Austrian Academy of Sciences
Acoustics Research Institute

Effects of Interaural Time Difference in the Temporal Fine Structure

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Overview

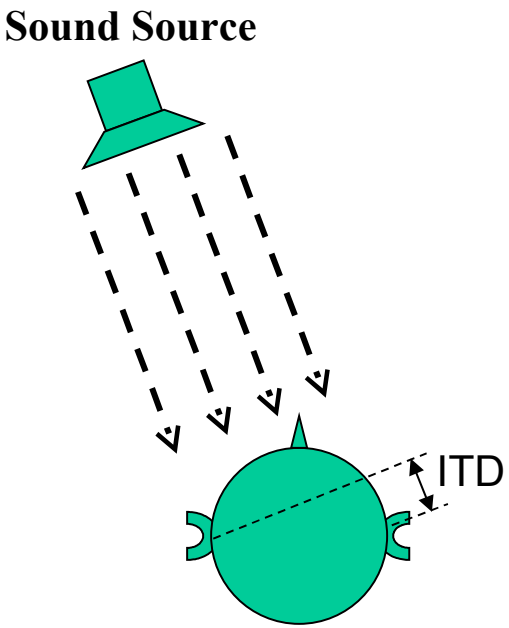
PART I

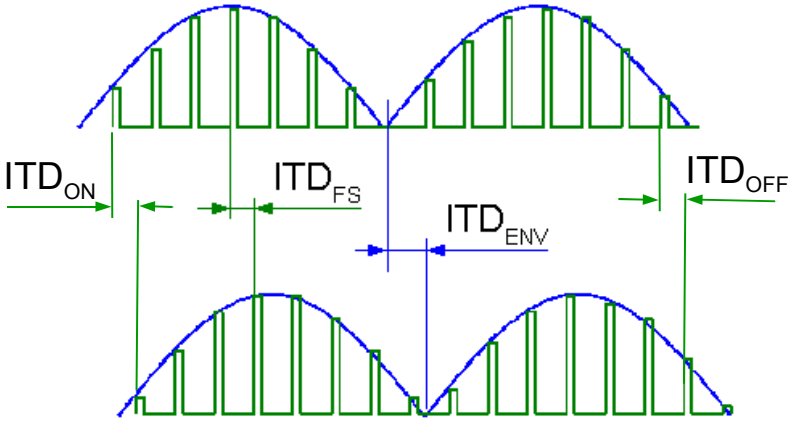
- Two studies on Fine Structure ITD Sensitivity of CI Listeners
  - Four-Pulse Sequences: ITD in Ongoing and Gating Signal Portions
  - Modulated Pulse Trains: ITD in Fine Structure and Ongoing Envelope

PART II

- Binaural Jitter Improves ITD Sensitivity in Electric Hearing

Interaural Time Differences (ITD)





Interaural Time Differences (ITD) occur in

- Gating portions (ITD_{ON} / ITD_{OFF})
- Temporal fine structure (ITD_{FS})
- Ongoing envelope (ITD_{ENV})

Motivation

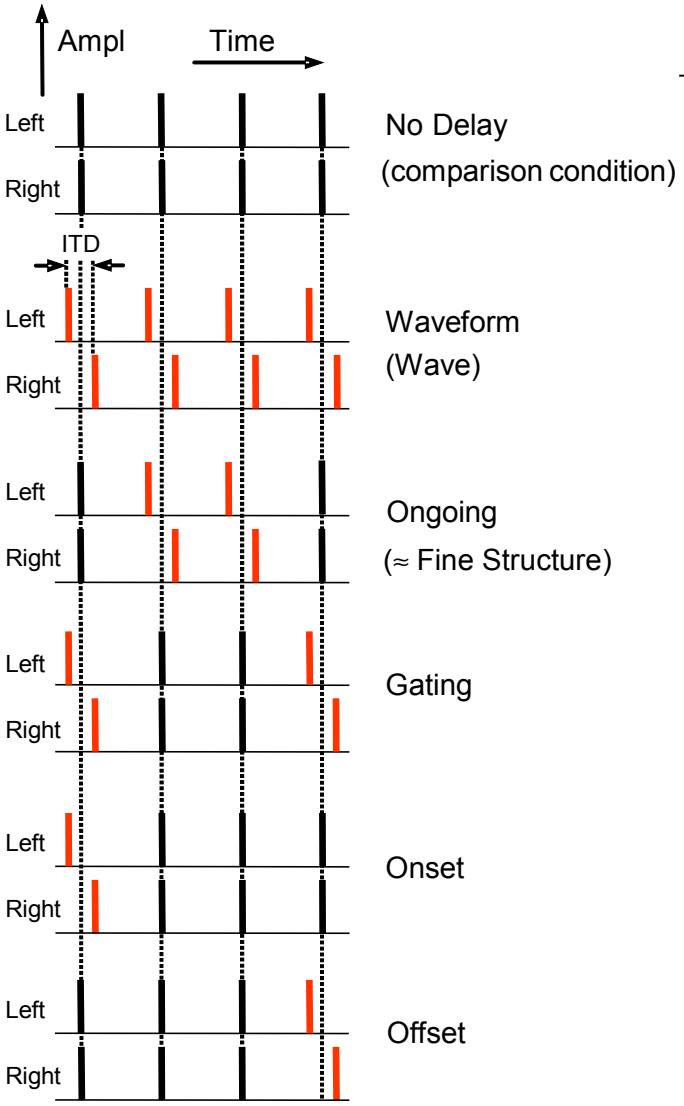
- Fine structure ITD is important for
  - Lateralizing sound sources (Wightman and Kistler, 1992; Smith et al., 2002)
  - Speech understanding in noise (Nie et. al., 2005; Zeng et al., 2005)
- Bilateral CI listeners are often sensitive to whole-waveform ITD (e.g. van Hoesel and Tyler, 2003)
- <u>Open Questions</u>:
  - Are CI listeners sensitive to ITD in the fine structure?
  - What is the contribution of gating ITD and ongoing envelope ITD?

Left/Right Discrimination of ITD in Ongoing and Gating Signal Portions: Four-Pulse Sequences

Laback, Majdak, and Baumgartner (2007) JASA 121, 2182-2191

Methods I

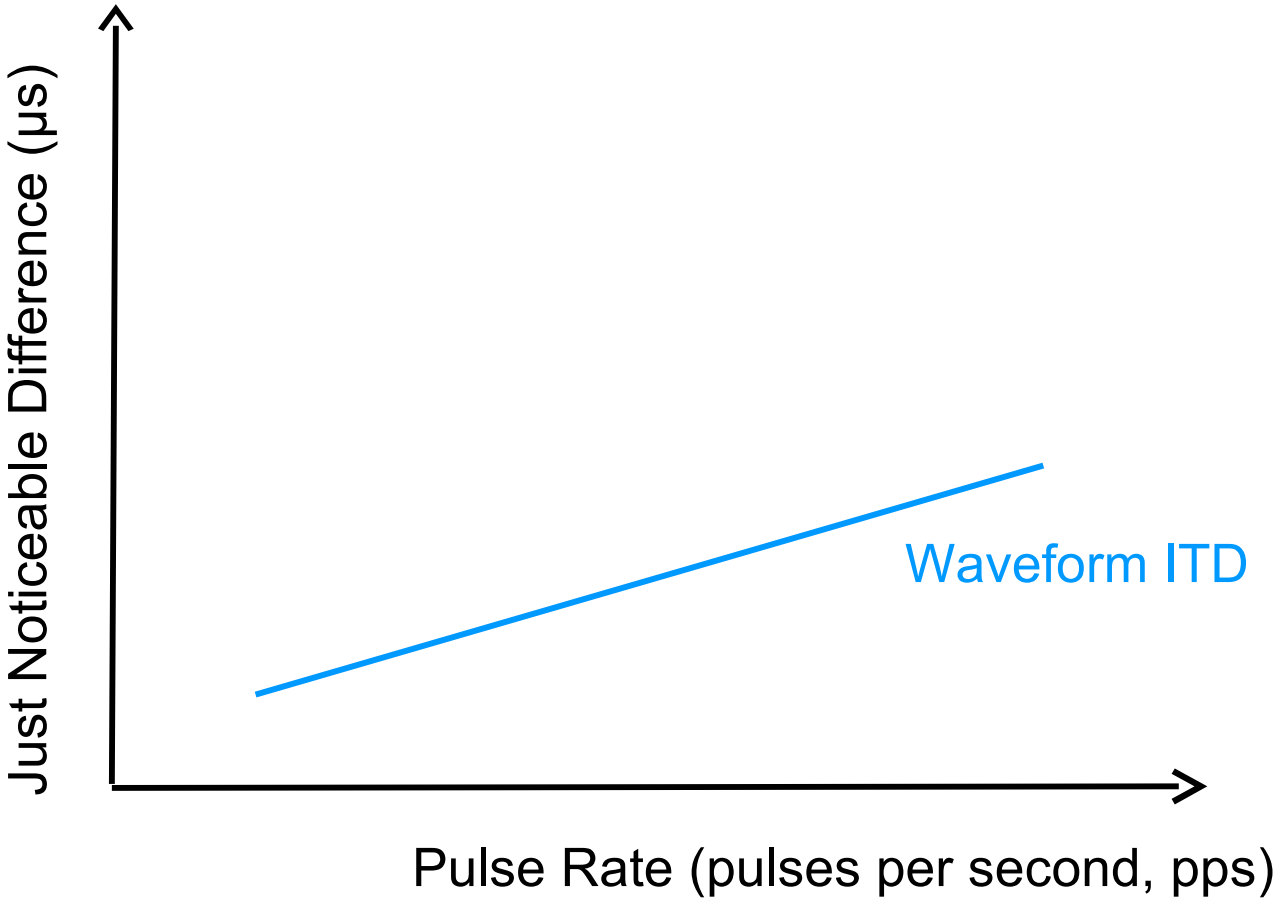
- Stimuli
  - Four biphasic pulses
  - Presented at a single interaural electrode pair (pitch-matched and loudness-balanced)
- ITD conditions (see right side)



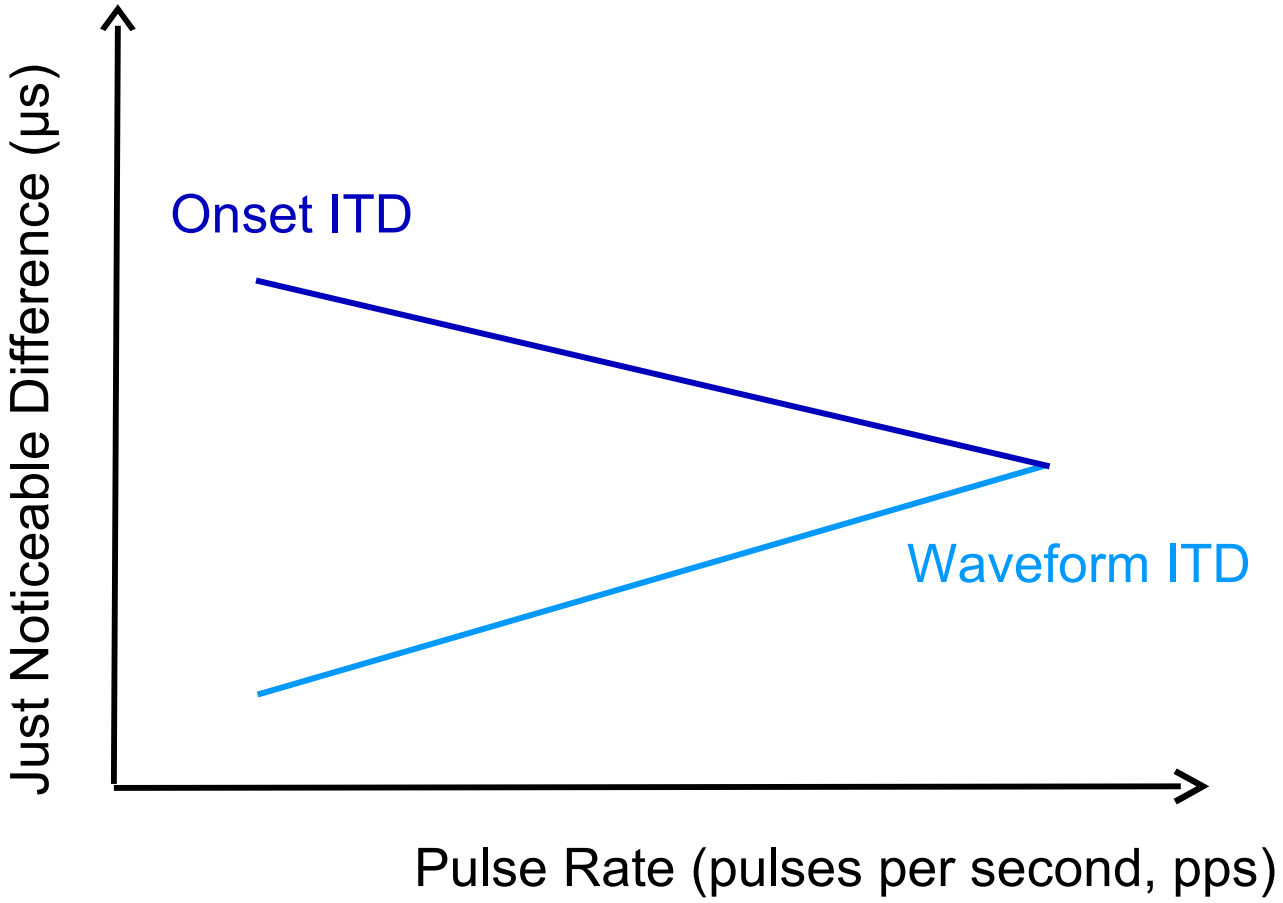
Methods II

- Subjects
  - Four bilateral CI listeners (*C40+*, *MED-EL*)
- Independent Variables
  - ITD condition
  - Pulse Rate (100 – 800 pps)
- JNDs for Left/Right Discrimination

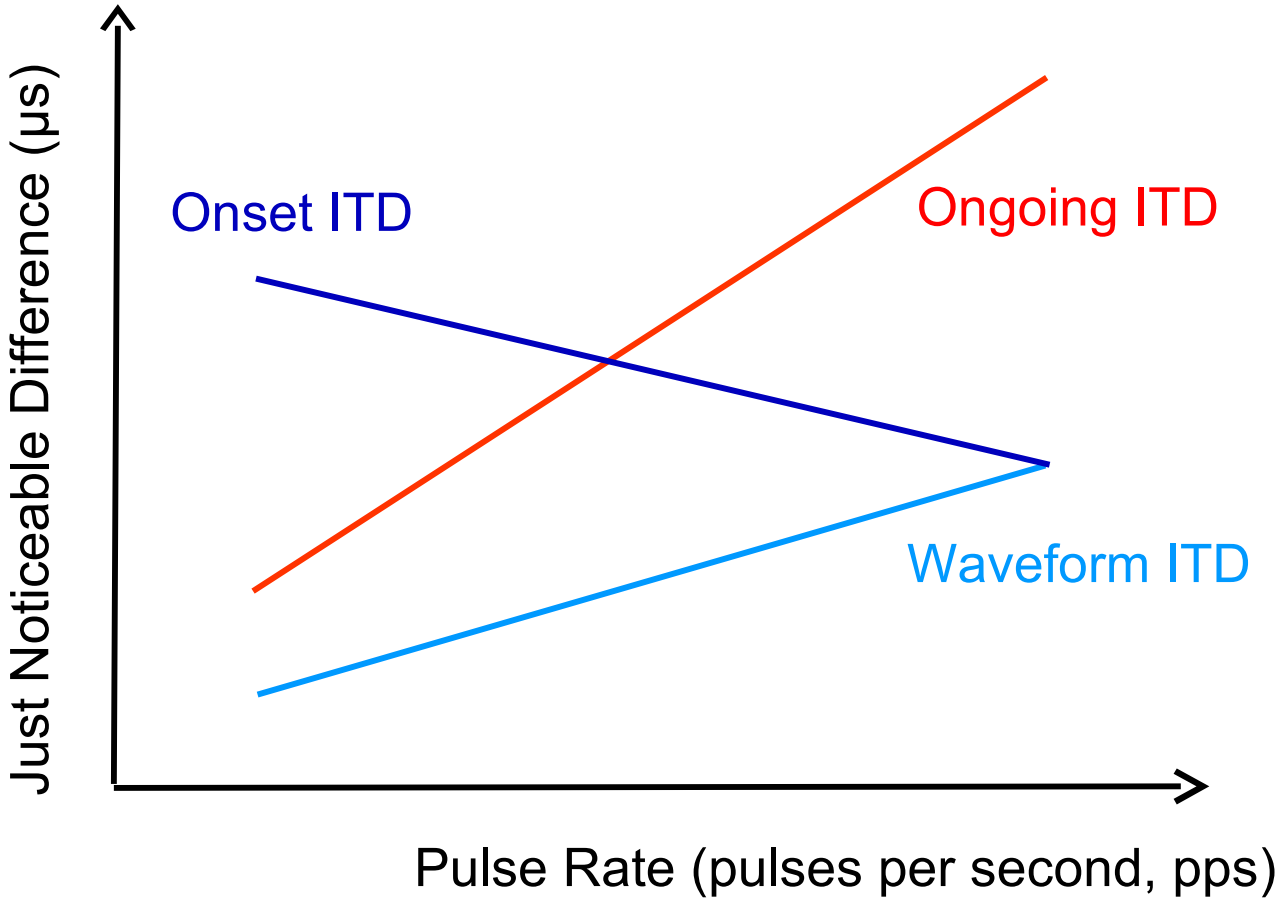
Expectations



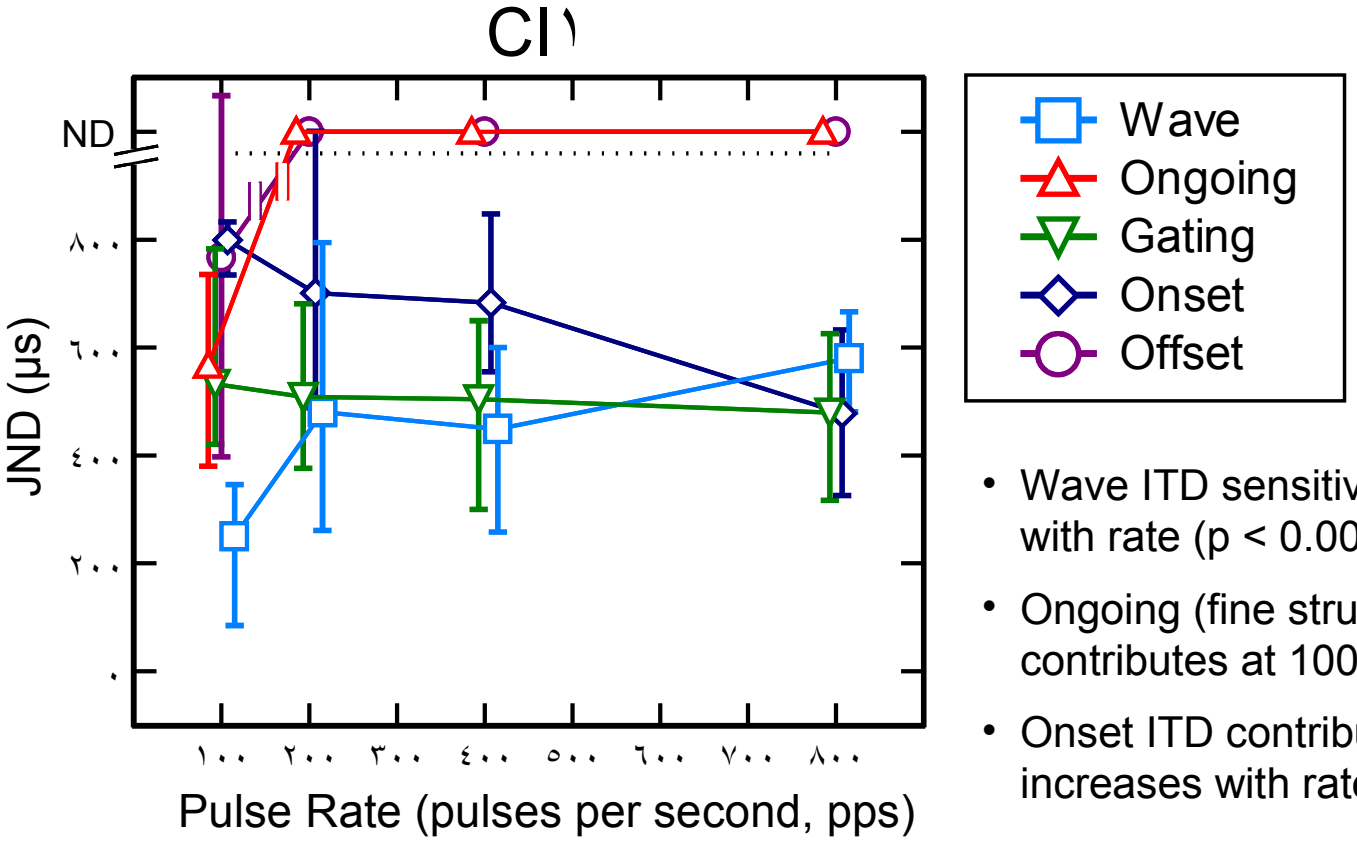
Expectations



Expectations



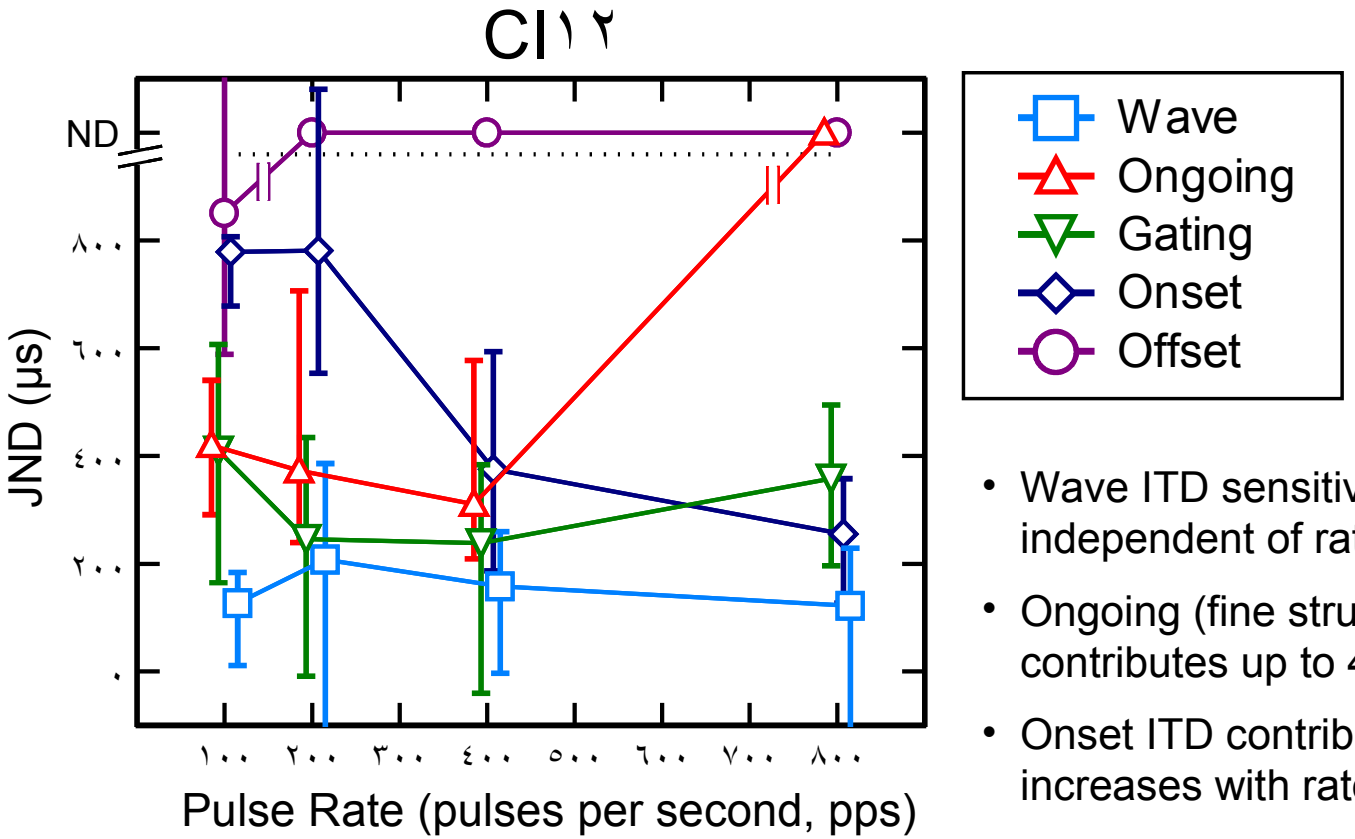
Results for CI listeners: CI1



- Wave ITD sensitivity decreases with rate ($p < 0.003$)
- Ongoing (fine structure) ITD contributes at 100 pps only
- Onset ITD contribution increases with rate ($p < 0.0001$)

Error bars: 95% confidence intervals

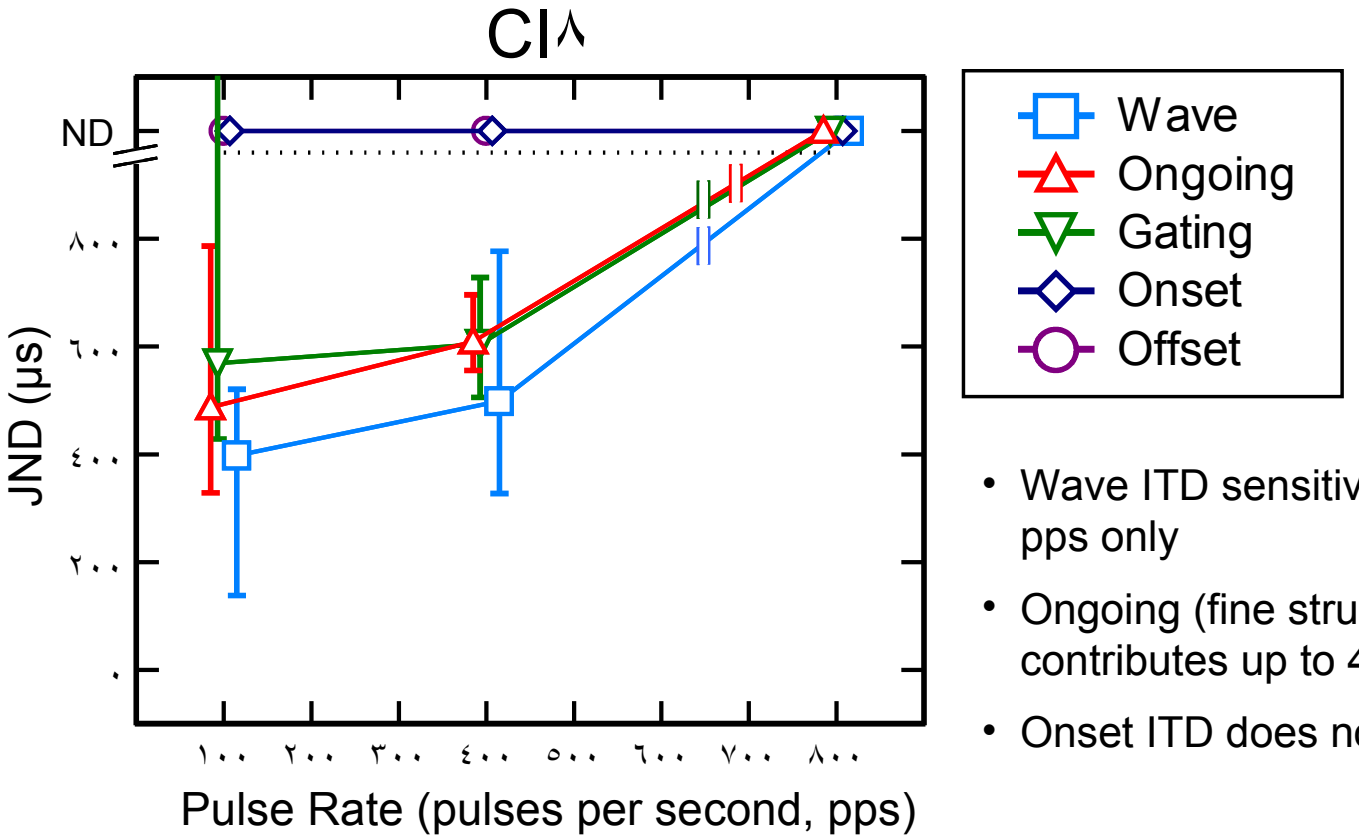
Results for CI listeners: CI12



- Wave ITD sensitivity independent of rate
- Ongoing (fine structure) ITD contributes up to 400 pps
- Onset ITD contribution increases with rate ($p < 0.034$)

Error bars: 95% confidence intervals

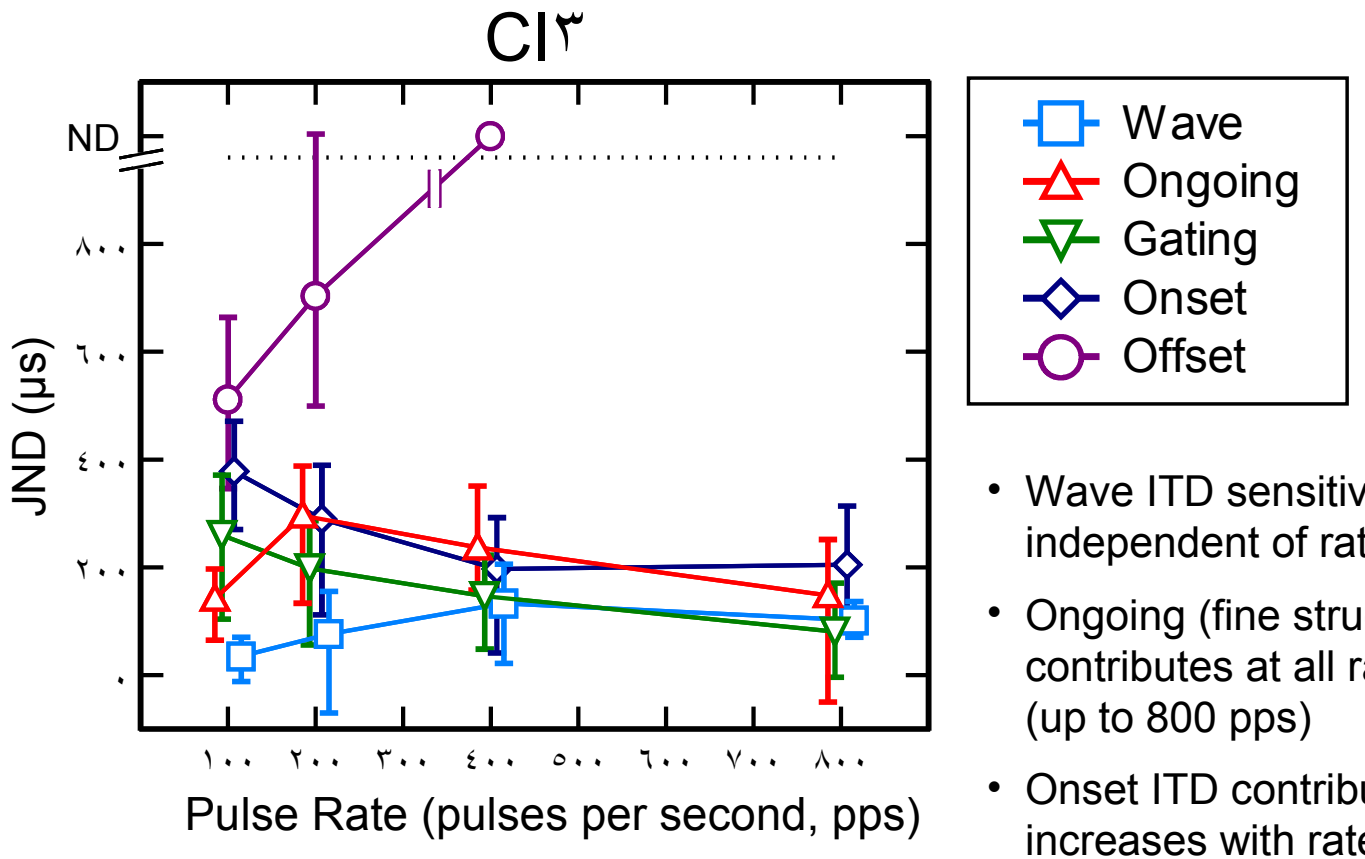
Results for CI listeners: CI8



- Wave ITD sensitivity up to 400 pps only
- Ongoing (fine structure) ITD contributes up to 400 pps
- Onset ITD does not contribute

Error bars: 95% confidence intervals

Results for CI listeners: CI3



- Wave ITD sensitivity independent of rate
- Ongoing (fine structure) ITD contributes at all rates tested (up to 800 pps)
- Onset ITD contribution increases with rate ($p < 0.04$)

Error bars: 95% confidence intervals

Conclusions of Study I

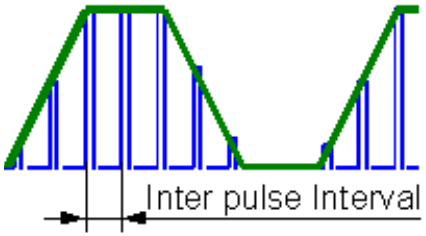
- CI listeners are sensitive to ongoing fine structure ITD in four-pulse sequences
- Highest rate showing fine structure ITD sensitivity varies between listeners (100 to 800 pps)
- Contribution of onset ITD increases with pulse rate
- Monaural cues not perceptible (tested in separate experiment)

Left/Right Discrimination of ITD in Fine Structure and Ongoing Envelope: Modulated pulse trains

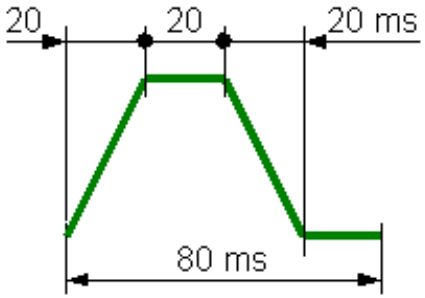
Majdak, Laback, and Baumgartner (2006) JASA 120, 2190-2201

Methods

- **Stimuli**
  - Amplitude modulated pulse trains
    - Duration: 300 ms
    - Modulation frequency: 13 Hz

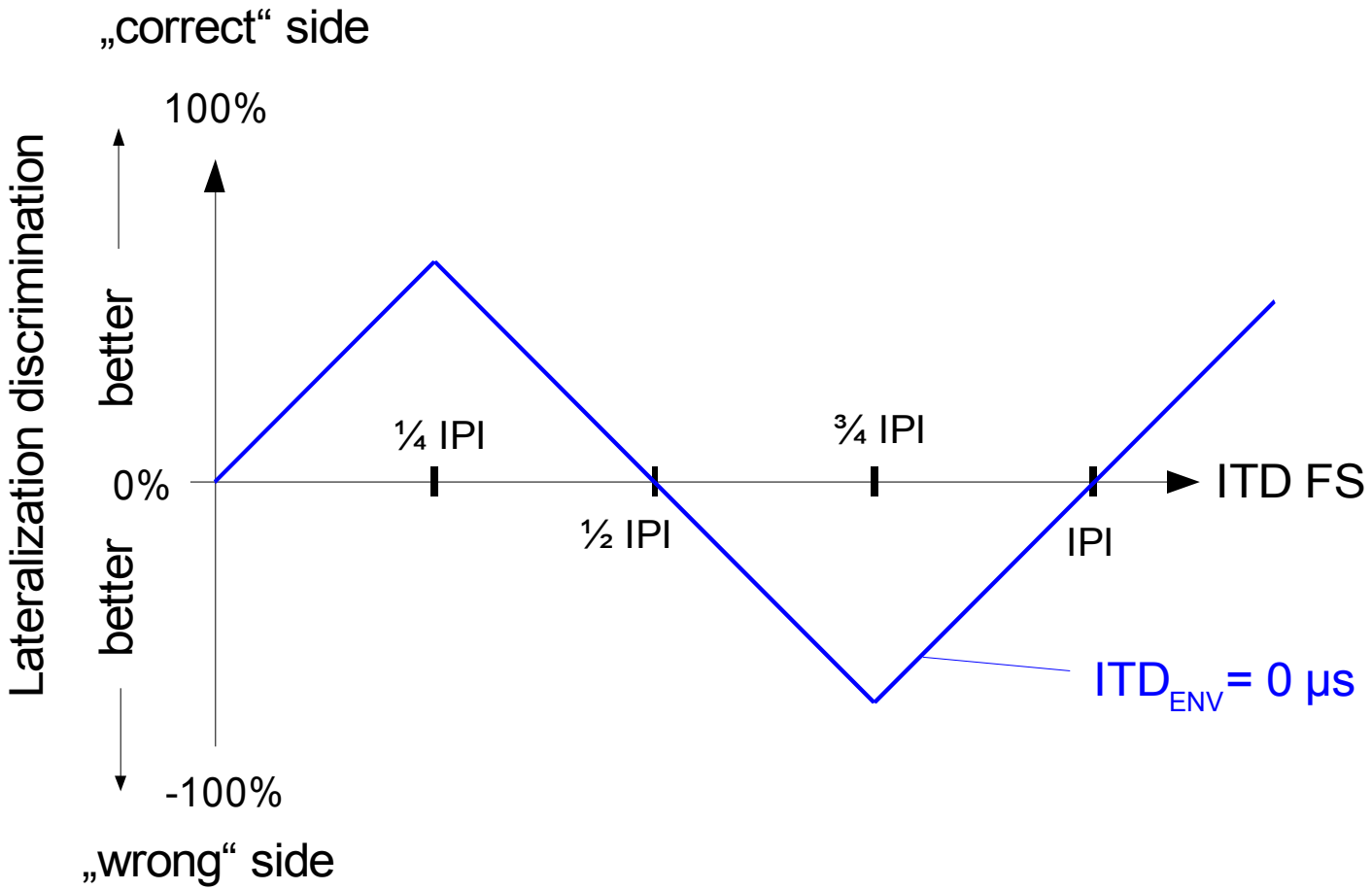


- **Subjects**
  - Four bilateral CI listeners (*C40+*, *MED-EL*)

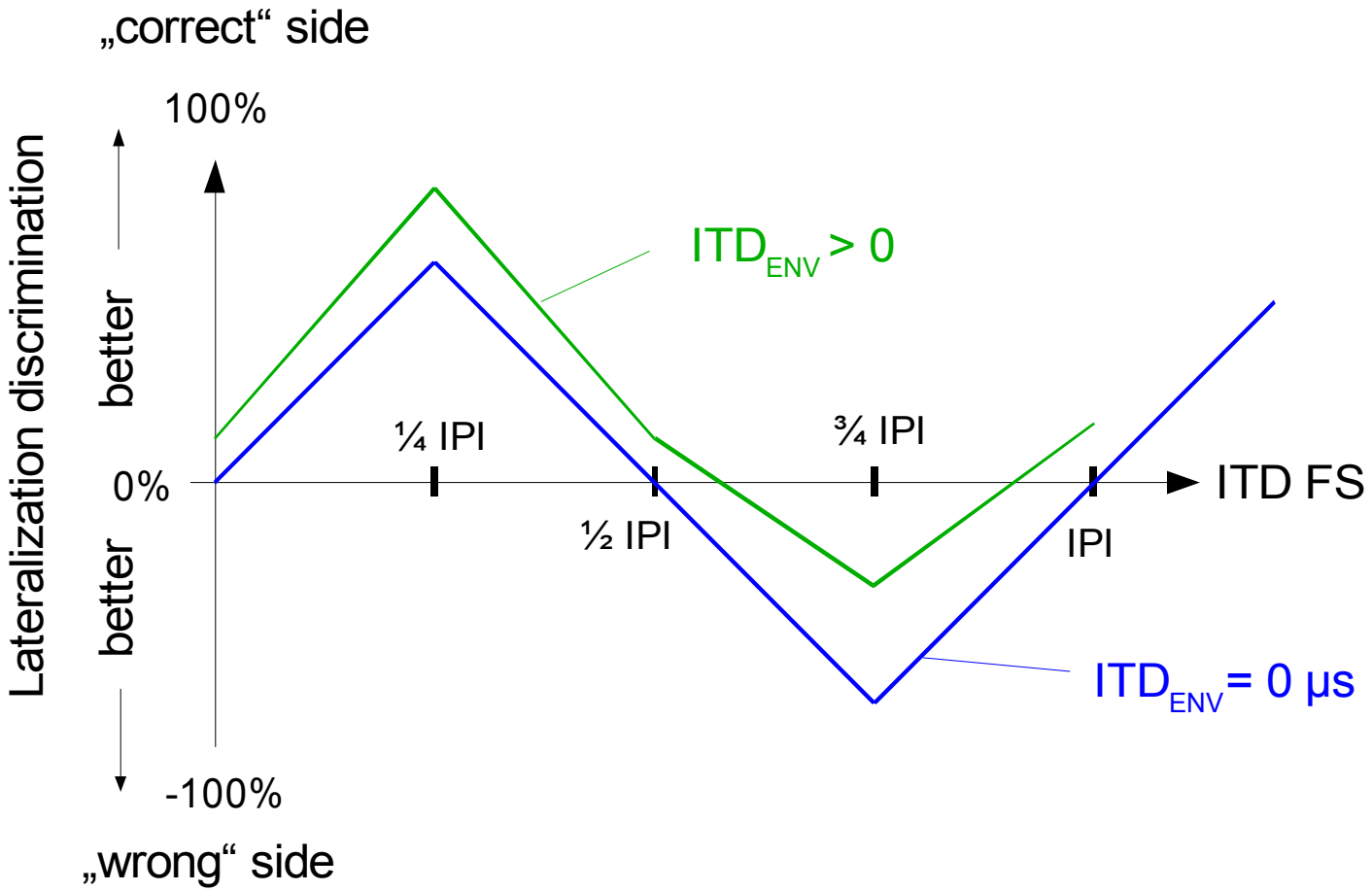


- **Independent variables**
  - ITD_{FS}: 0 … IPI (inter-pulse interval)
  - ITD_{ENV}: 0 … 800 µs
  - Pulse rate: 100 … 1600 pps

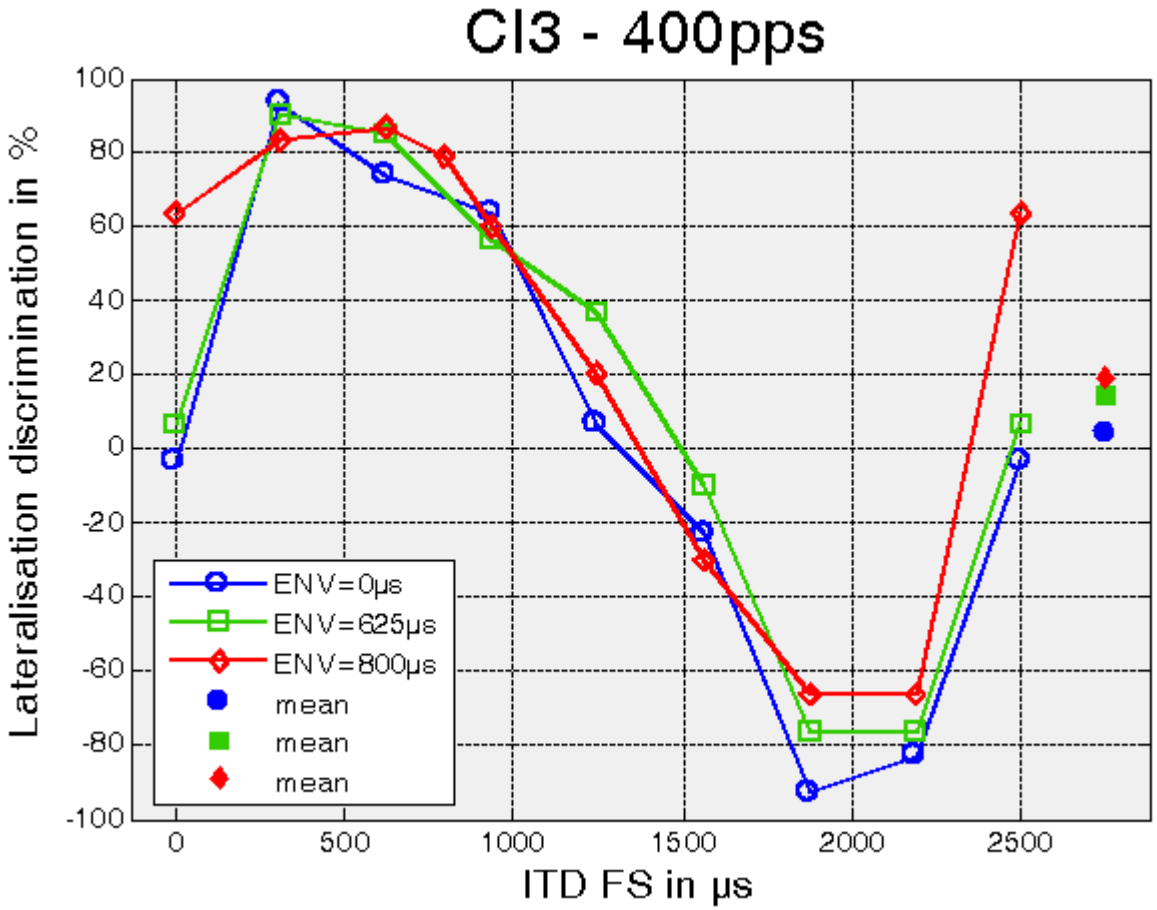
Expectations



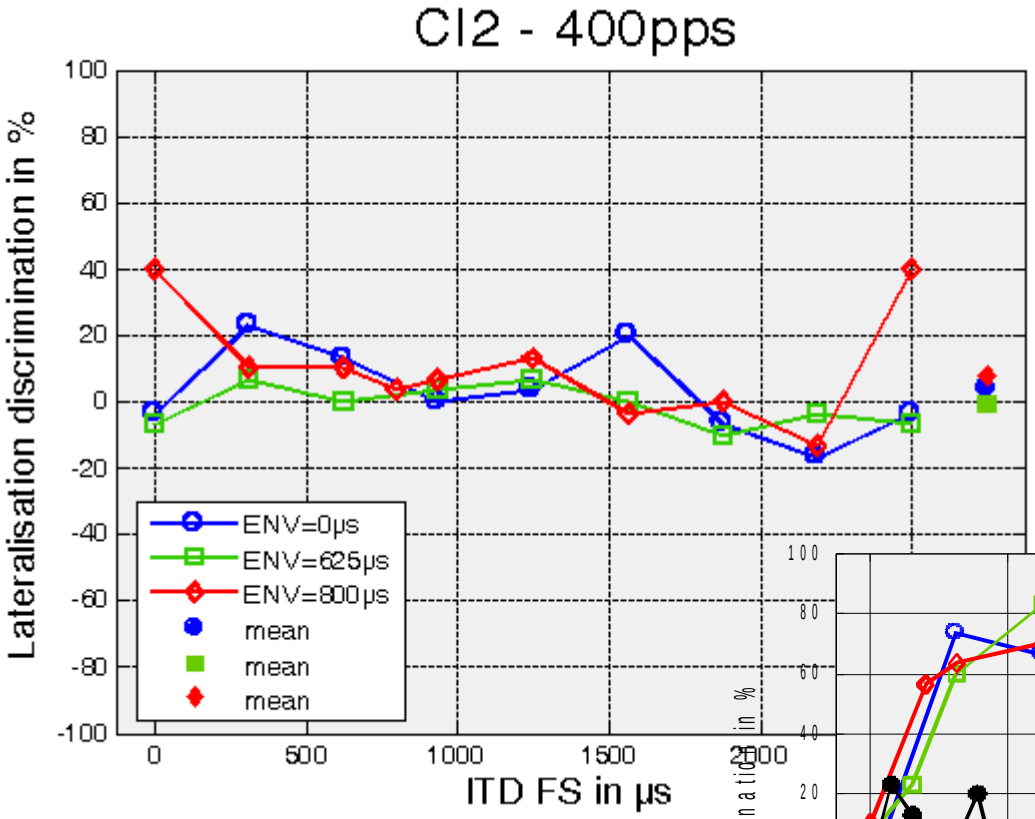
Expectations

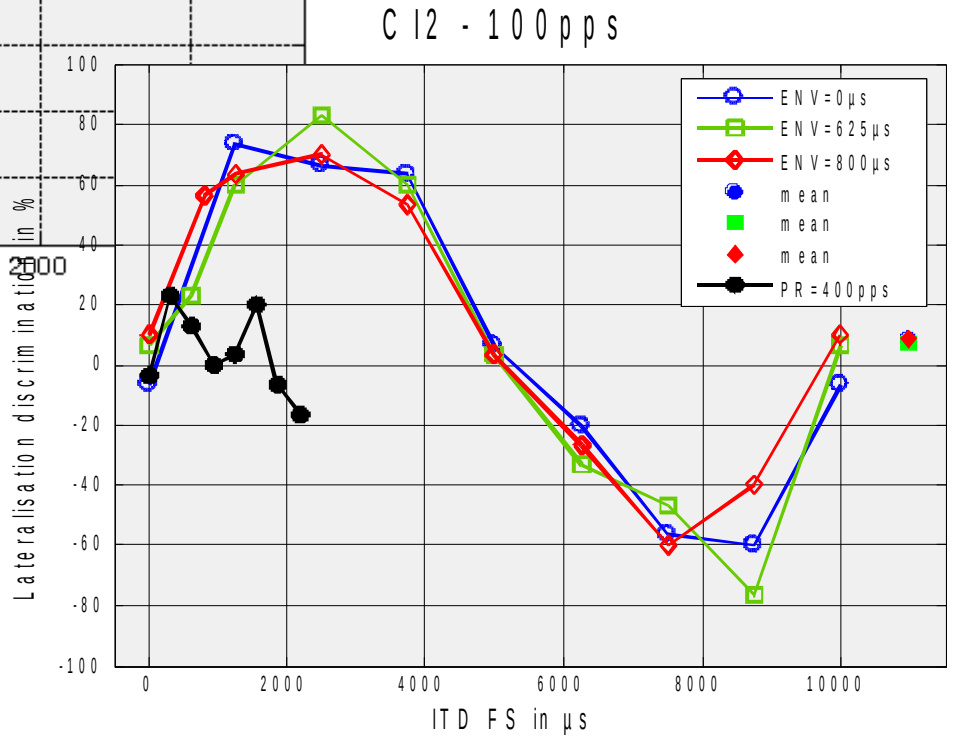


Sample Results for Lower Pulse Rates I

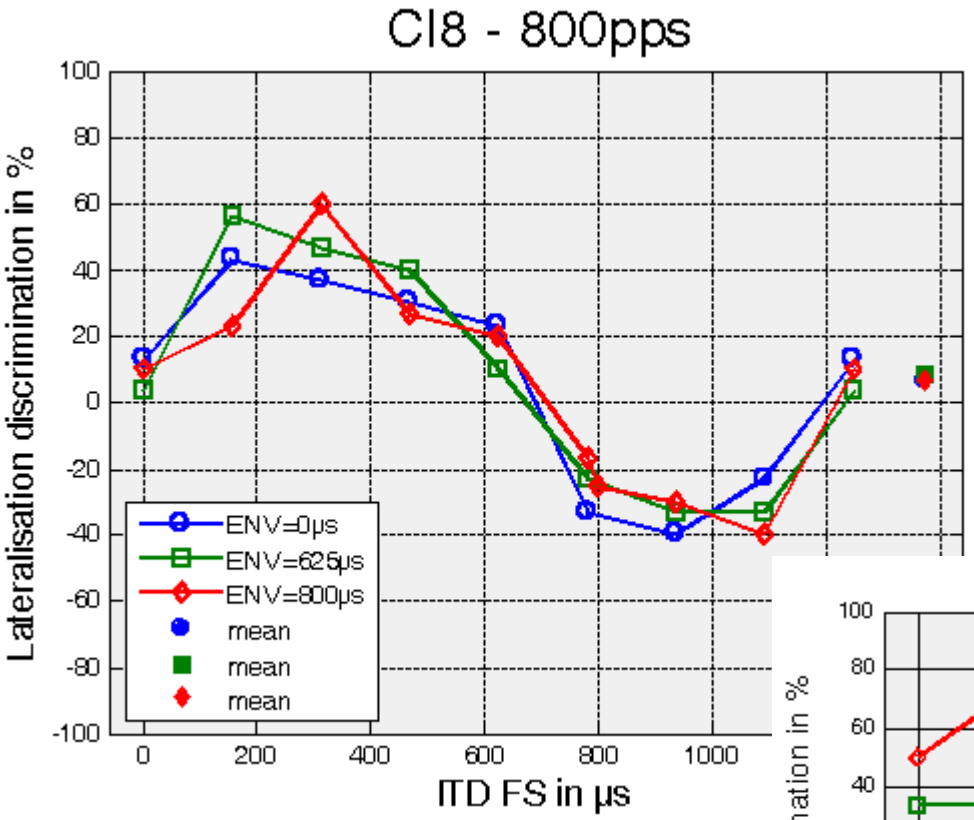


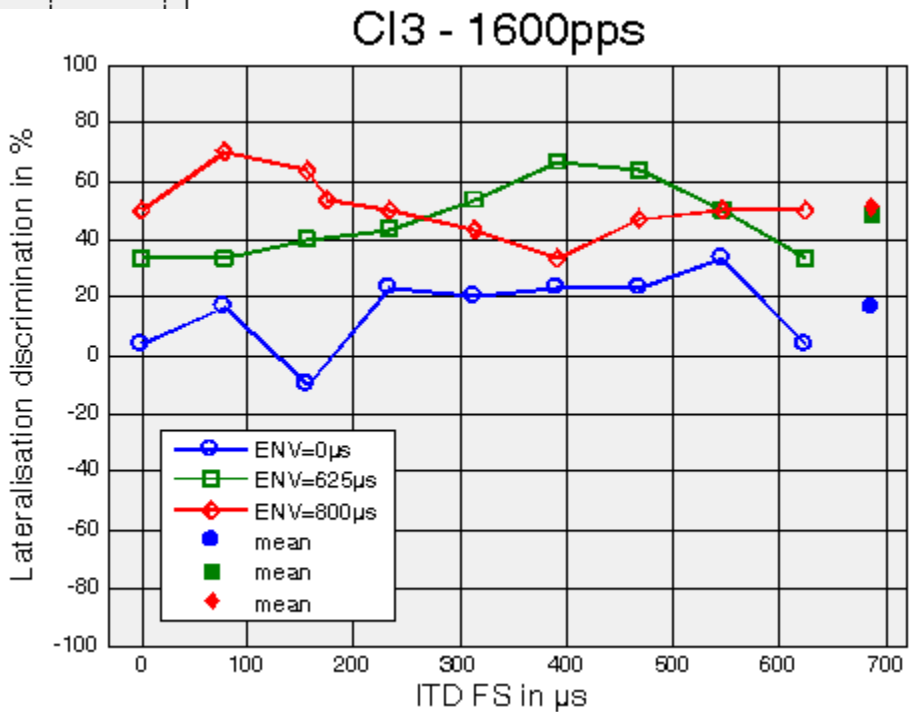
Sample Results for Lower Pulse Rates II





Sample Results for Higher Pulse Rates





Sensitivity to Fine Structure ITD

Pulse rate	CI1	CI2	CI3	CI8
100		< 0.001	-	-
150		< 0.001	-	-
200	< 0.001	0.01	-	-
400	0.75	0.21	< 0.001	< 0.001
600	-	-	-	-
800	-	-	<0.001	<0.001
938	-	-	-	0.45
1600	0.46	-	0.11	-

Conclusions of Study II

- Sensitivity to ITD_{FS} (in 2 of 4 subjects up to 800 pps)
- Low sensitivity to ITD_{ENV} (low modulation rate used)
- High inter-subject variability of performance

Overall Conclusions from both studies

- CI listeners are likely to benefit from encoding fine structure ITD at low pulse rates
- The rate limit for fine structure ITD sensitivity is lower than the 1500 Hz limit in acoustic hearing with sinusoids (Zwislocki and Feldman, 1956; Klumpp and Eady, 1956)
- How can we overcome this limitation?

PART II Improving ITD sensitivity in electric hearing

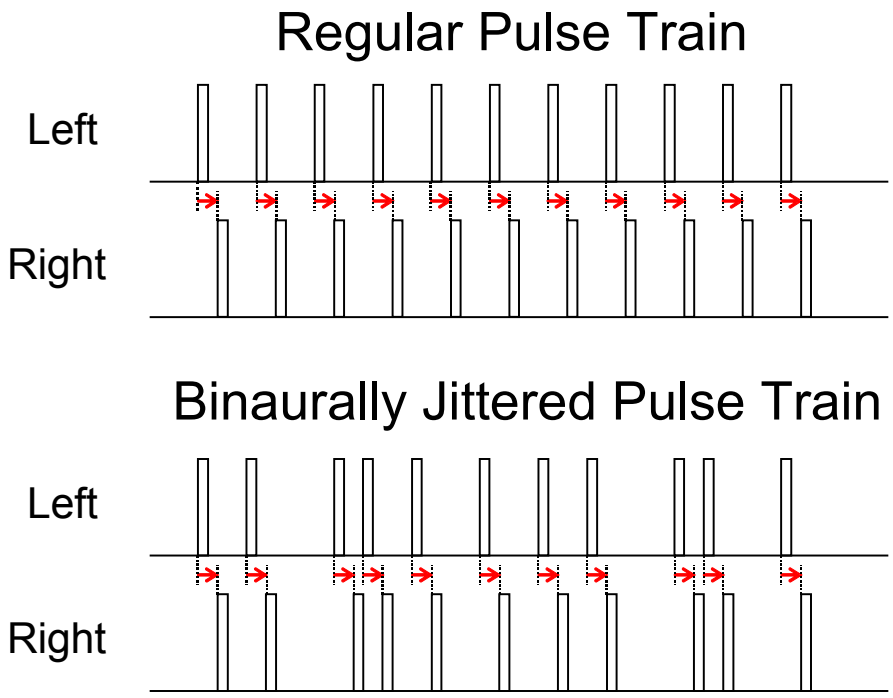
NH literature

- ITD sensitivity degrades with increasing modulation rate of high-frequency carrier signals
  (Hafter and Dye, 1983; Bernstein and Trahoitis, 2002)
- For high modulation rates increasing stimulus duration does NOT improve ITD sensitivity (Hafter and Dye, 1983; Buell and Hafter, 1988)
- *Binaural adaptation* occurs: only onset is necessary
  (Saberi, 1996; Stecker and Hafter, 2002)
- Introducing a change (trigger) in the stimulus causes recovery from binaural adaptation
  (Hafter and Buell, 1990; Stecker and Hafter, 2002)

Hypotheses

- CI listeners are experiencing a strong form of binaural adaptation at higher pulse rates, causing the rate limitation for fine structure ITD
- A purely temporal change causes a recovery from binaural adaptation
- If we can introduce an ongoing trigger without affecting the ITD information, we will improve ITD sensitivity

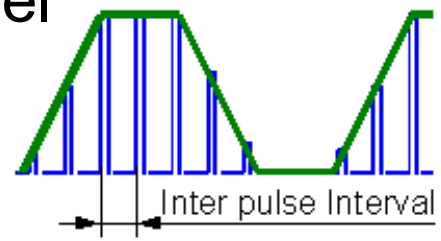
Stimuli to Test the Hypotheses



- Interpulse-interval (IPI) is random, but binaurally synchronized
- ITD is constant

Stimulus Parameters

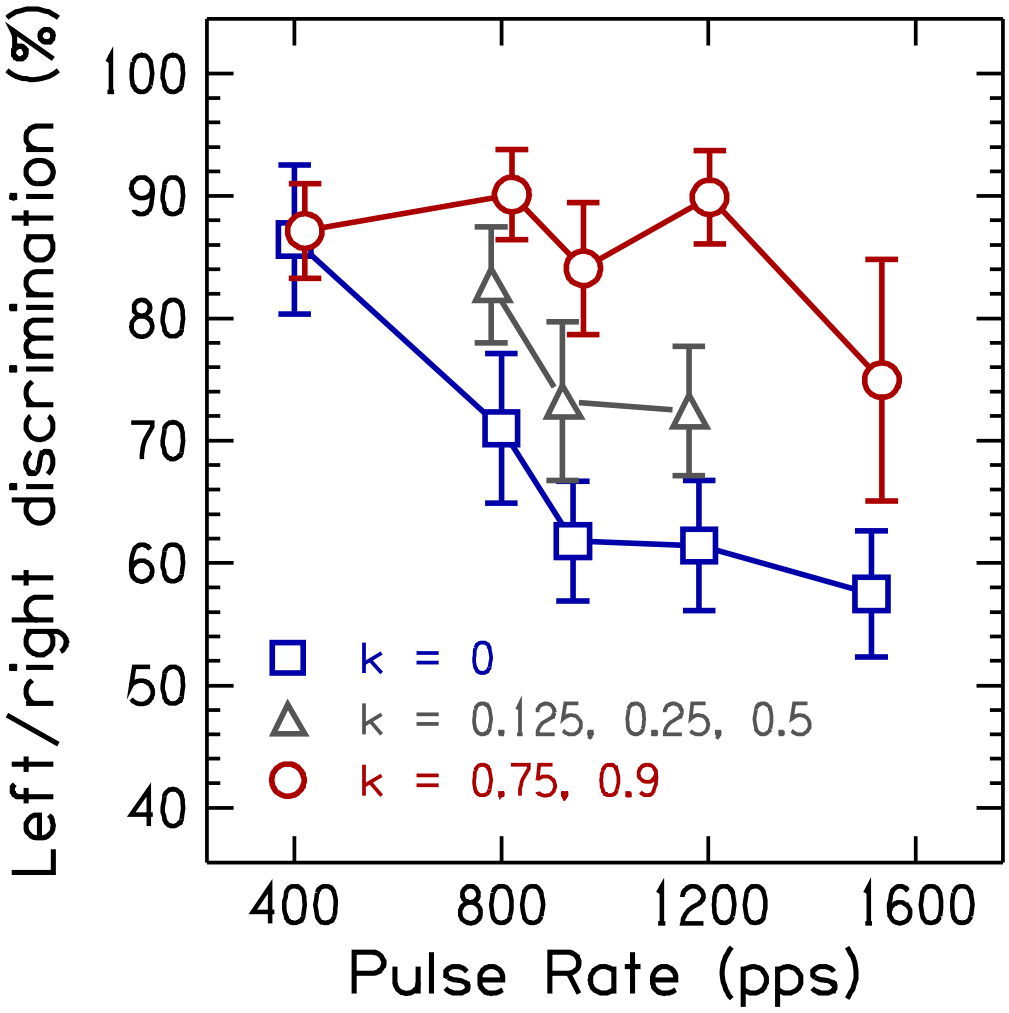
- Interaurally pitch-matched electrode pair
- Jitter follows rectangular distribution
  - *k* defines width of distribution relative to IPI
  - *k* = 0: periodic condition … *k* = 1: maximum jitter
- *k* = 0, 0.125, 0.25, 0.5, 0.75, 0.9
- ITD = 100, 200, 400, 600 µs
- Pulse Rate = 400, 800, 938, 1182, and 1515 pps
- Current levels adjusted at each rate to obtain a centralized image at a comfortable level
- Duration = 300 ms
- Amplitude modulation: 13 Hz



Subjects and Procedure

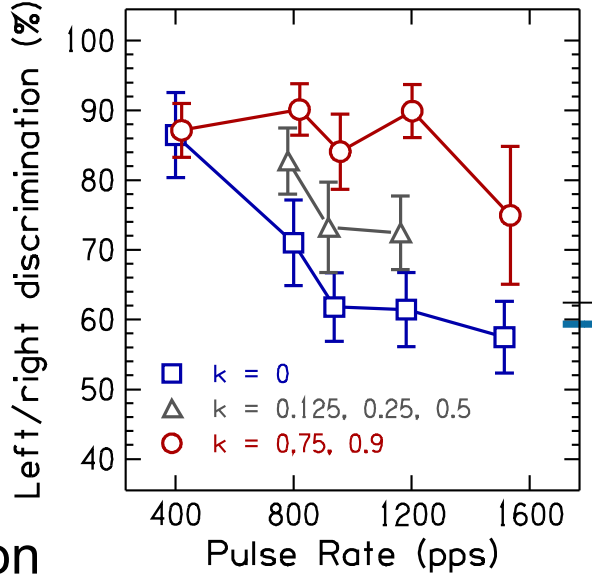
- 5 Listeners (*C40+*, *MED-EL*)
- Two-interval left/right discrimination
- 100 repetitions per condition

Results averaged over 5 listeners and ITDs (200, 400, and 600 µs)



Error bars:
95% Conf. Interv.

Analysis of Effects



- At 400 pps
  - P_c generally high
  - No difference between binaurally-jittered and period condition
- At rates > 400 pps
  - Periodic condition: P_c decreases sharply with increasing pulse rate (p = 0.000002)
  - Binaurally-jittered condition: Large improvements relative to periodic condition
    - Large Jitter (k = 0.75, 0.9): $p < 0.000001$
    - Small Jitter (k = 0.125, 0.25, 0.5): p = 0.0005
  - Large Jitter: P_c constant up to 1182 pps; decline at 1515 pps, but still significantly above periodic condition (p = 0.006)

Interpretation of Results

- Periodic condition: Decrease with increasing rate consistent with previous studies (van Hoesel and Tyler, 2003; Majdak et al., 2006; Laback et al., 2007)

  ⇒ At 400 pps performance is high: thus, if binaural adaptation hypothesis is true, no improvement by jitter can be expected

- Binaurally-jittered condition: Makes CI listeners sensitive to fine structure ITD at rates up to 1515 pps (comparable to NHs)

  ⇒ Indication for recovery from strong form of binaural adaptation

Explanation in terms of Binaural Adaptation

- Assuming that excessive form of binaural adaptation is indeed the reason for the rate limitation (periodic condition), why could it occur?
  - High degree of phase locking and across-fiber synchrony in electric stimulation (e.g. Abbas, 1993; Dynes and Delgutte, 1992; Litvak et al., 2001).
- Artificial temporal variation may circumvent this and consequently avoid binaural adaptation

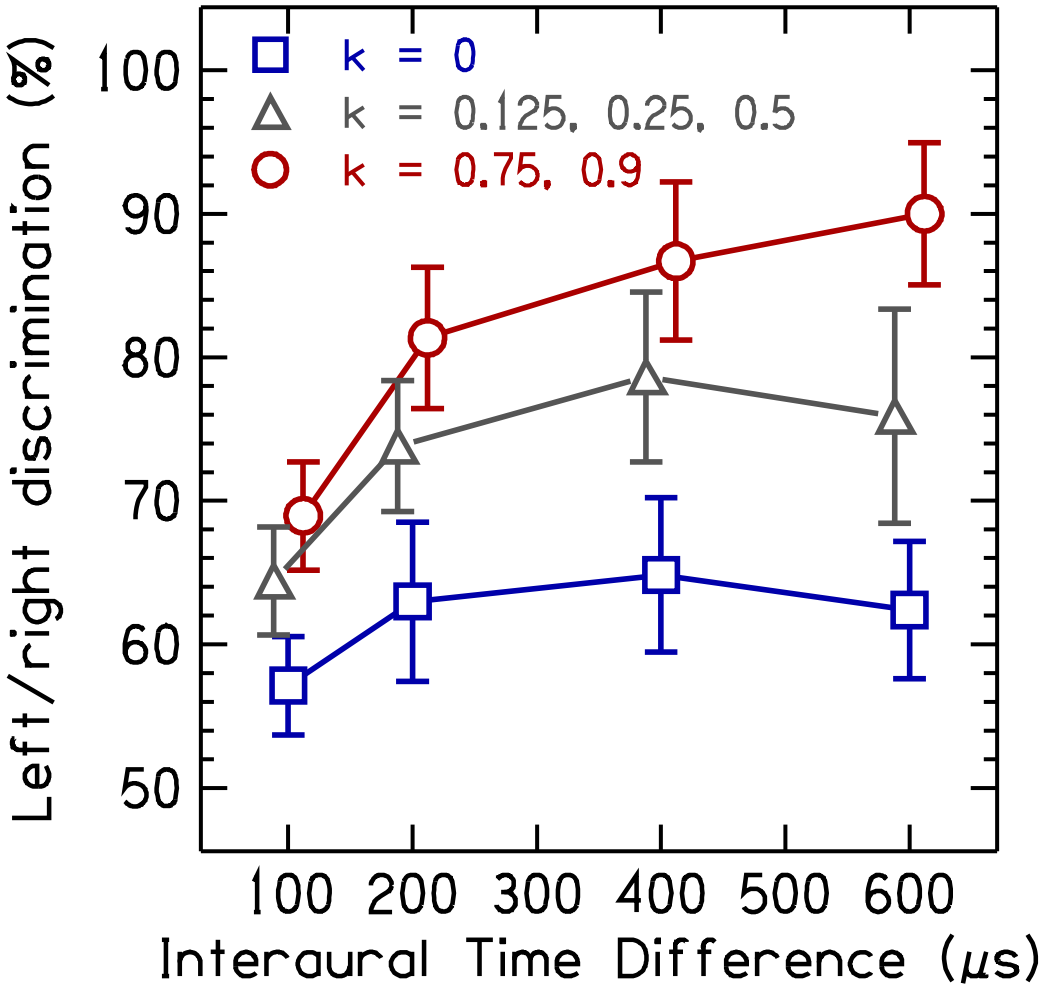
Monaural Explanation?

- Jitter may cause better neural representation of temporal information by causing stochastic responses (e.g. Rubinstein et al., 1999; Zeng et al., 2000)

  ⇒ Jitter should also improve rate pitch perception

- Chen et al. (2005) studied the effect of jitter on monaural pitch perception
  - Tested only small jitter and found no effect besides a deterioration at low rates
  - Did not test larger jitter for which we found largest improvements
  - However, larger jitter would most likely smear the pitch cue
- Thus, recovery in our experiment is most likely a binaural effect, not a monaural

Average Results for Rates ≥ 800 pps (where periodic condition has low P_c)



Error bars:
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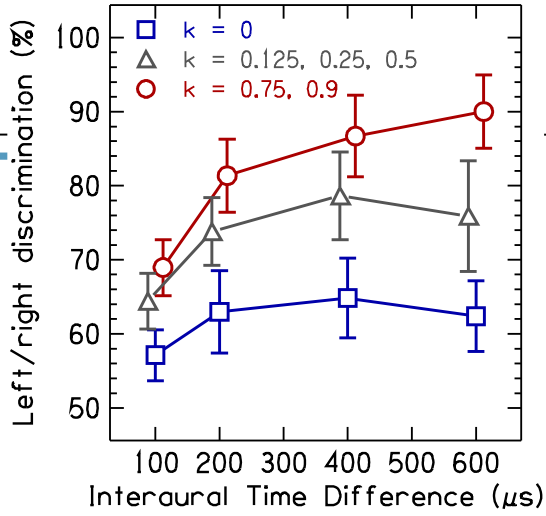
Analysis & Interpretation



- Periodic condition: P_c constantly low across ITD values
- Binaurally-Jittered condition:
  - P_c increases with ITD
  - Maximum Improvement of 28% for large jitter ($p < 0.00001$) and 14% for small jitter ($p = 0.007$)
- Intriguing finding: Binaural jitter improves P_c even for ITDs with ambiguous fine structure cues
  - Example: ITD = 400 μs is within ¼ to ¾ of IPI at all rates from 800 to 1515 pps, and still jitter improves P_c ($p = 0.0001$)
  - Possible explanation: Auditory system picks out pulse pairs with large IPIs (multiple looks model, Viemeister and Wakefield, 1991)

Summary & Conclusions

- Observed dramatic improvement of P_c by introducing binaurally-synchronized jitter in electric hearing strongly suggests:
  - Rate limitation for ITD perception is at least partly due to binaural adaptation
  - Purely temporal trigger causes recovery from binaural adaptation
- Binaural jitter removes pulse rate limitation, allowing ITD perception at much higher rates
- Advantage for localizing sounds and speech perception in noise with fine structure coding strategies

Acknowledgements

Many thanks to

- Our listeners for their patience
- The Austrian Academy of Sciences for fundng the project

Individual Subjects' Results