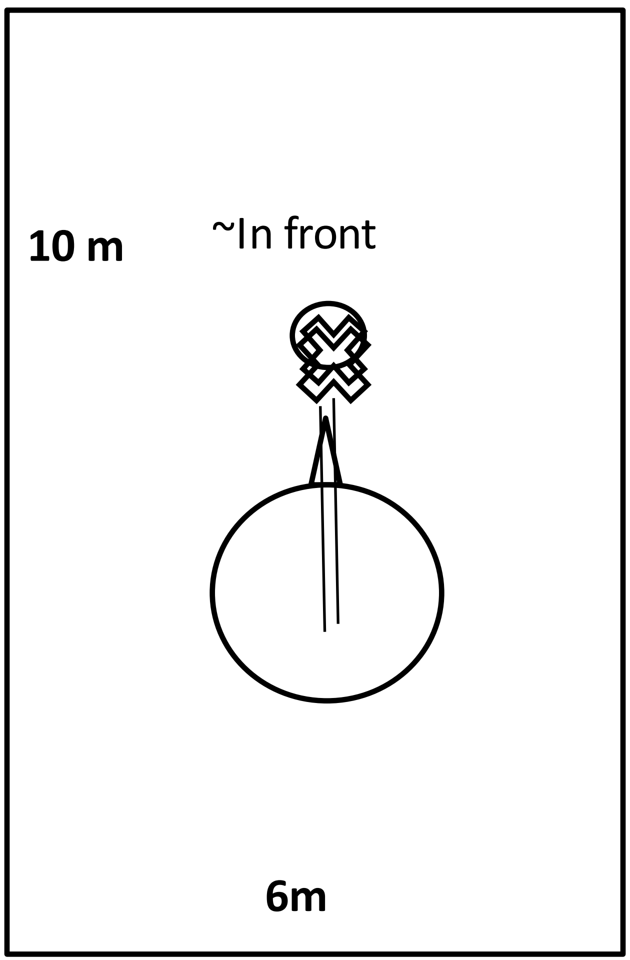
      Each masker set to ~45 dB above SRT in quiet (65 dB SPL)
    - Hearing impaired

      Each masker set ~25 dB above SRT in quiet in HI, when possible
  - Target level varied

- For HI 11, discomfort thresholds limited masker level, so target could be limited by audibility (less than 10 dB above quiet threshold, Duquesnoy, 1983)

Colocated task

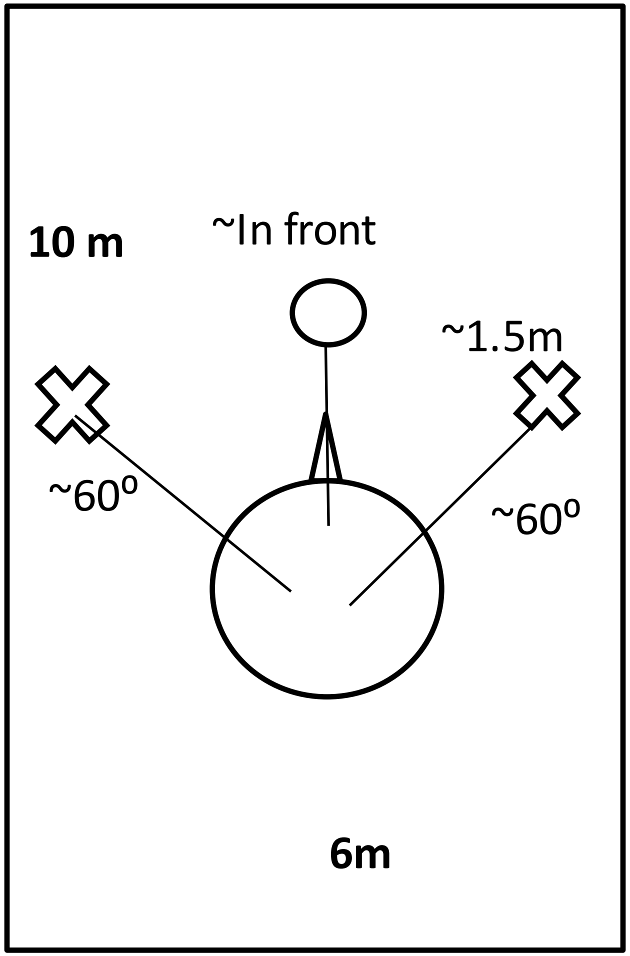
Sources ~ 1.5m away from head



Difficult case, in general…

- All talkers in the same position
- No separation-related cues

Symmetric maskers condition

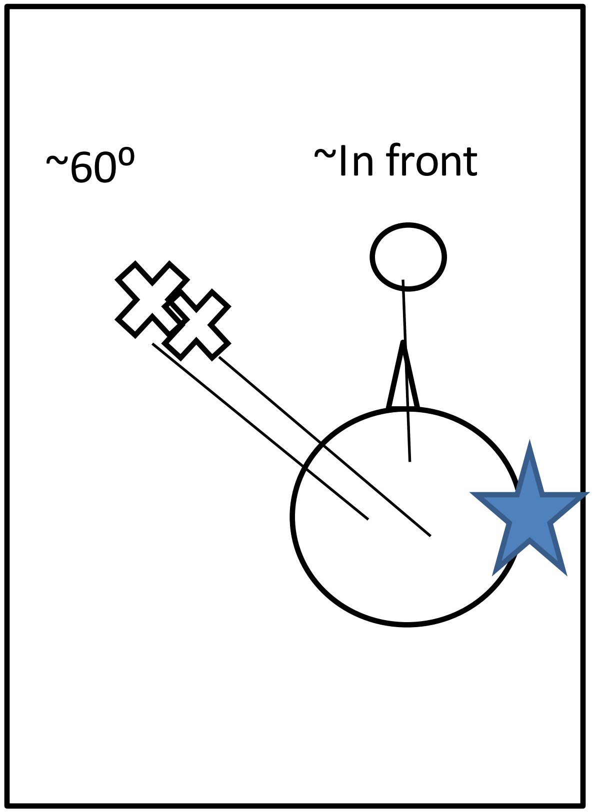


Moderately difficult…

- Interaural differences
- No long-term better ear

Anti-symmetric maskers condition

Sources ~ 1.5m from head



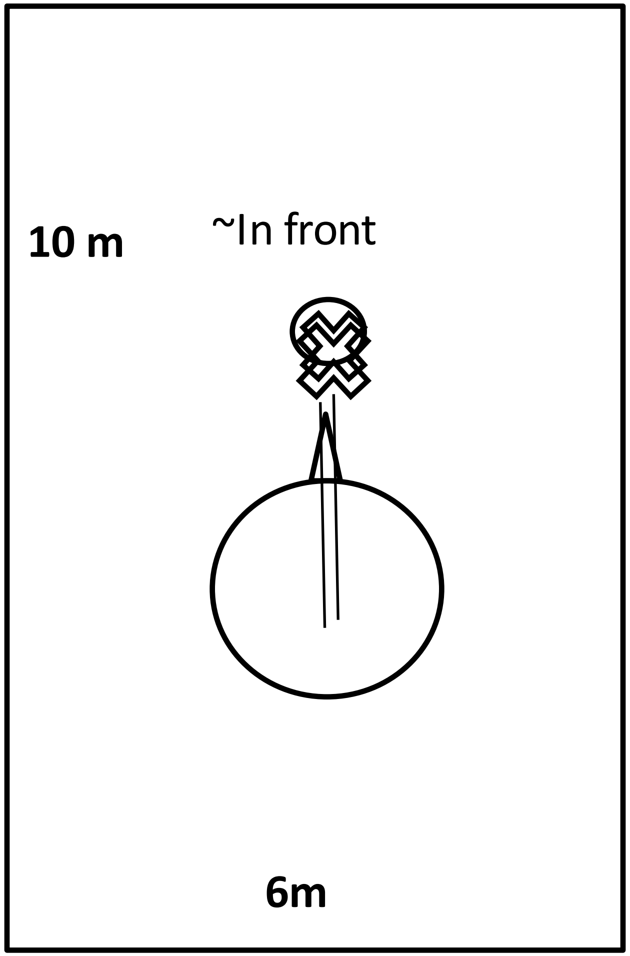
Expected to be easier than colocated…

- Long-term better ear, contralateral to ear with dominant masker
- Interaural time differences
- Interaural level differences

Measured performance both right-ear better and left-ear better

Colocated task

Sources ~ 1.5m away from head



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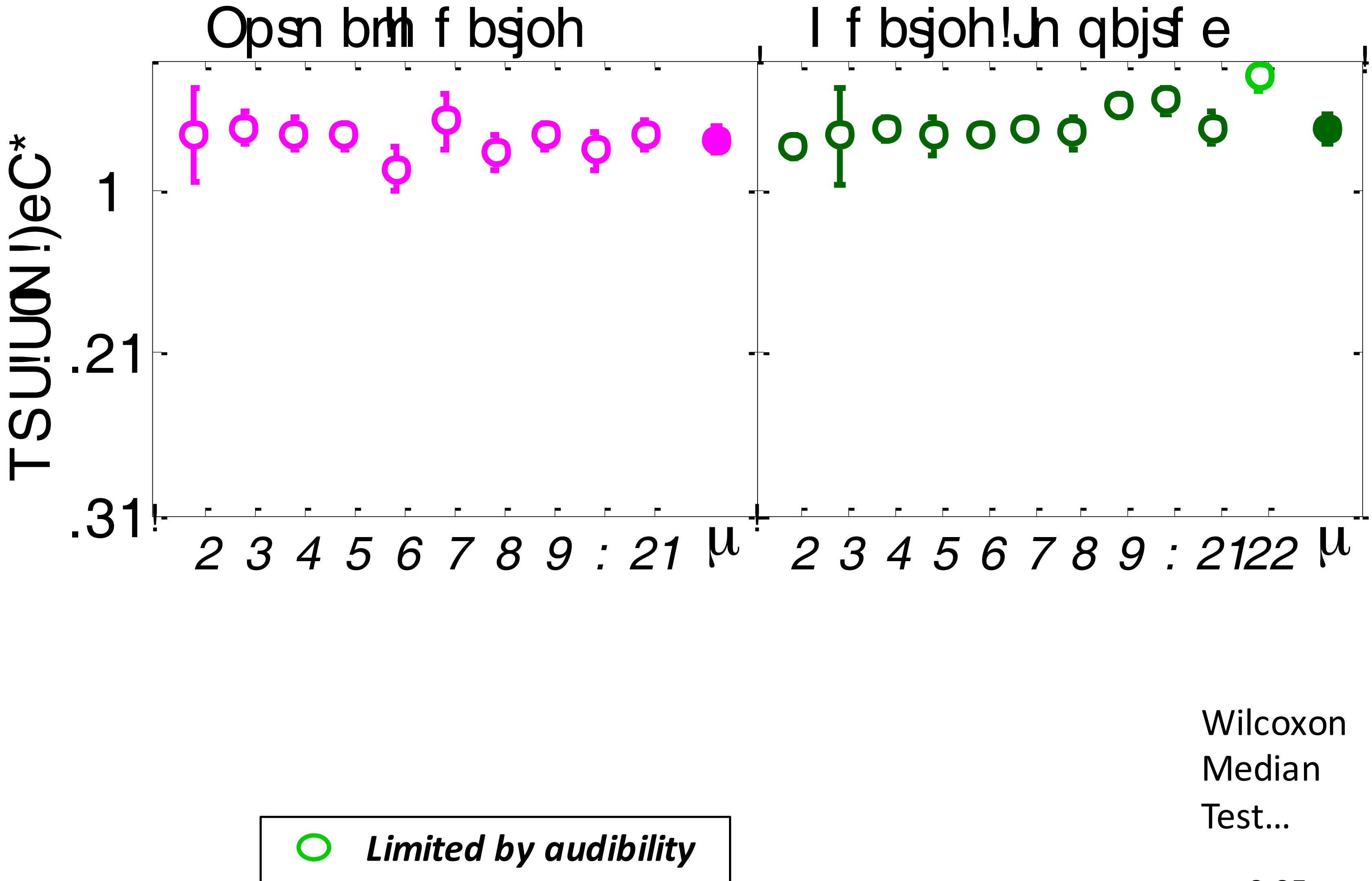
Colocated SRTs

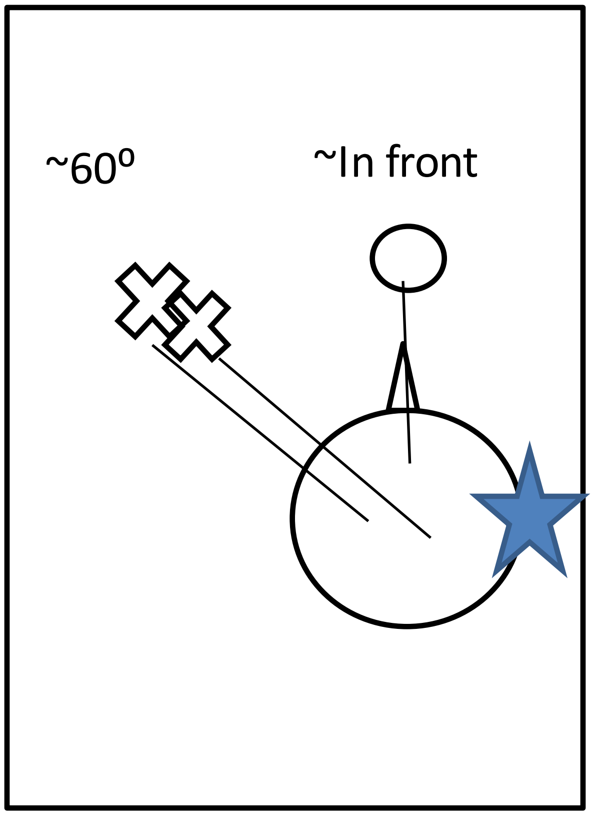


Wilcoxon
Median
Test…

$p>0.05$

Anti-symmetric condition

Sources ~ 1.5m from head



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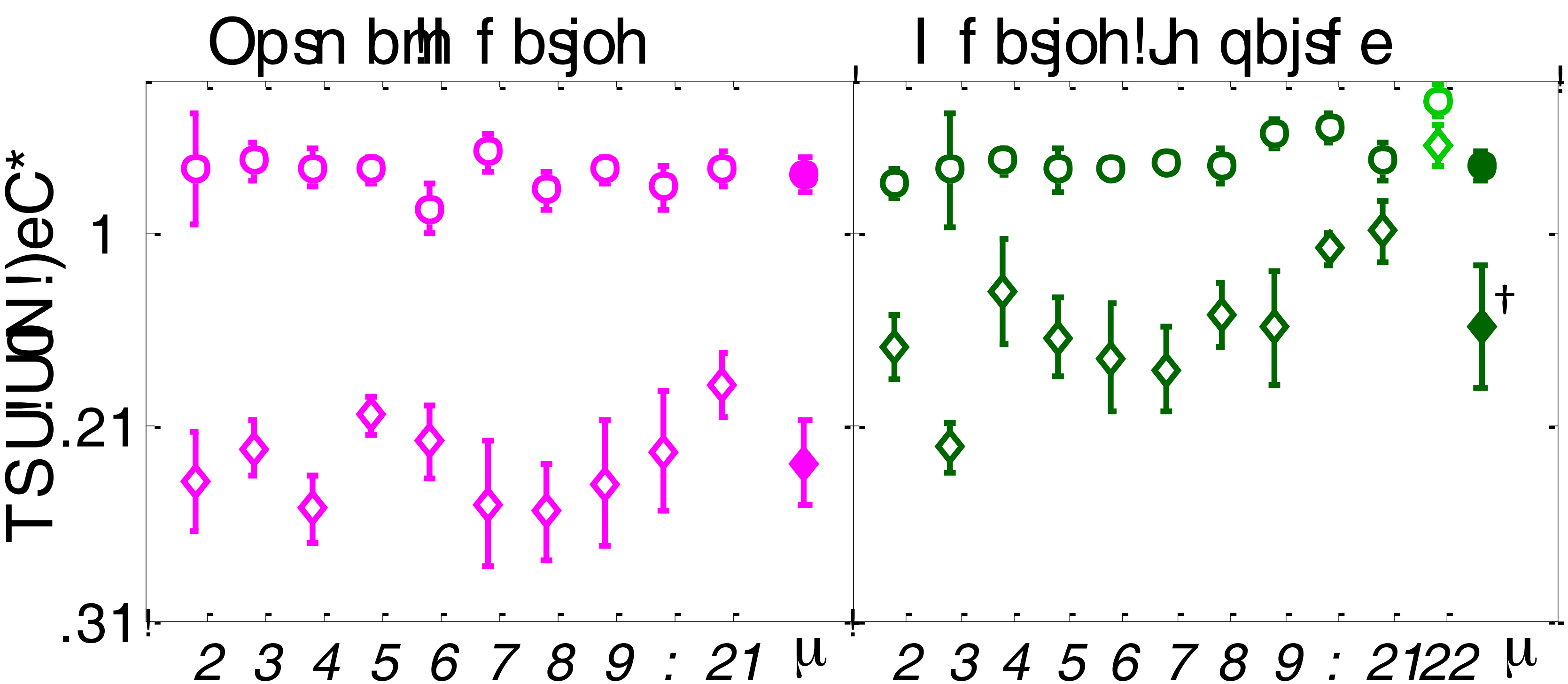
Anti-symmetric SRTs



- “Spatial release from masking”
- Individual differences are evident

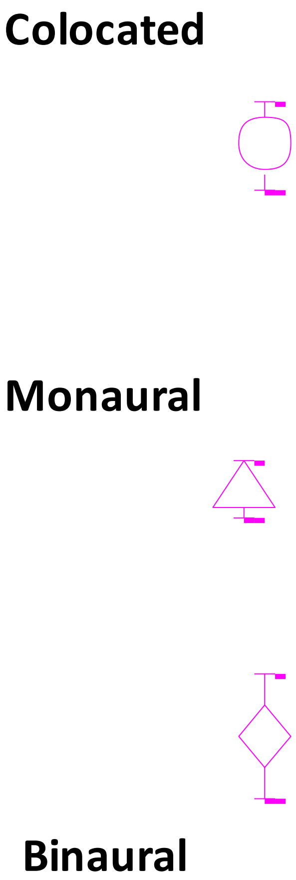
Wilcoxon Median Test…

† $p<0.05$

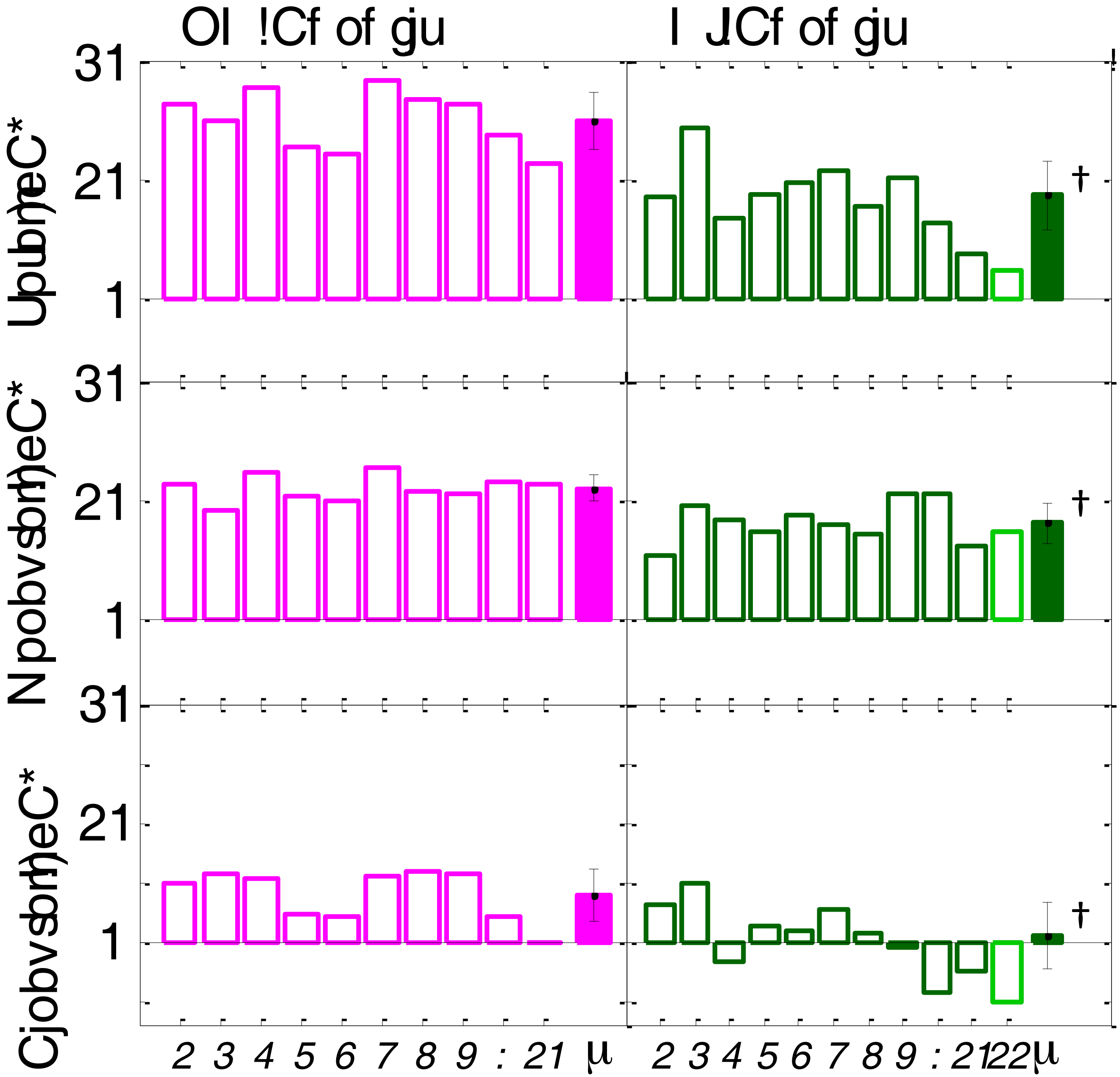
Determining benefits of spatial separation

- **Total benefit** = colocated - spatially separated
- **Monaural benefit** = Colocated – separated monaural

  Separated monaural is measured at better ear
- **Binaural benefit =**Total benefit – monaural benefit



Anti-symmetric benefits of spatial separation



Wilcoxon
Median
Test…

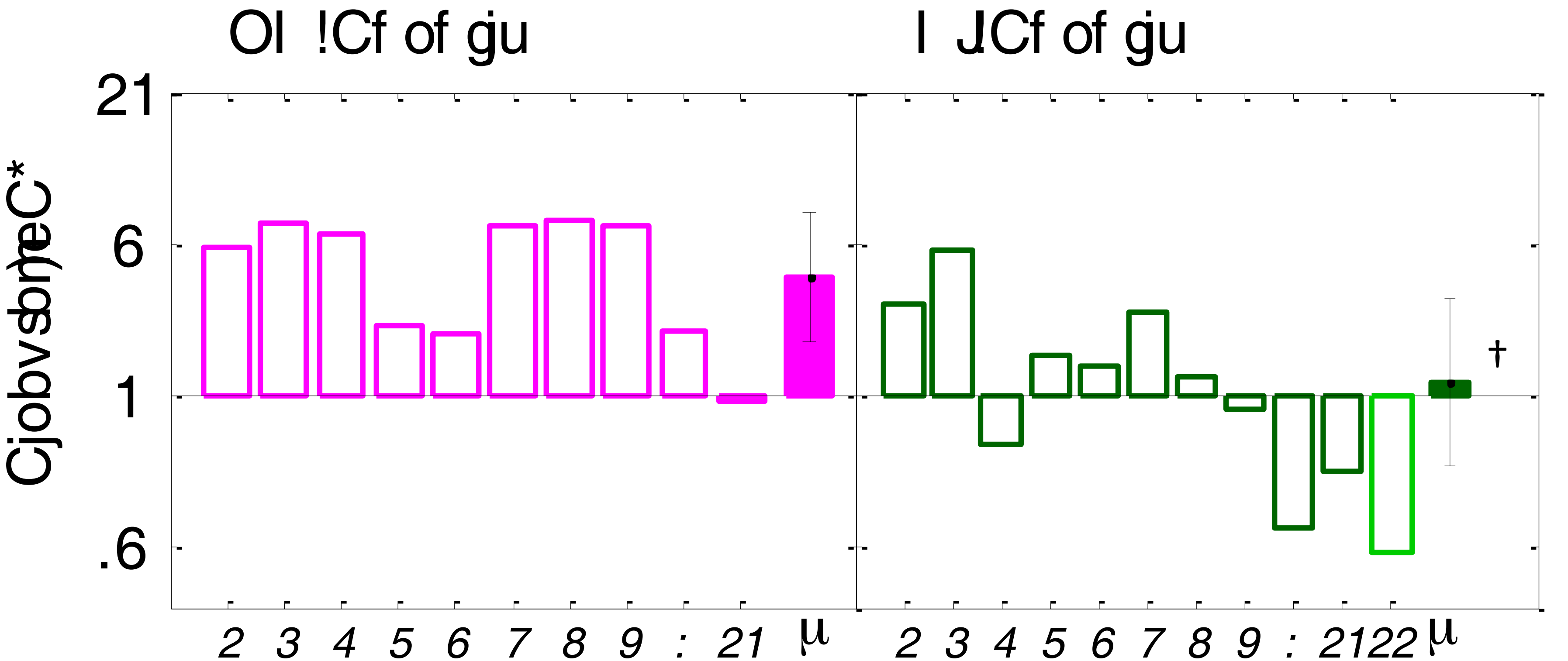
† $p<0.05$

Large
monaural
benefit

† $p<0.05$

† $p<0.05$

Anti-symmetric binaural benefit

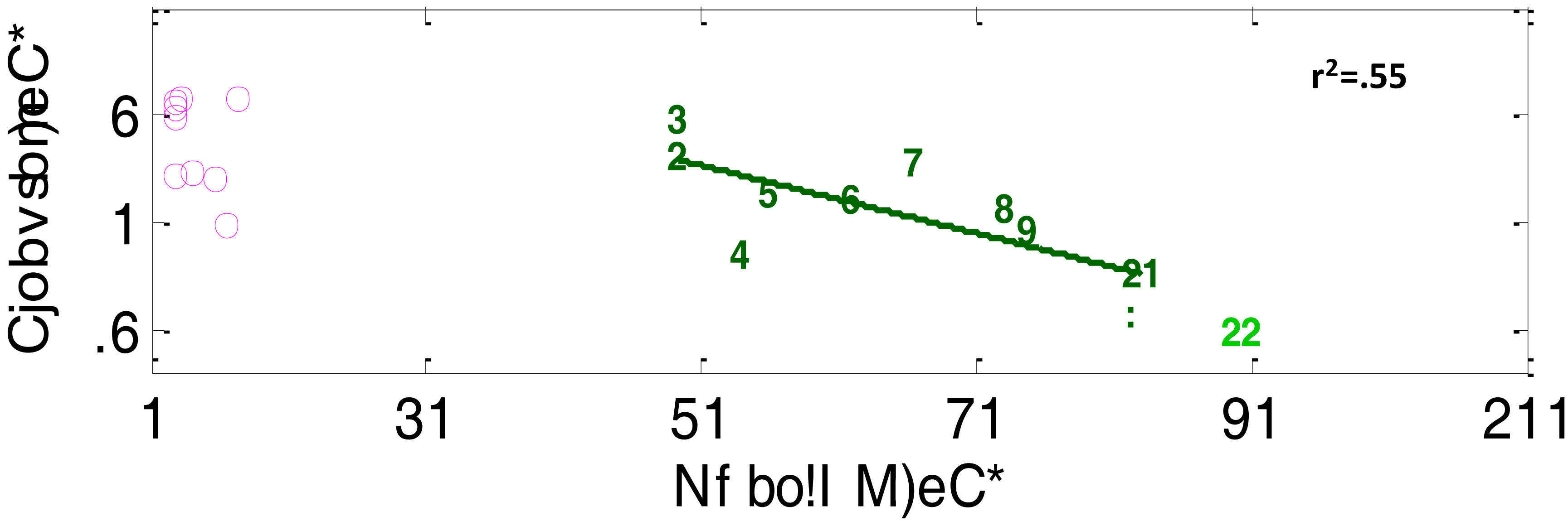


High inter-subject variability in both groups

Wilcoxon
Median
Test…

† $p<0.05$

Anti-symmetric binaural benefit as a function of hearing loss



Anti-symmetric binaural benefit as a function of interaural difference sensitivity

r^2 shown in table

Red means $p<0.05$

NH

	Binaural Benefit
ILD 500	r^2 <0.2
ILD 4k	**r^2 =0.67**
ITD 500	**r^2=0.51**
ITD 4k	**r^2 =0.39**

Correlation for **most** interaural difference sensitivity thresholds

HI 1-10

Binaural Benefit
r^2 <.2
r^2 <.2
r^2 <.2
r^2 N/A

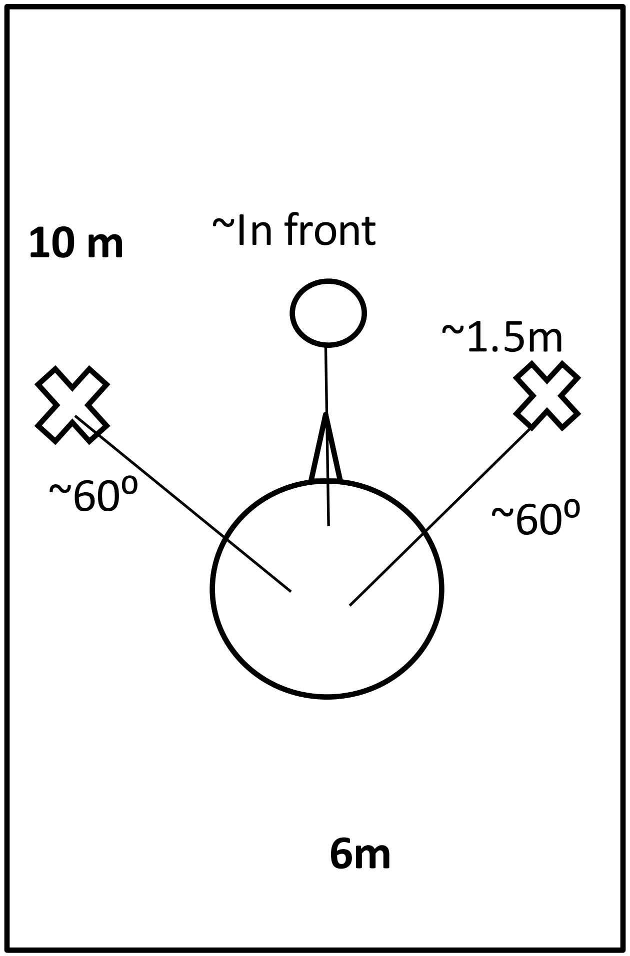
Correlation for **no** interaural difference sensitivity thresholds

HI 1-8 (<70 dB HL)

Binaural Benefit
N=8 r^2 =.53
N=6 r^2= 0.64
N=8 0.54
N=4 r^2 N/A

Correlation for **some** interaural difference sensitivity thresholds

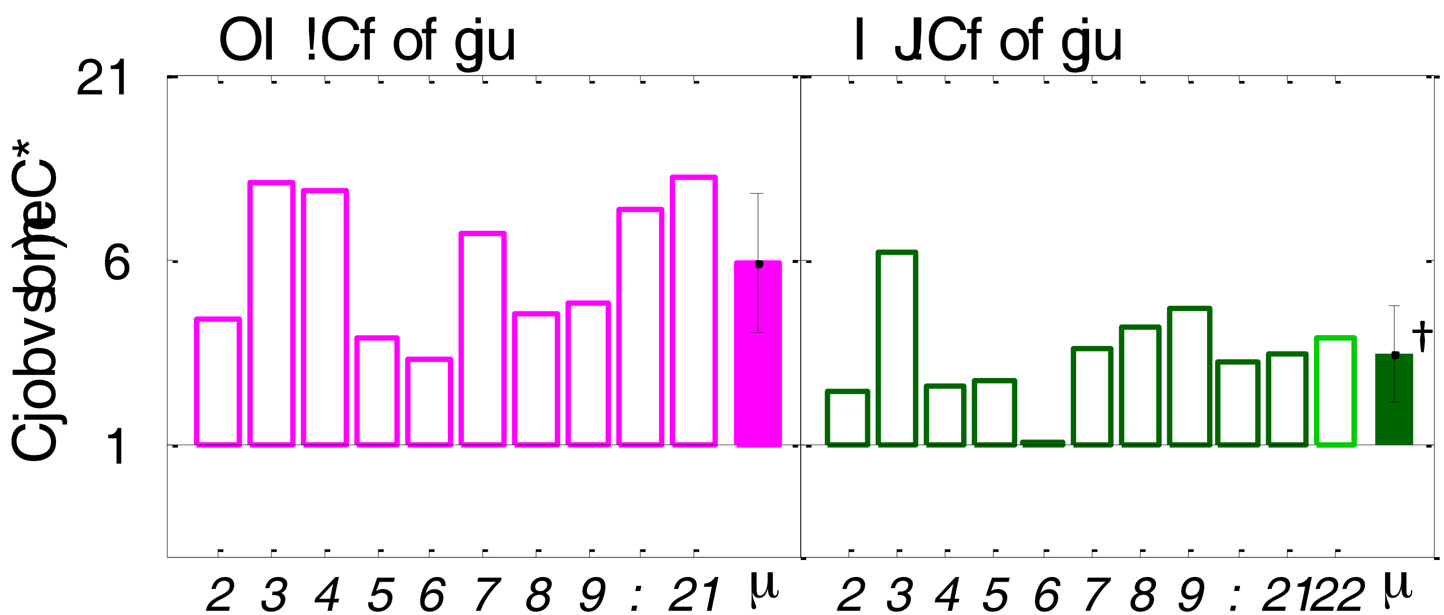
Symmetric task



Moderately difficult…

- Interaural differences
- No long-term better ear

Symmetric binaural benefit



† $p<0.05$

Wilcoxon Median Test...

High inter-subject variability among each subject group

Symmetric binaural benefit

- Binaural benefit did not correlate with hearing loss in either group
- Binaural benefit did not correlate with interaural difference sensitivity thresholds in either groups

Data Conclusions

- Hearing loss a key factor in the binaural benefit for the anti-symmetric condition but not for the symmetric condition

- In most cases, hearing-impaired listeners benefited from binaural listening
  - Binaural benefits mostly positive for ***anti-symmetric*** condition
  - Binaural benefits were always positive for HI in the ***symmetric*** condition

- In the anti-symmetric condition, binaural benefit was correlated with some interaural difference sensitivity thresholds for both ***normal-hearing*** and ***subset of hearing-impaired*** listeners

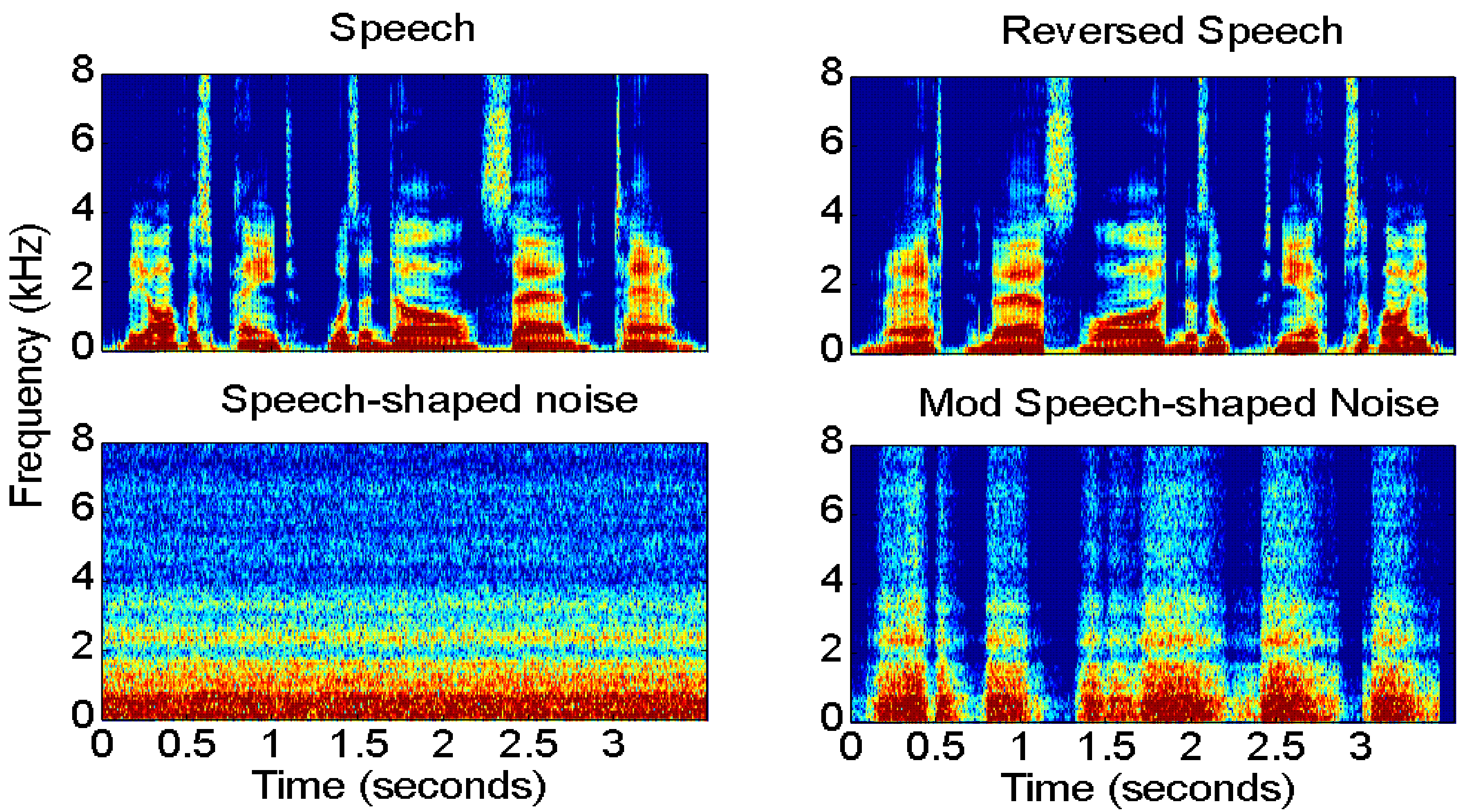
- In the symmetric condition, binaural benefit not correlated with interaural difference sensitivity thresholds

Time window processing factor?

- In the symmetric case, with speech maskers, listeners benefit from selectively listening in optimal direction (and/or to the better ear) differently in different time intervals

- This factor is distinct from interaural resolution factors and from attenuation factors

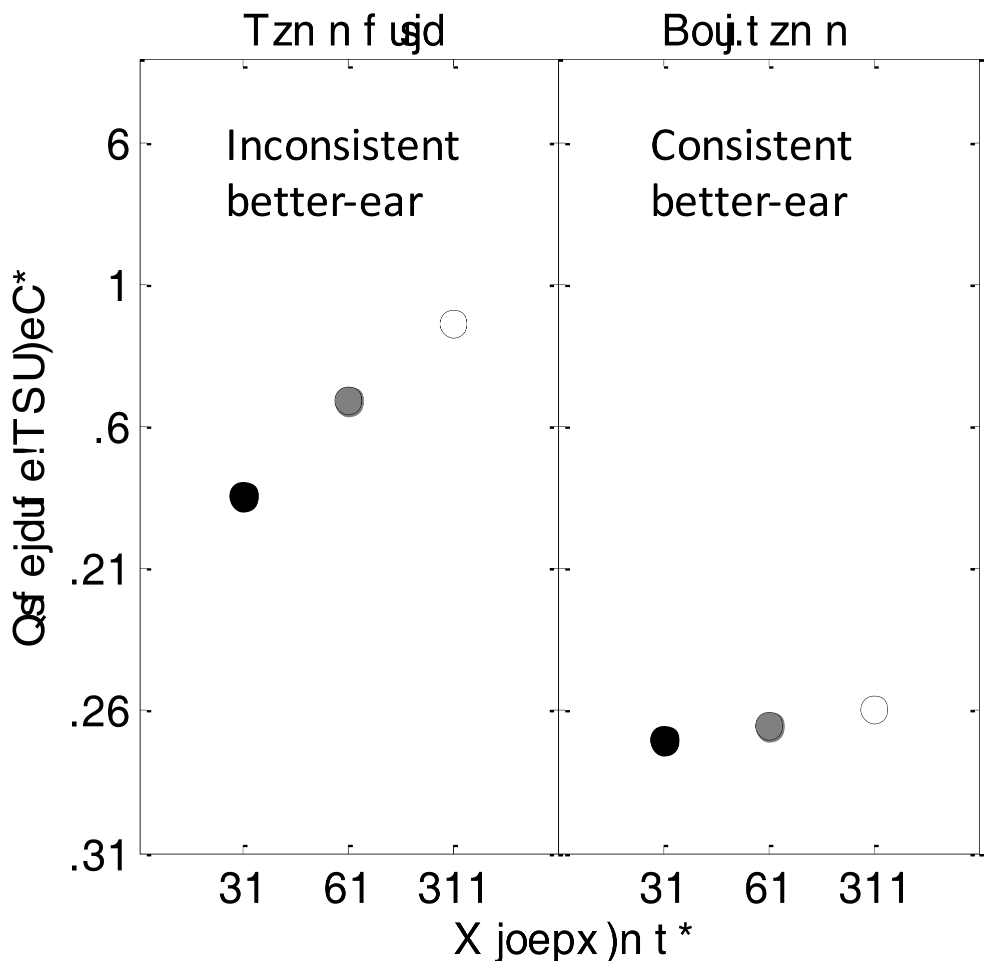
•Speech Spectrogram



Frequency (kHz)

Time (about 3.5 seconds)

Effect of EC window length on SRT (1x Jitter)



Overall Conclusions for this study

- ***Binaural benefit in anti-symmetric condition for HI group decreases with hearing loss***
- ***Interaural difference sensitivity a key factor for binaural benefit for anti-symmetric speech condition***
  - Correlations were observed for normal hearing group and for hearing-impaired subgroup with less-than-severe average hearing loss
  - Model predictions show large effect of jitter standard deviation
- ***Interaural difference sensitivity and hearing loss each unrelated to binaural benefit for symmetric condition***
  - Neither interaural difference sensitivity nor hearing loss correlated with binaural benefit in the symmetric condition
  - Modeling results show influence of processing window duration
  - Suggest independent estimation of processing window length

Take home message?

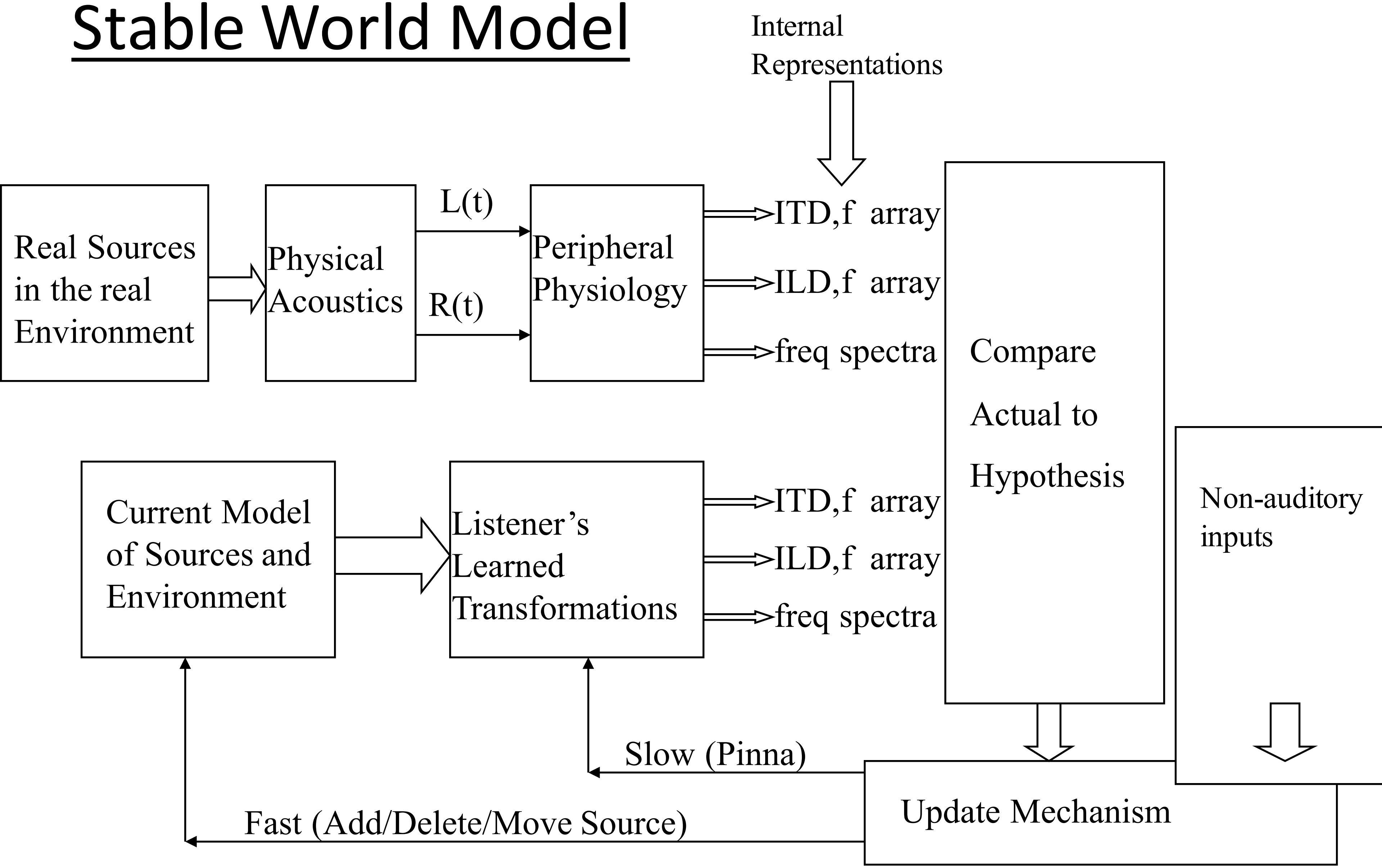
- The processing in multiple speech interference situations is very complex
  - Depends on locations, nature of sources, positions of maskers, individual ability to use the multiple cues, and possibly on temporal window factors.

- Neither the audiogram nor abilities to do simple discrimination tasks are predictors of abilities in complex environments
- Tests to be done with hearing aids in complex environments seem important to develop.

Ongoing work on this topic (with Theo Goverts at VUMC)

- Attempt to characterize difficult environments
  - Recording (binaurally) difficult environments as reported by listeners with hearing impairments
- Analysis of recordings and comparisons with subjective impressions
- Work to develop a speech-in-complex-environments test that could be used to evaluate hearing aids in the clinic.

Stable World Model



Colburn and Kulkarni (2005)

Acknowledgements

- IRC hearing-aid company consortium
- National Institutes of Health Grant support:
  - NIDCD R01 DC00100
- Many Colleagues, especially Gerald Kidd, Theo Goverts, Suzanne Carr Levy, Nathan Spencer

The End!!