Factors limiting spatial hearing performance with bilateral cochlear implants and first steps to reduce the shortcomings

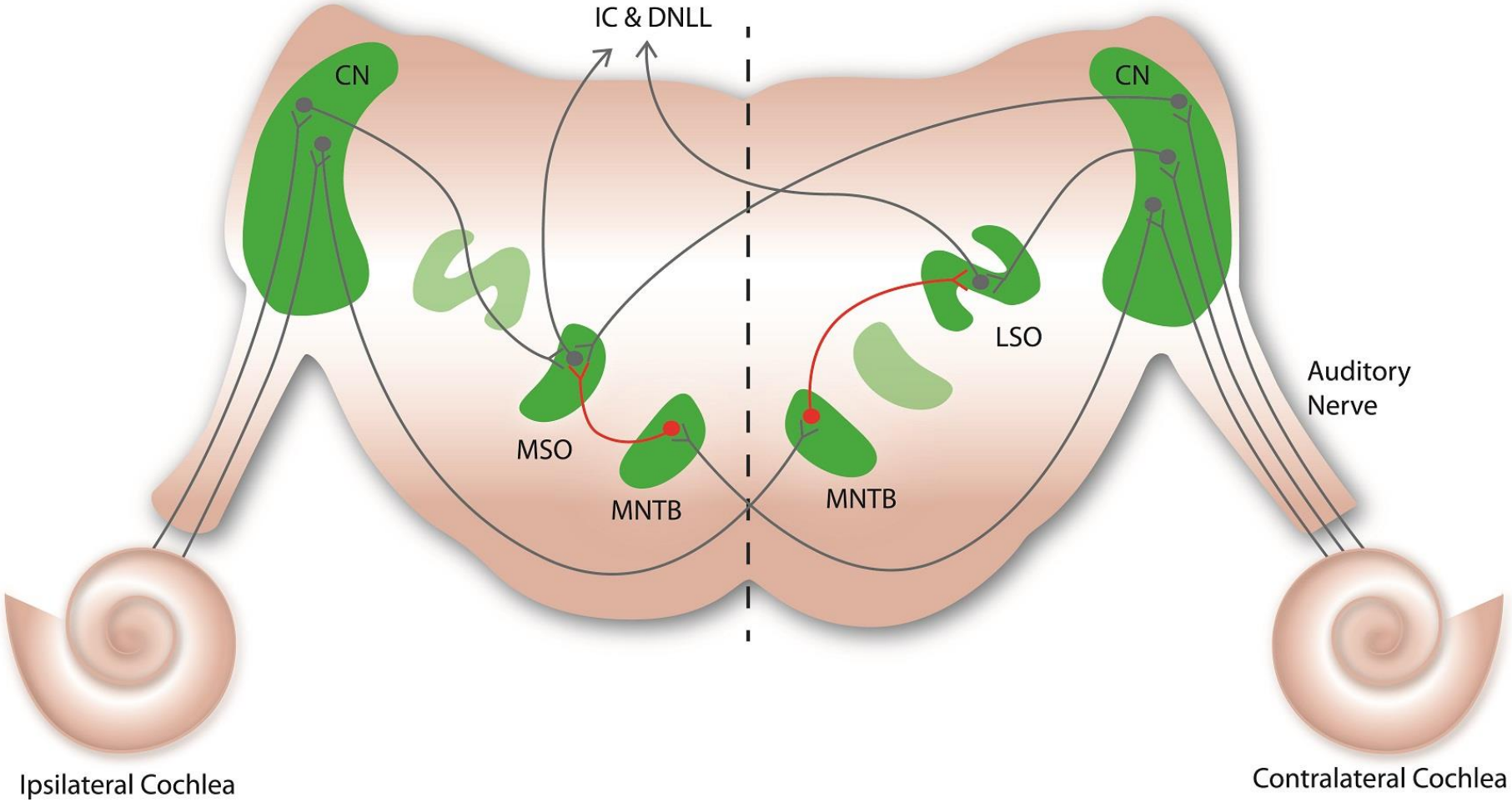
Mathias Dietz, Hongmei Hu, Regina Baumgärtel, Darly Kelvasa, Ben Williges, Sebastian Ausili (Donders Inst.)

Intro I

Processing stage	Alternative
BTE microphones	Pinna microphones
12-22 band-pass filters 0-9 KHz	Virtual channels
Acoustic speech enhancement and directional filters	Binaural beamformers, binaural cue preservation Applying optimized binaural cues at electrodogram level
Envelope extraction	Carrier phase related pulse (burst) timing
Compression, adaptive gain control, dynamic range optimization	Binaurally coordinated
Continuous sampling	Smart sparse sampling
n-of-m selection	Binaurally coordinated
Output current mapping	Binaural fitting
Monopolar biphasic pulses	Tripolar stimulation Multipolar stimulation

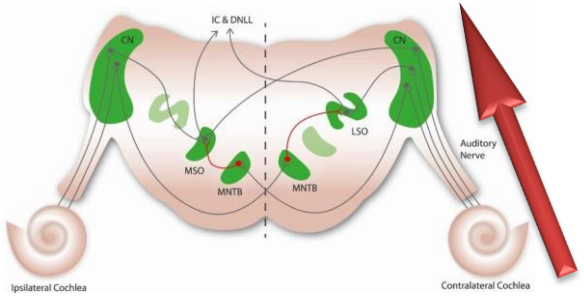
Bad for spectral cues
Bad for ITD
Bad for ILD

Intro II: Auditory brainstem



Intro II: Auditory brainstem

Auditory Pathway Stage	Problem(s)
Spiral ganglion stimulation	Identify electrode positions and local interface to neurons Identify relative timing of stimulation
Ventral cochlear nucleus (bushy cells)	Not studied with CI input
MNTB	Not studied with CI input
LSO pathway	Not studied with CI input
MSO pathway	Not studied with CI input experimentally Models indicate need for more experimental insight. MSO may be missed out with electric stimulation
Central stages	Spatial decoding of stimulus dependent ITD tuning difficult Experimental data indicate need for models to include developmental aspects



Critical for ITD sensitivity

Critical for ILD sensitivity

Outline

1. Identifying interaurally matched electrode pairs
2. ITD-based lateralization
3. Speech coding strategies

4. Problem of L/R independence
5. Directional filters

6. Bringing it together

1. Identify interaurally matched electrode pairs

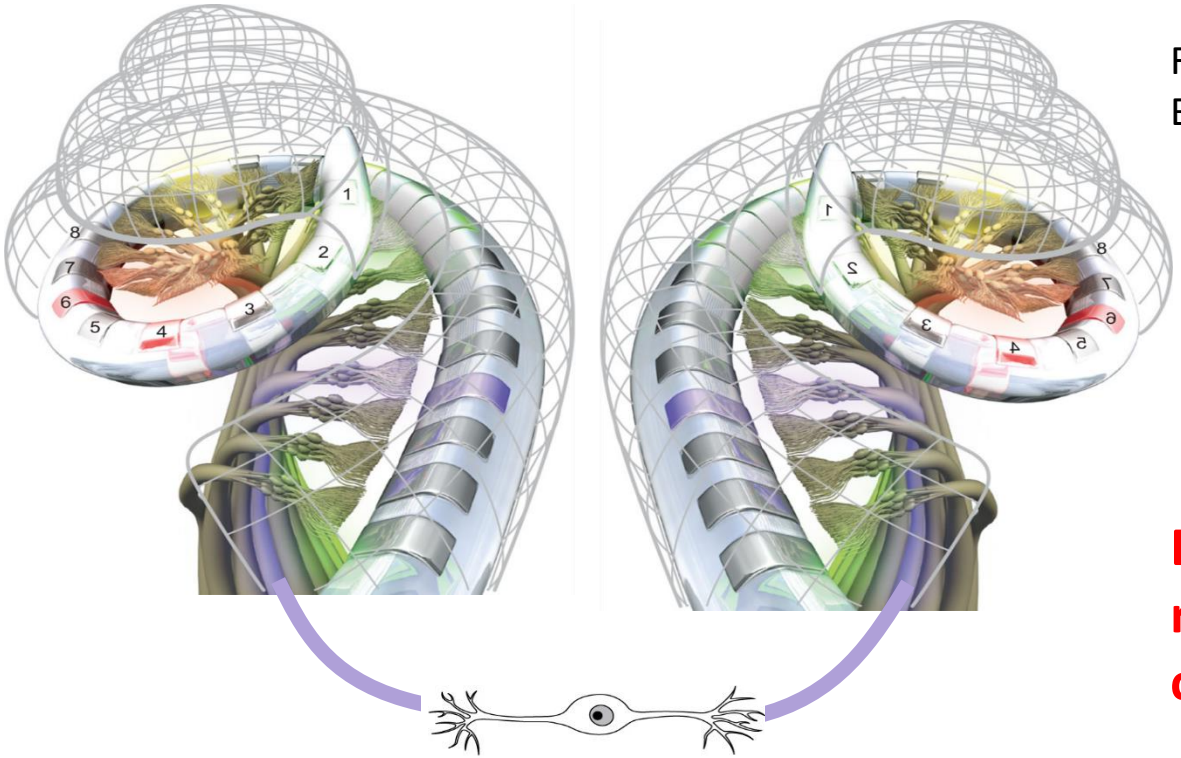


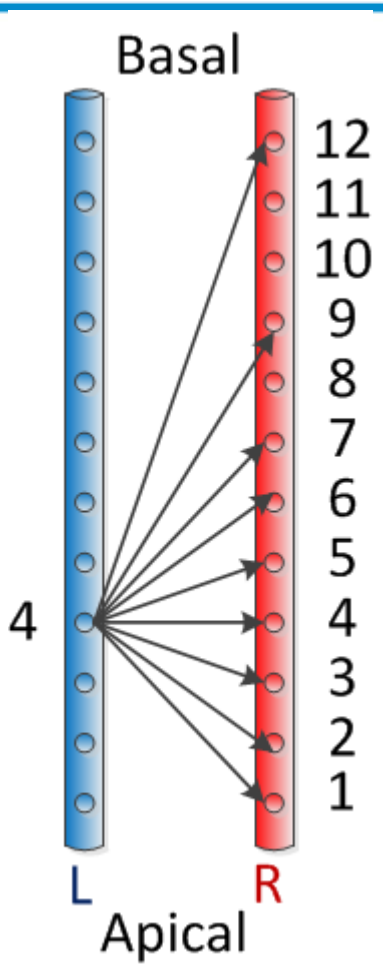
Figure adapted from
Boulet et al, 2016

Binaural neurons receive input only from corresponding places

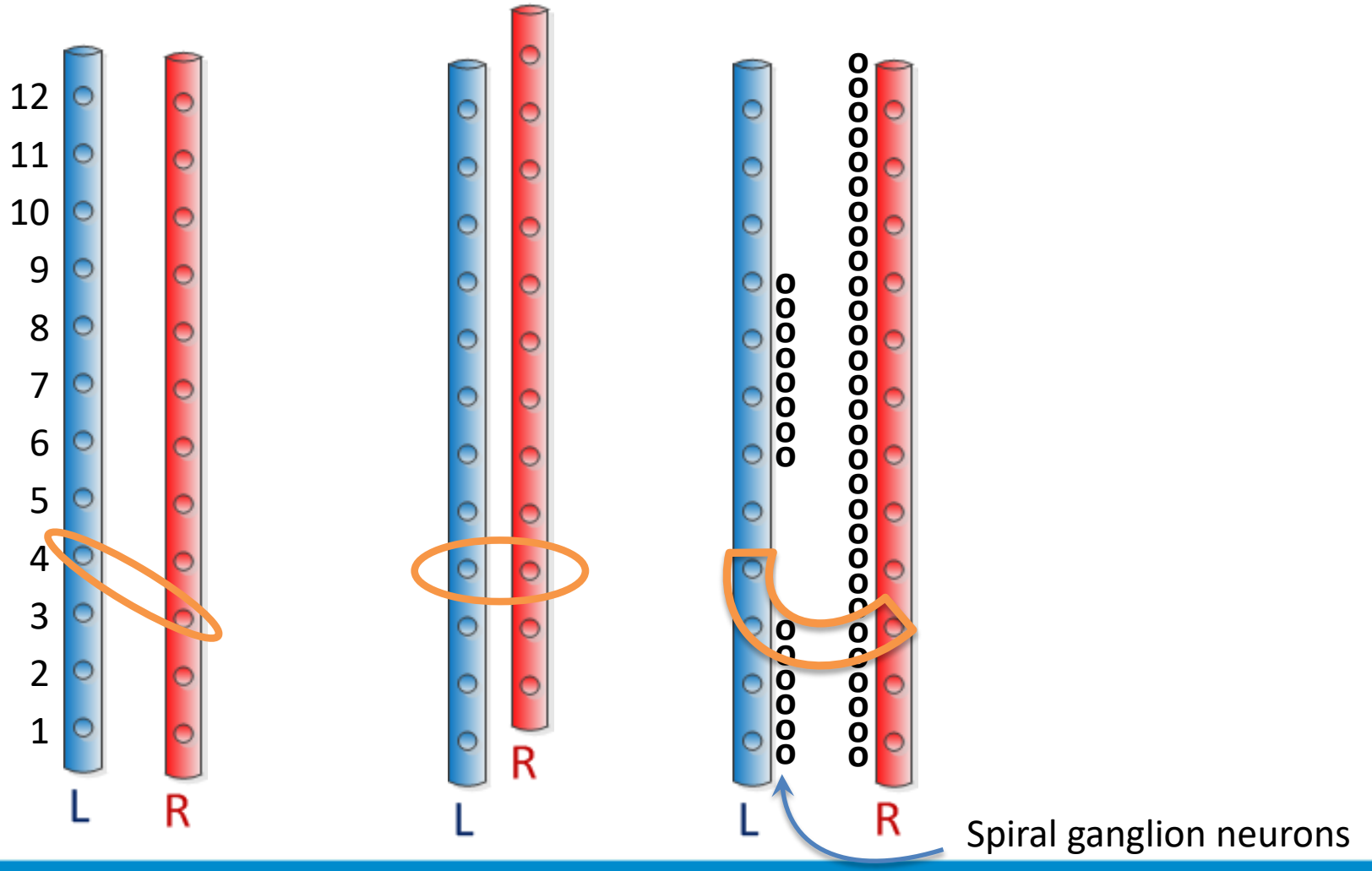
Aronoff et al. 2016:
Only 2 of 16 users have sufficiently similar interfaces. 14 of 16 do not!

Three Methods for Interaural Electrode Pairing

- Interaural (place) pitch matching
- Maximum interaural time difference (ITD) sensitivity
- Largest binaural interaction component (BIC)

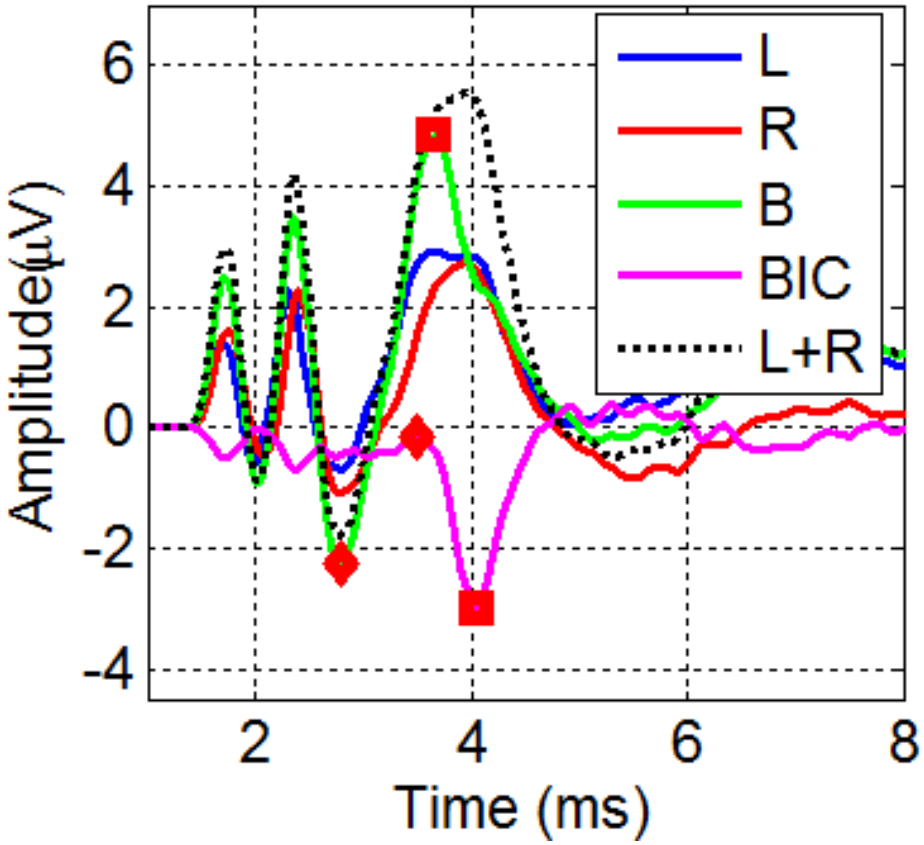


Possible reasons for mismatch



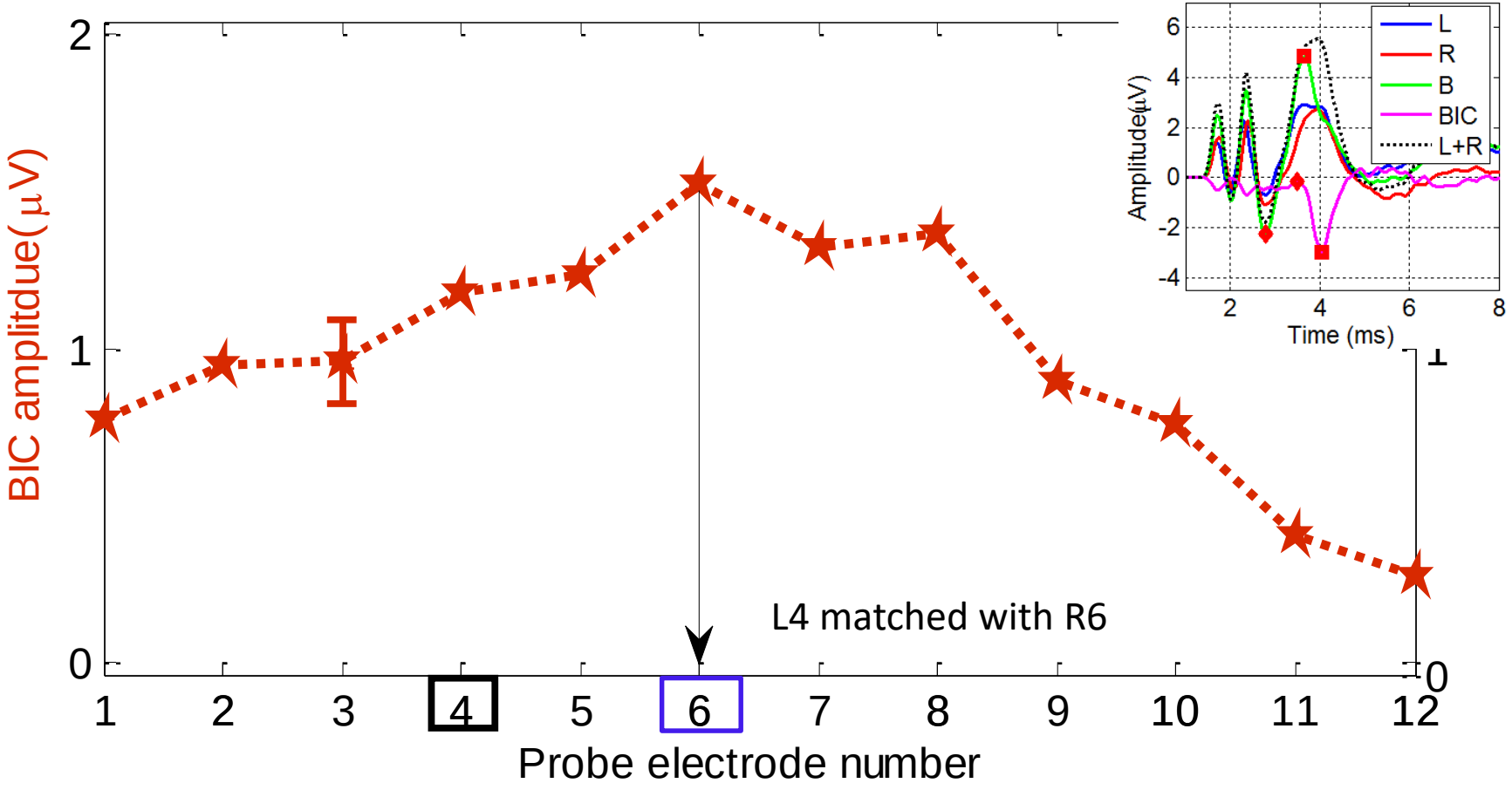
Binaural interaction component (BIC)

BIC= B-(L+R)



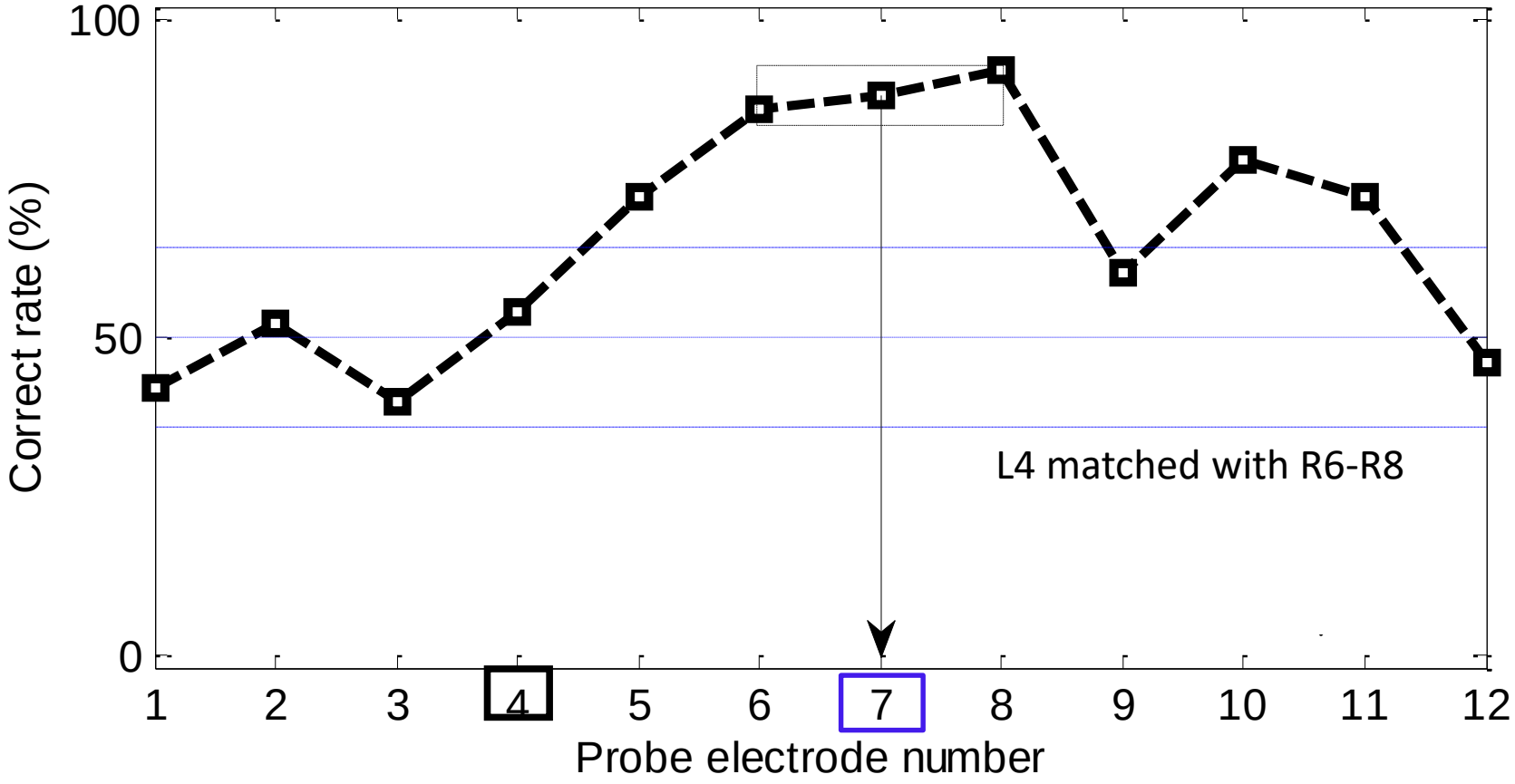
Hu and Dietz 2015; Hu et al. 2015

Result 1:
BIC data from one subject

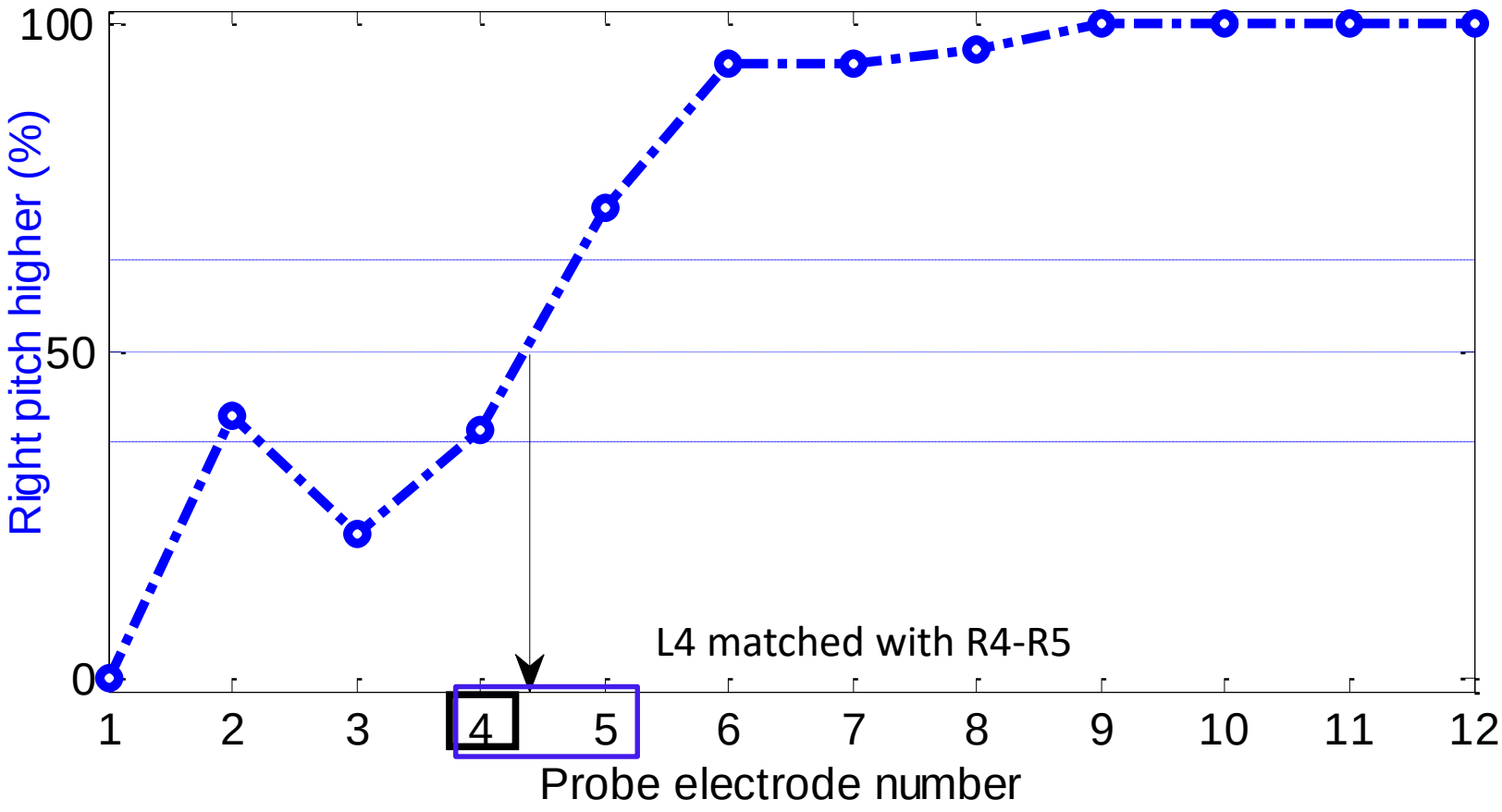


Hu and Dietz 2015

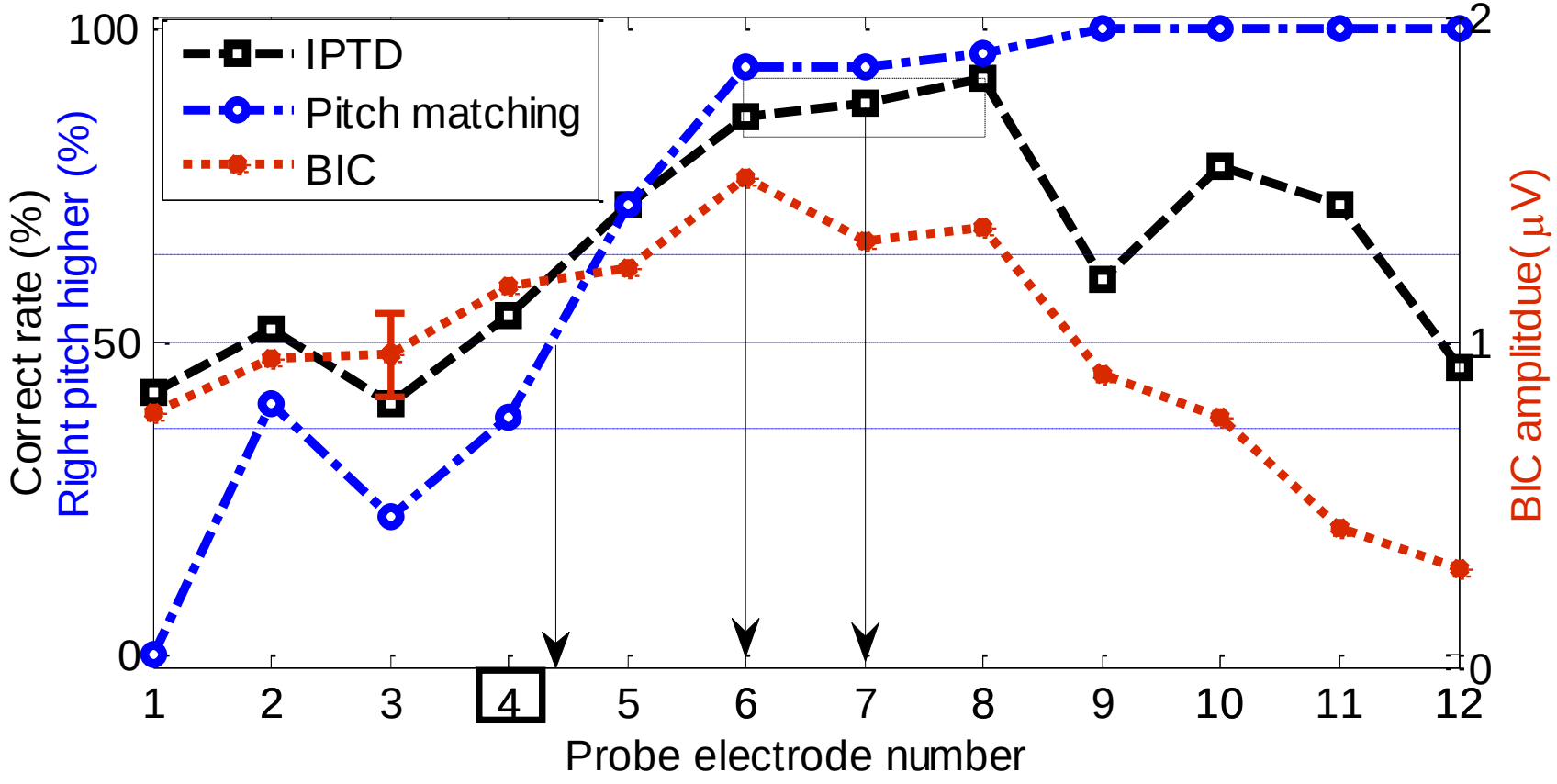
Result 2:
ITD data from same subject

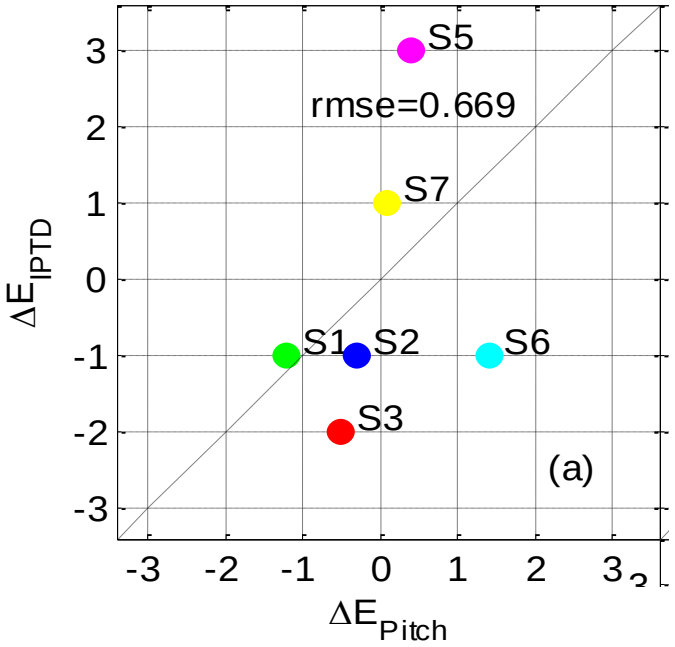


Result 3:
Pitch matching data from same subject



Summary:
All data from one subject





Population Data

Interaural electrode pairing: Conclusions

Differences in relative electrode positions are common and severely reduce binaural sensitivity (and binaural fusion)

Plasticity reduces pitch mismatch over time

- ➢ Good for patients with mismatch
- ➢ Pitch is not a good tool to measure mismatch

Binaural sensitivity does not appear to be plastic (at least not in post-lingually deaf adults)

- ➢ Bad for patients with mismatch

Interaural electrode pairing: Further thoughts and notes

Compensation not straight forward.
Easy case: Difference in insertion depth

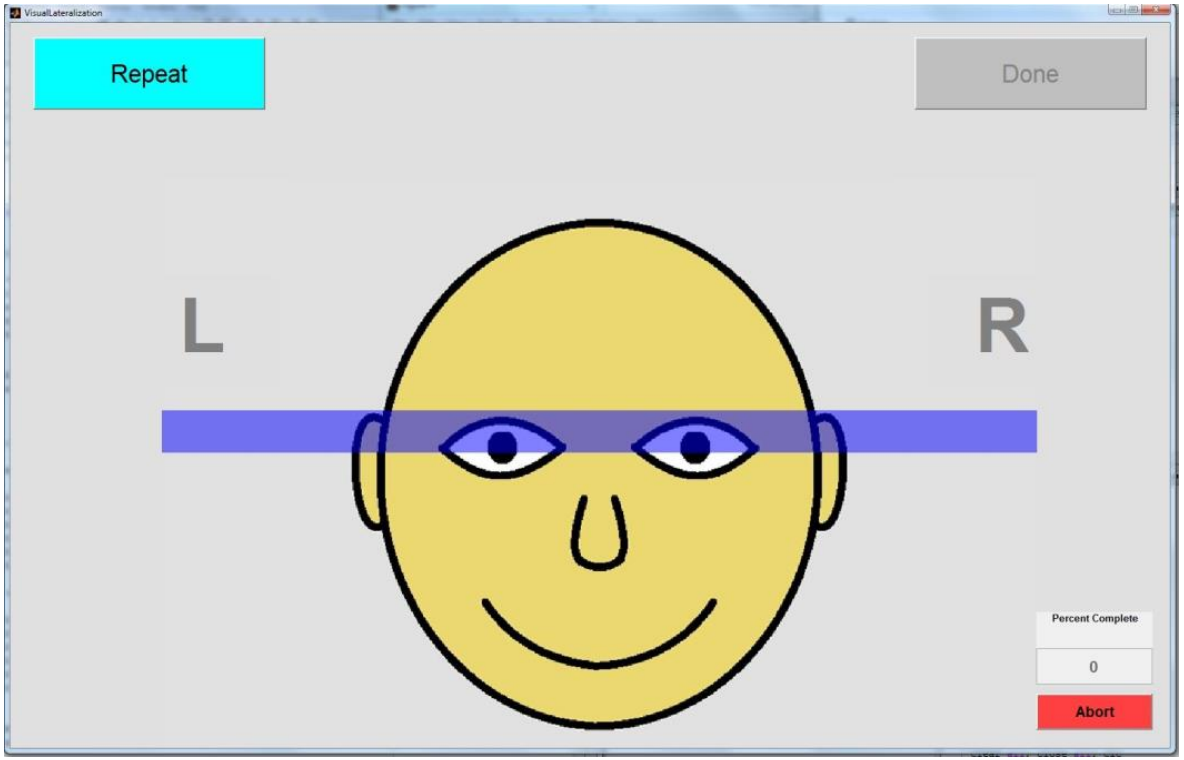
- consider shifting frequency allocation table

Differences in relative place of stimulation are massive in SSD patients with a CI.

- consider to make a true Greenwood frequency mapping (e.g. increase all frequencies bands by almost 1 octave)

More on this later

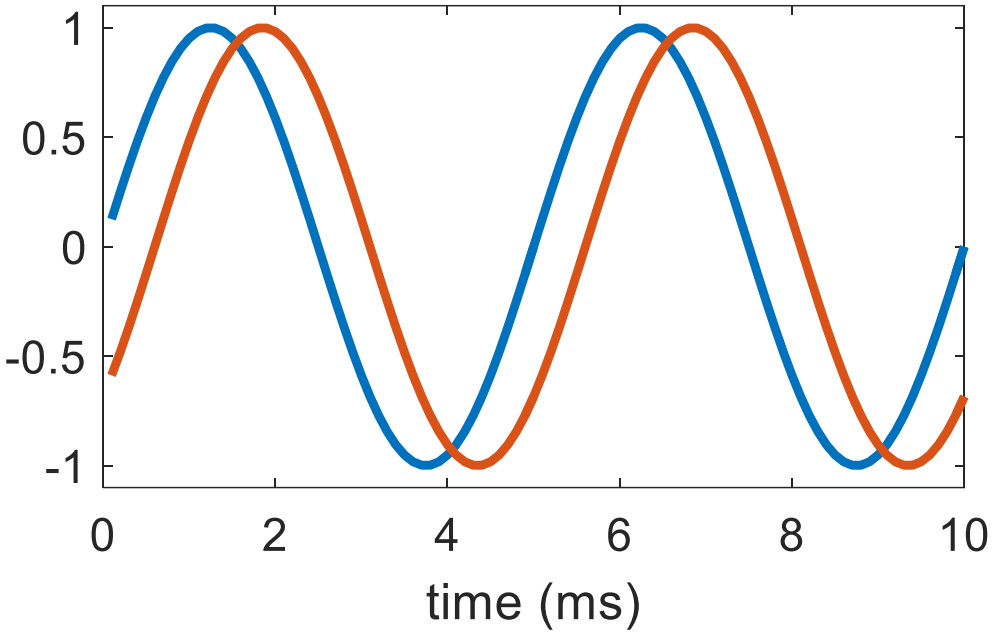
2. ITD-based extent of lateralization

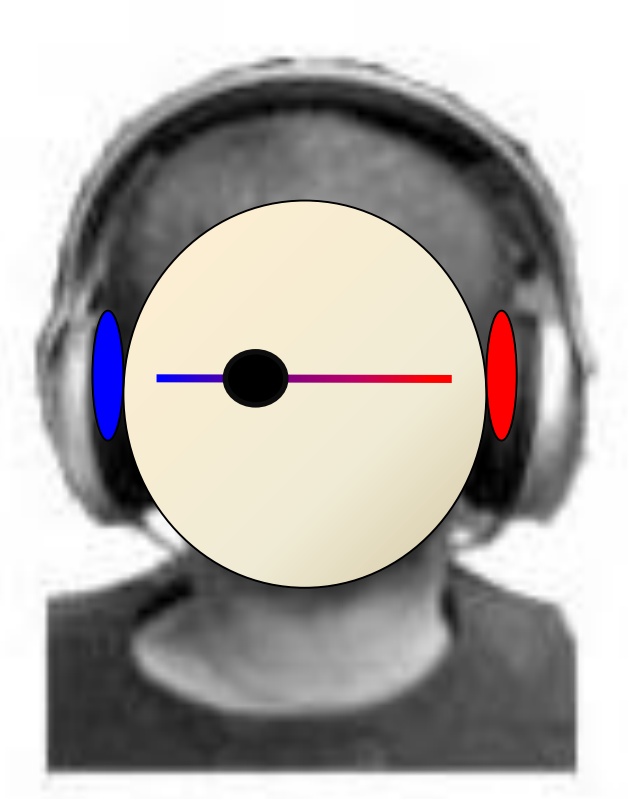


Kan et al. 2013

Indicate where the sound was heard with respect to the face

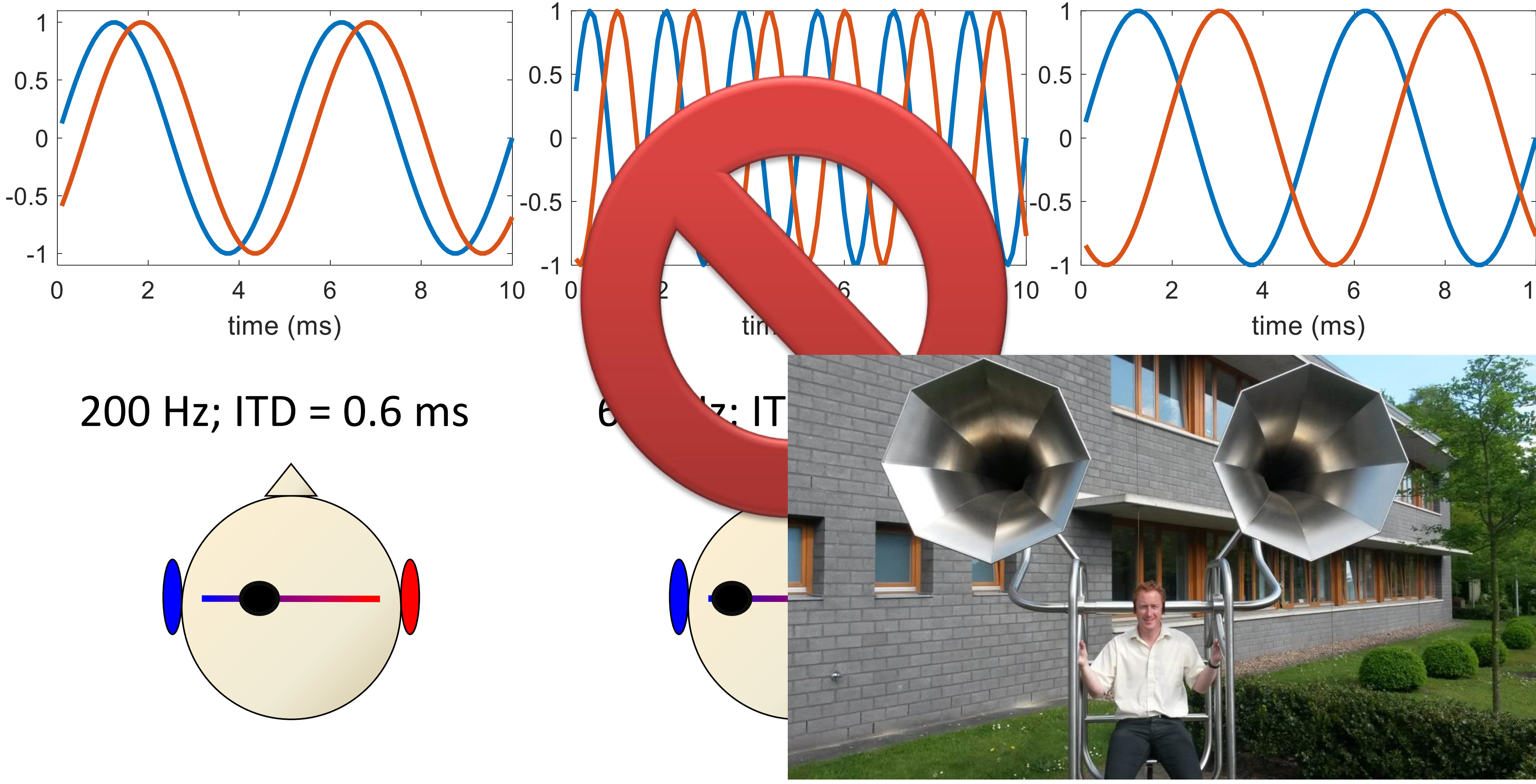
Sound image lateralization



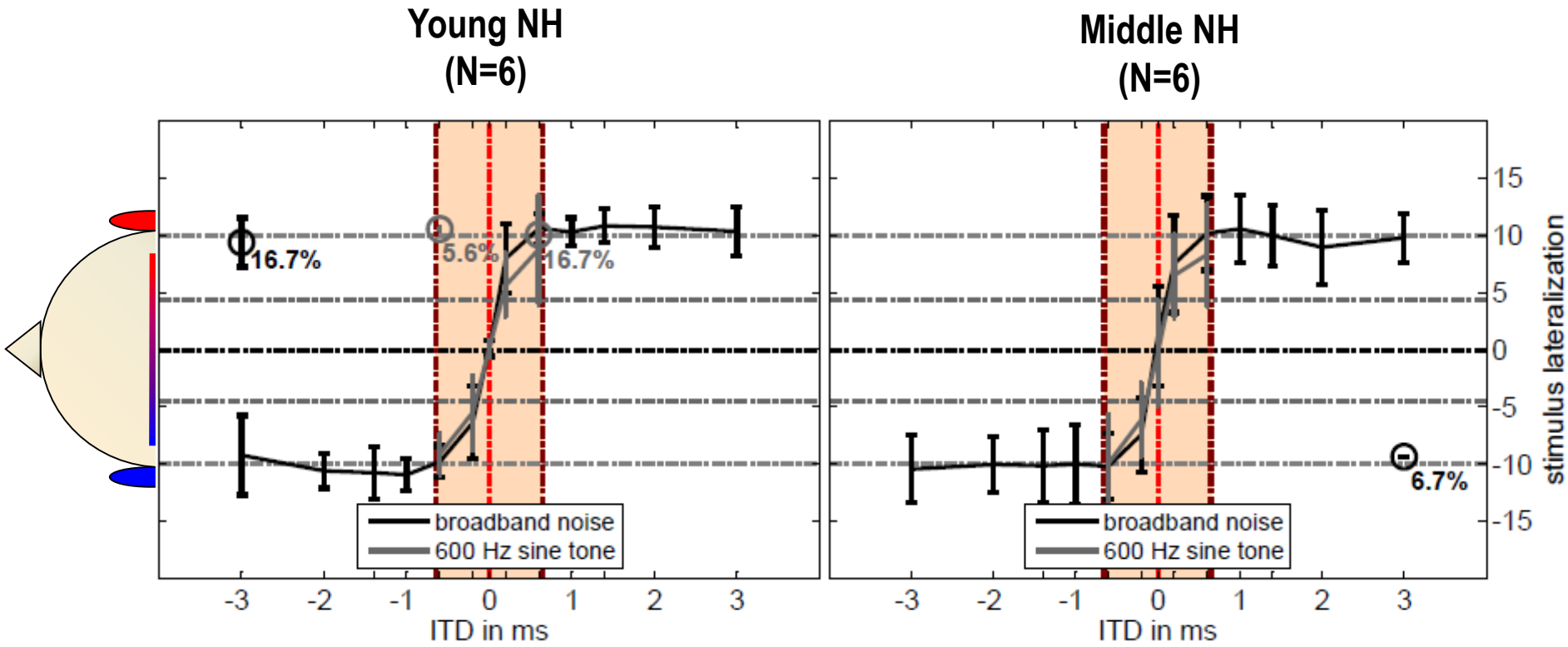


200 Hz; ITD = 0.6 ms

Motivation: ITD coding for CI
Example: Sayers 1964



NH Results



Baumgaertel et al. (JASA 2017)

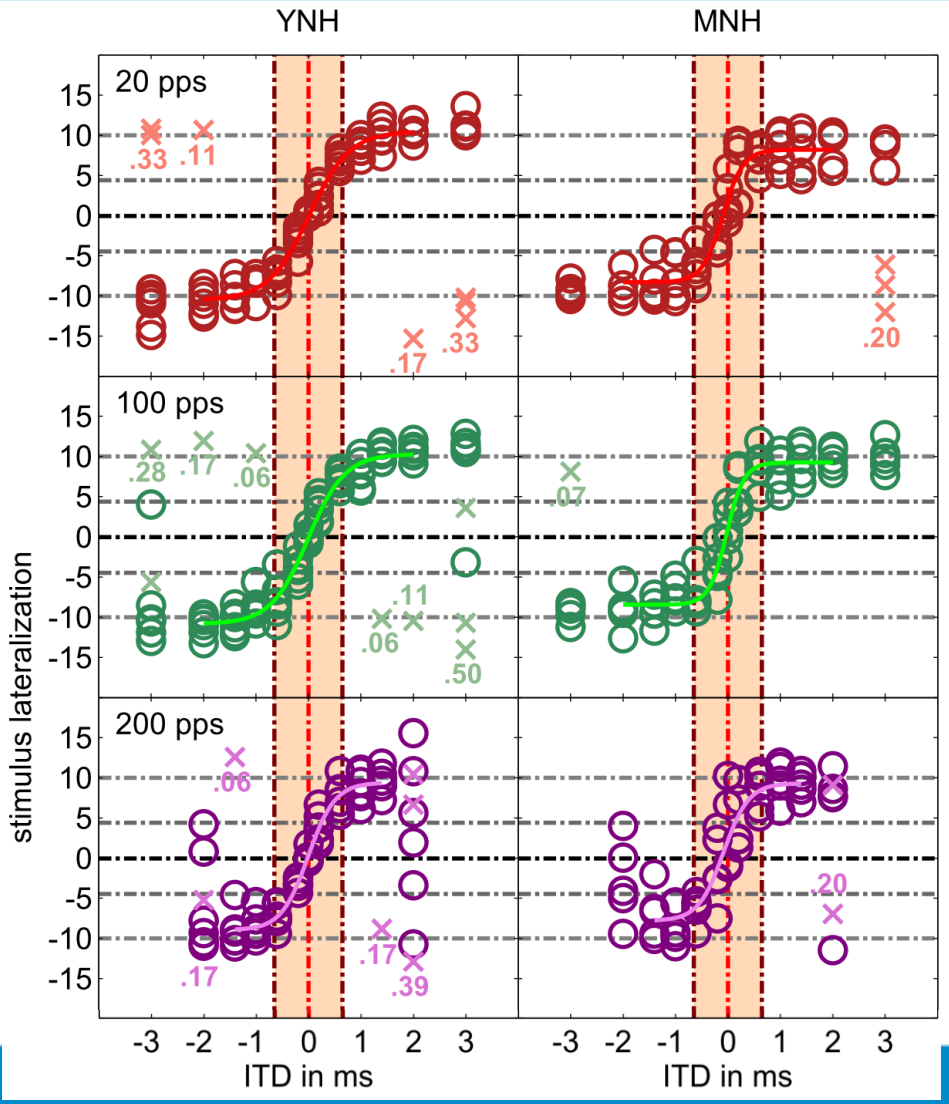
NH Results: CI simulation

CI simulation with 3-5 KHz filtered click trains (Hafter and Dye 1983)

20 pps

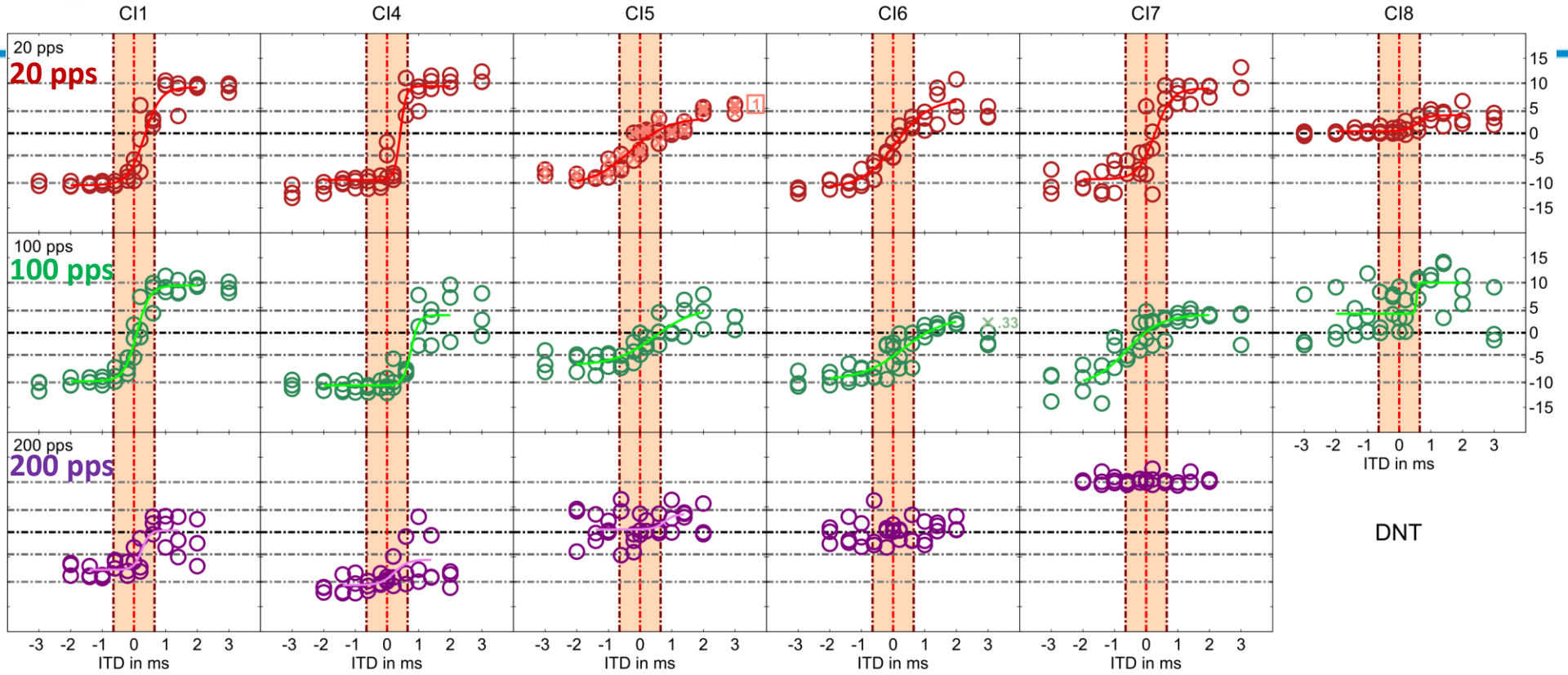
100 pps

200 pps



Baumgaertel et al. (JASA 2017)

BiCI Results



- ITD-based lateralization possible, but only at very low PPS.
- At ITDs > 600 µs lateralization continues to increase sound image fusion persists

Baumgaertel et al. (JASA 2017)

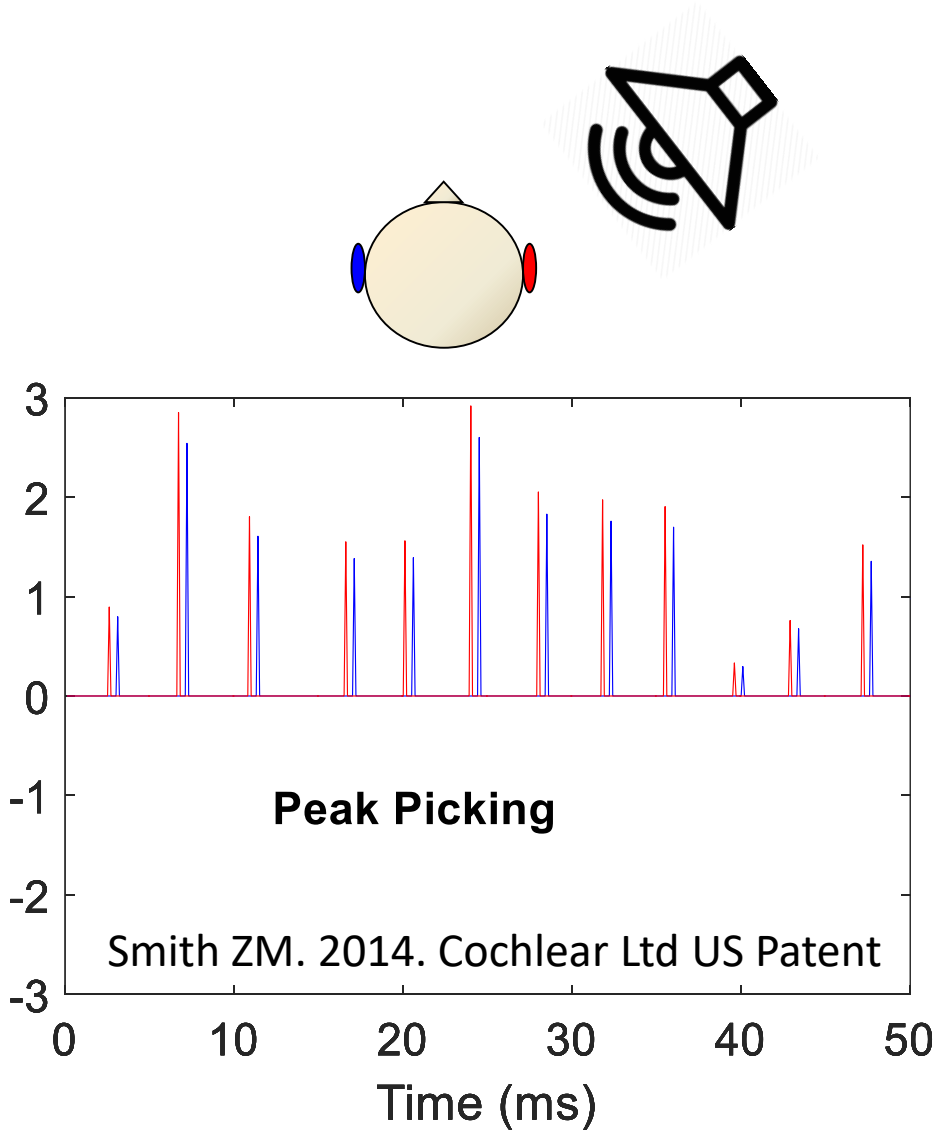
ITD-based lateralization: Further thoughts and notes

- Not relevant for CIS
- Rate limit (~100 pps) even too low for FS4 except,maybe, electrode 1
- If peak-picking is used with bilaral CI subjects, natural ITDs are not enough to move image from left to right

➢ Option 1: Increase headsize ------->
➢ Option 2: Artifically increase ITD

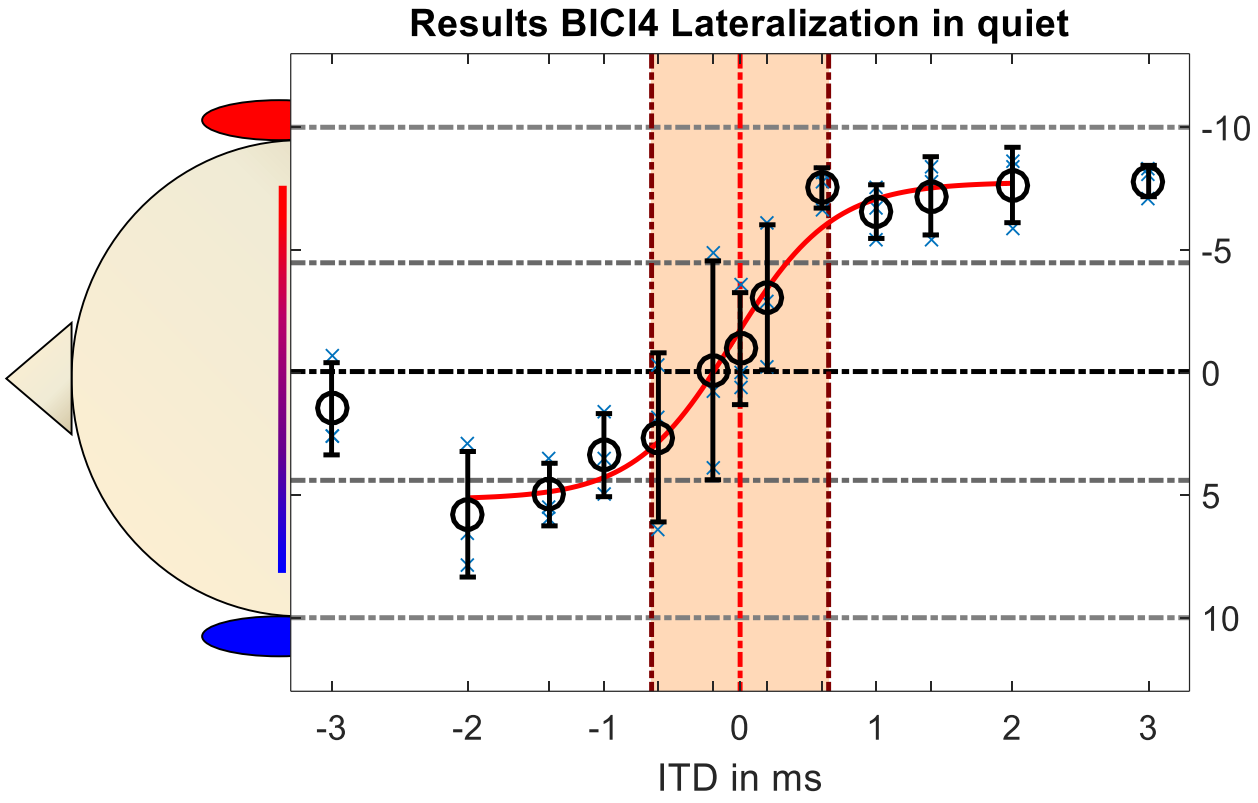
3. Speech Coding Strategies

Processing stage
BTE microphones
12-22 band-pass filters 0-9 KHz
Acoustic speech enhancement and directional filters
Envelope extraction
Compression, adaptive gain control, dynamic range optimization
Continuous sampling
n-of-m selection
Output current mapping
Monopolar biphasic pulses



3. Speech Coding Strategies

speech with peak picking and ITD only



Best subject (out of 6)

3. Speech Coding Strategies
Summary

A lot of things must be considered to get ITD-based lateralization:

1. Little or no interaural mismatch in place (see part 1)
2. Good L/R level balancing
3. Very low pulse rate or very strong modulation
4. Possibly more…

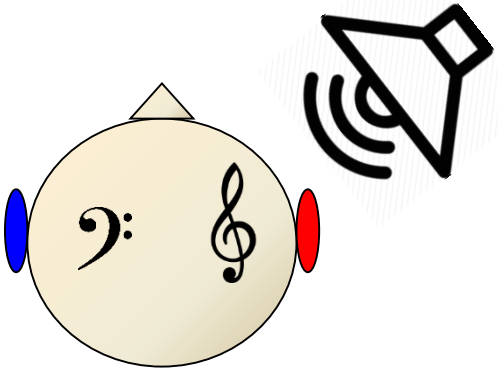
Outline

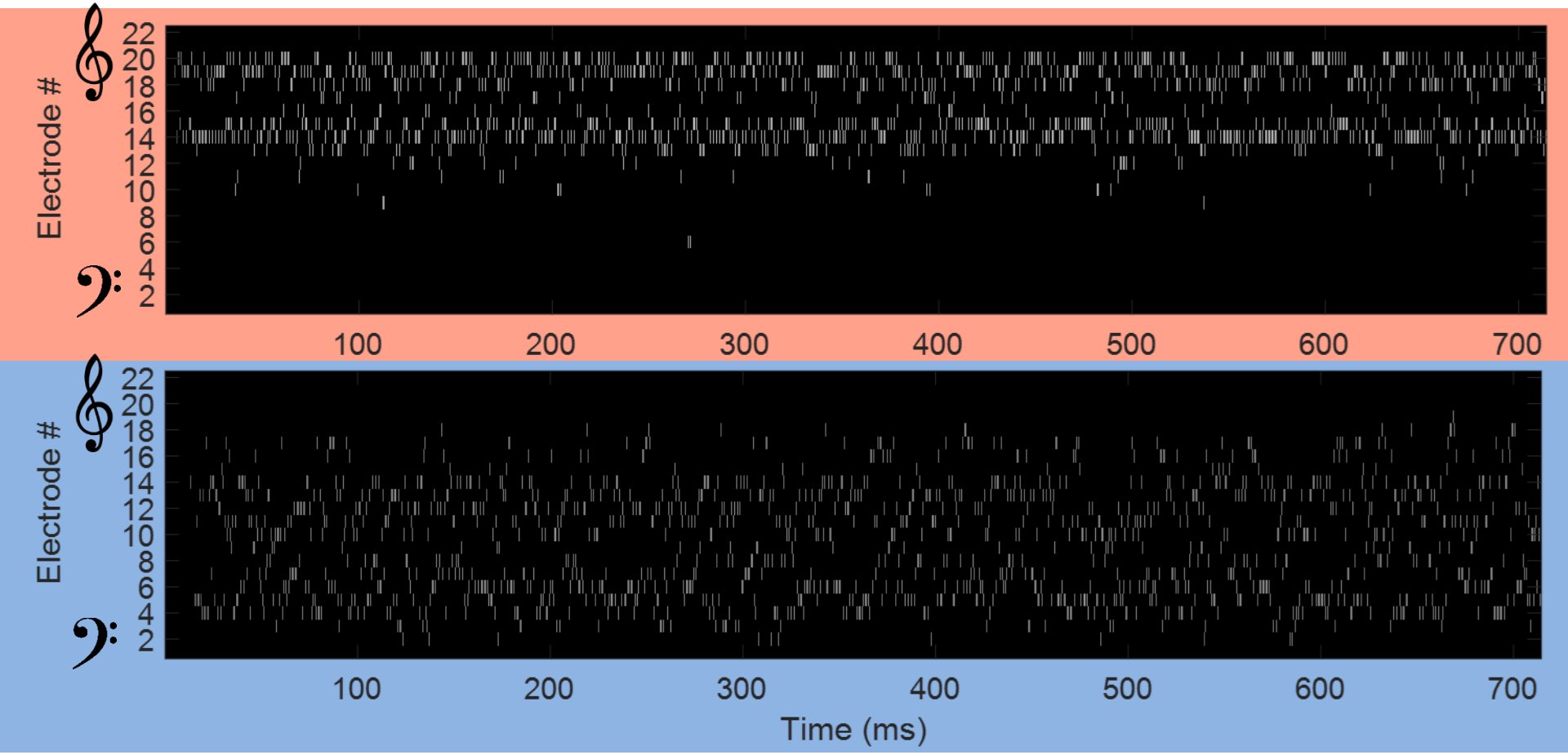
1. Identifying interaurally matched electrode pairs
2. ITD-based lateralization
3. Speech coding strategies

4. Problem of L/R independence
5. Directional filters

6. Bringing it together

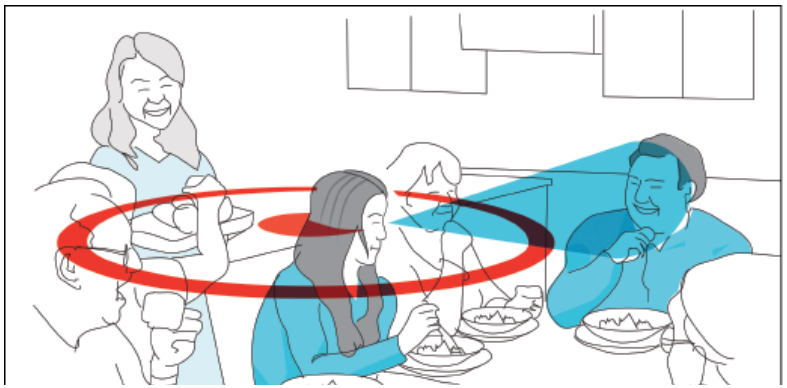
4. Problem of L/R independent n-of-m selection





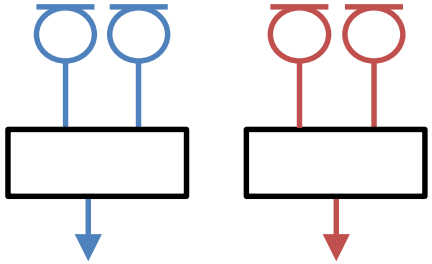
Kelvasa and Dietz (TIH 2015)

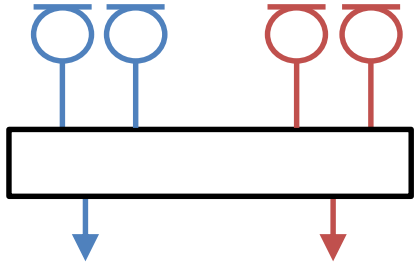
5. Directional filters – Speech Intelligibility



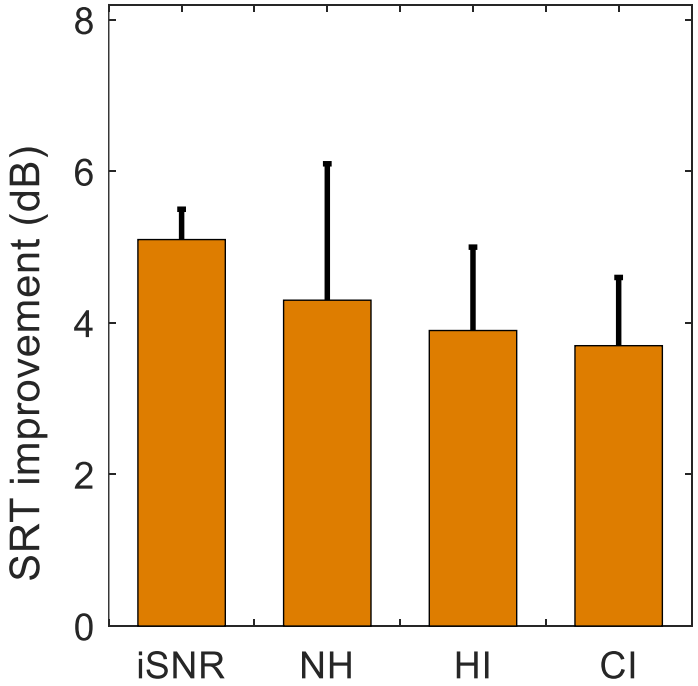
Baumgaertel et al. (2015 a,b) Völker et al (2015)

5. Directional filters – Speech Intelligibility

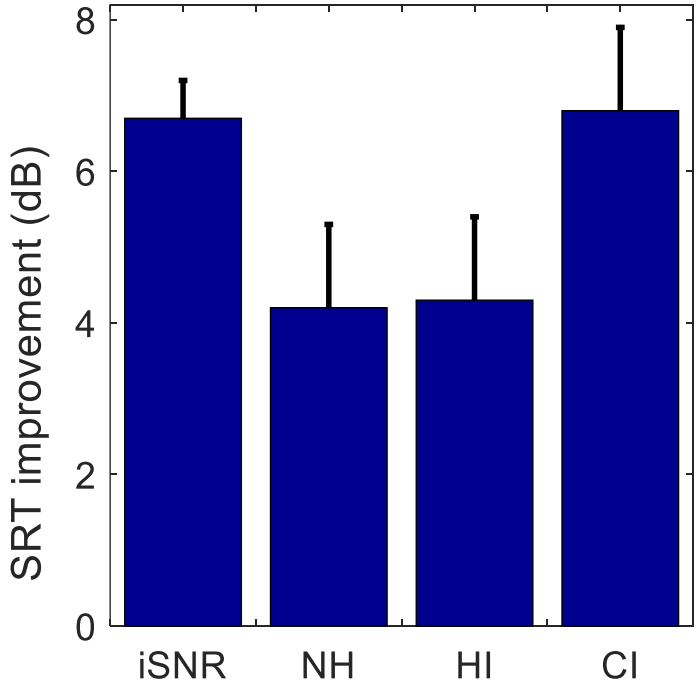




2x monaural directional micro



4-channel binaural beamformer

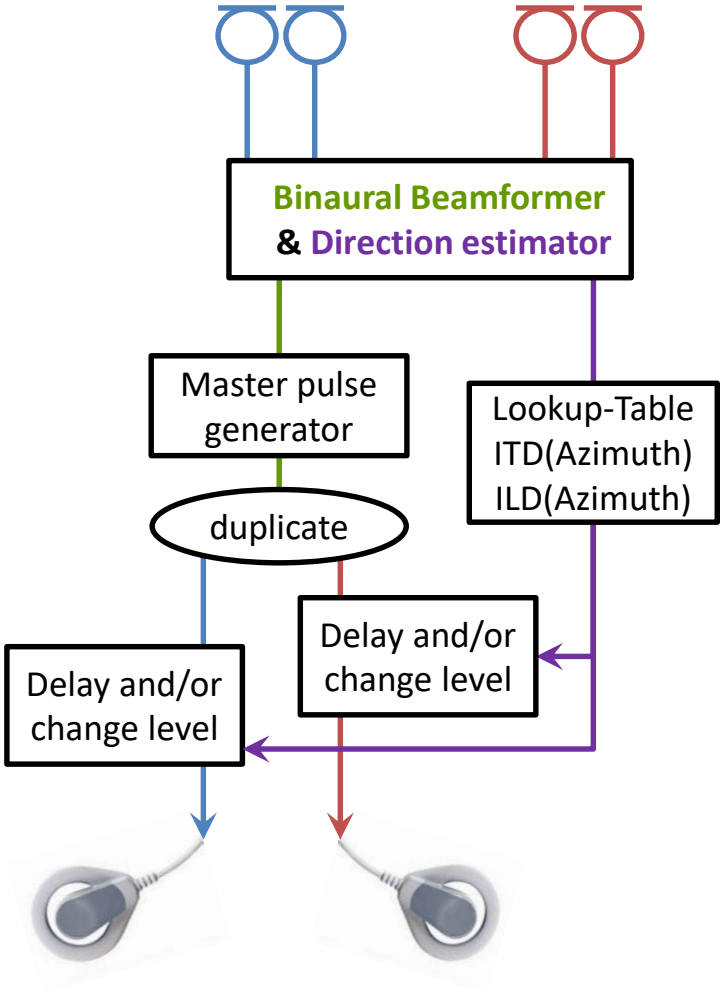


Baumgaertel et al. (2015 a,b) Völker et al (2015)

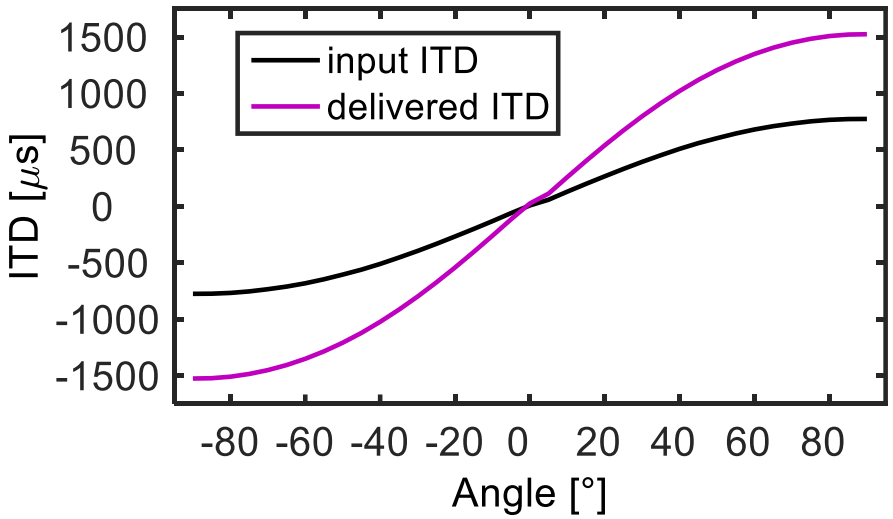
Interim Summary: Some components for better bilateral CIs

1. Binaural fitting (amplitude and frequency)
2. ITD enhancement (Baumgaertel et al. JASA 2017); or ILD (Francart et al. 2011)
3. Peak-picking-like speech coding strategy (e.g. Smith 2014)
   - Pro 1: ITD and f_0 preserved in pulse timing
   - Pro 2: low rate (users can exploit ITD and rate pitch)
   - Con 1: lower dynamic range (T-level higher)
   - Con 2: not robust
4. Matched AGC (Dorman et al. 2014) and n-of-m (Kelvasa and Dietz 2015)
5. A steering binaural beamformer (e.g., Adiloglu et al. TIH 2015)
   - Pro 1: largest SRT improvement (Baumgaertel et al. TIH 2015)
   - Pro 2: causes high interaural coherence output
   - Pro 3: very robust – even at negative SNR
   - Con: pre-decides target direction (loss of spatial awareness)

6. Bringing it together:
A Localization Enhancement Algorithm



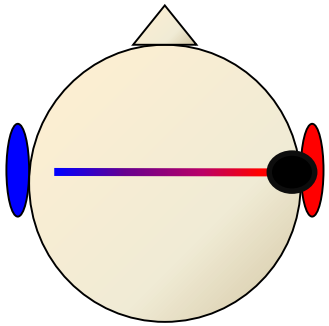
- 4-channel input (or 2 or 6)
- 1-channel conversion to electrodogram
- 2-channel output
- Interaural coherence = 1
- Individual mapping of ILD and/or ITD (e.g.: 90° = 1.5 ms ITD)



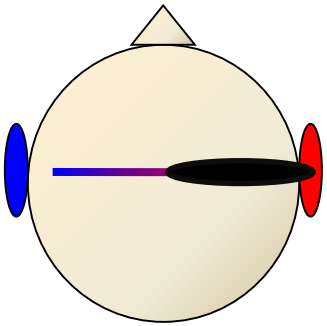
Dietz and Backus (patent application 2015)

6. Bringing it together: Summarizing example

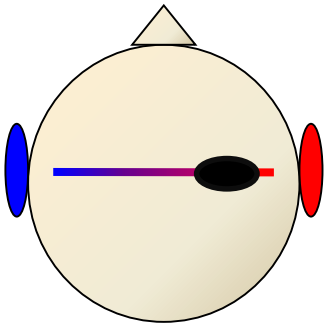
Lateralization of speech from the right (SNR ~ 0 dB)



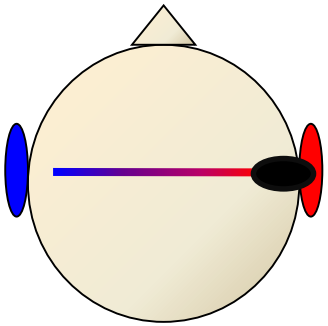
NH Subject



Good bilateral CI Subject



Steering binaural beamformer



Our Algorithm with ITD enhancement (best subject)

Conclusion: ITD-based localization is possible even at 0 dB SNR but you have to get many things right at the same time

Conclusions & suggestions

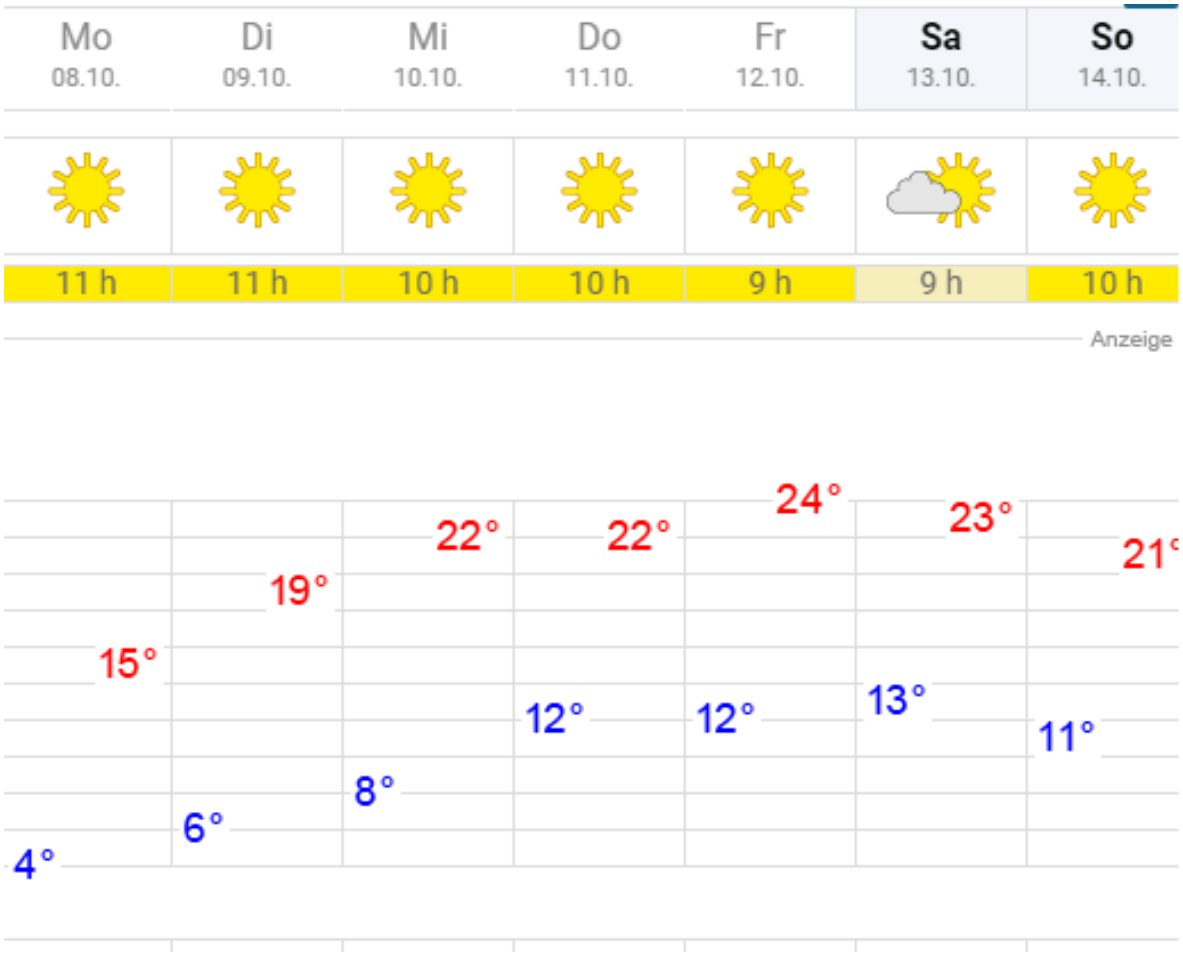
1. The more elaborate the speech coding strategy the more relevant is binaural fitting and binaurally coordinated stimulation

   CIS < ACE < FS4 < peak picking
2. Fitting suggestion: To date an important and realistic goal for bilateral CI fitting is to get a centralized percept for central sources, independent of frequency and level.
3. For SSD, good bimodal, subjects with different electrodes, or subjects with known implantation problems a frequency adjustment may be beneficial. Use pitch matching but only for newly implanted subjects to find pairs.

Optimistic outlook

1. Next generation CI speech processors synchronize AGC and m-of-n
   - Much better ILD-based lateralization
     - Correct electrode pairing gets more important
     - Basis for further ILD modifications
2. Coding strategies start providing perceptually relevant ITDs
   - Correct electrode pairing gets very important
   - Likely only ever useful in the absence of interfering sources or with beamformers
3. With a binaural fitting and a steering binaural beamformer the average bilateral CI user should be able to understand and localize a conversation partner even at slightly negative SNRs.

Postdoc position available in my lab



BiCI publications from our lab

- Dietz and Backus 2015 patent application: Convert only one acoustic signal to electrodogram
- Hu and Dietz TIH 2015: Electrode Pairing. BIC works; be careful with pitch matching.
- Baumgaertel et al. TIH 2015 a,b: Binaural beamforms enhance SRT more than in hearing aids
- Adiloglu et al. TIH 2015: Steering binaural beamformer robust even at negative SNR
- Kelvasa and Dietz TIH 2015: BiCI model. Effects of compression and N-of-M
- Dietz NETWORK 2016: Review on BiCI models and related topics
- Baumgaertel et al. JASA 2017: CI users require ITD > 1 ms and < 200 pps for full lateralization
- Williges et al. TIH 2018: Pure ITD-based localization of speech in noise possible
- Hu et al. JASA 2017: In AM pulse trains NH listeners are most sensitive to onset ITDs but CI users are most sensitive to ITDs at modulation maximum (bad in reverb)
- Hu et al. BMSPC 2015: single- and multi-channel eABR and eBIC artifact reduction