**Bilateral cochlear implantation**

**Functional benefits:**
1. Sound localization
2. Speech understanding in noise

With clinical Processors:
Performance is better with 2 vs. 1 CIs.
But generally poorer and more variable compared with normal hearing listeners

→ Research Processors: Binaural electrical stimulation: Demonstrate sensitivity to binaural Cues
Ultimate Goal: Identify best approaches for restoring binaural hearing

**Changing Criteria**

<table>
<thead>
<tr>
<th>Adults / Children</th>
<th>Functional Abilities</th>
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<td>Bilateral CIs</td>
<td>Spatial</td>
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<td>Single sided deafness with CI</td>
<td>Bilateral</td>
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<tr>
<td>Unilateral hearing loss</td>
<td>Binaural</td>
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**Measures**

- Quality of life
- Listening effort
- Cognition/attention

**Bilateral cochlear implantation is becoming more common**

**Functional benefits:**
1. Sound localization
2. Speech understanding
3. Poorly Documented: Reduced listening effort and fatigue

However,
(1) Binaural benefits are highly variable across patients.
(2) Very rare to see a CI user perform as well as normal-hearing listeners

**Binaural cues on the horizontal plane**

Sound reaches the near ear first
→ Interaural time difference (ITD)
→ At low frequencies

**Functional benefits that bilateral cochlear implantation can provide**

- **Sound Localization** improves significantly
- **Speech understanding in quite** improves (redundant speech information in the two ears)
- **Hearing speech in noise** (taking advantage of spatial separation between sources)
- **Listening effort** is reduced (“release from effort”)
Binaural cues on the horizontal plane
Sound reaches the near ear with greater intensity
→ Interaural level difference (ILD)
 & Monaural head shadow
→ At high frequencies

Spatial Release from Masking (SRM)

Children using clinical processors during testing

Co-located
Separate

Target speech
Masking speech

SRM = (Thresholds<sub>Co-located</sub>) – (Thresholds<sub>Separated</sub>)

Spatial Release from Masking in Children

Possible reasons for small improvement with spatial cues in children with bilateral CIs
1. Poor access to binaural cues
2. Poor ability to perceive and use cues
3. Not enough experience with bilateral CIs from a young age?

Spatial Release from Masking

BiCI

Better

SRM (dB) = SRT<sub>Co-located</sub> - SRT<sub>Separated</sub>

B.C.I.
5-6 yr. 7-9 yr.

Normal Hearing
5-6 yr. 7-9 yr. Adult

Misurelli and Litovsky, 2012

Spatial Release from Masking

BiCI

Better

SRM (dB) = SRT<sub>Co-located</sub> - SRT<sub>Separated</sub>

BiCl 2.5 yrs
NH 2.5 yrs

B.I.C.
5-6 yr. 7-9 yr.

Normal Hearing
5-6 yr. 7-9 yr. Adult

Hess and Litovsky, in revision
Misurelli and Litovsky, 2015

Quiet
Contralateral Separation

Monaural
Dichotic Separation

Misurelli and Litovsky, 2012
Early activation with bilateral CIs seems to promote spatial release from masking in children.

Bilateral CI users can attend to one ear and ignore the other.

What about sound localization?

Sound localization in the horizontal plane

Localization in children with Normal Hearing

Ages 4-5 years

Spatial "map" along the horizontal plane is well developed in early childhood

Example from 3 children; similar data from >30 children

Localization in children with bilateral CIs

Ages 5-12 years

Example from 3 children; similar data from >30 children

Example from 3 children; similar data from >20 children

Litovsky et al. (in prep)

Localization in children with Normal Hearing

Ages 2-3 years

In fact, spatial "map" along the horizontal plane is well developed by 2.5 years of age

Example from 3 children; similar data from >20 children
What if the children are implanted by 12 months of age and bilateral hearing starts early?

Ecologically valid task
Test with ‘Reaching for sound’

Discrimination Left - Right Localization

Child only sees 2 holes in curtain:  
+/- .60 
+/- .45 
+/- .30 
+/- .15

Child sees 9 holes in curtain:  
+/- 60 +/- 45 +/- 30 +/- 15 0

EXAMPLE OF 3 TODDLERS WITH BICLS

But they have no ‘spatial map’

Early activation of bilateral hearing seems to promote better performance in some children on some tasks
• Spatial release from masking by age 2.3
• Discrimination Right-Left at 15 degrees

However
• Young implanted children do not have a spatial map (yet?)
• And performance is overall, poorer and more variable with bilateral CIs than NH

Two Directions
1. Peripheral: Restore binaural hearing (ITDs) in multi-channel processing.
2. Top-down:
   • Processing time / cognitive load, listening effort
   • Measures of cognition, attention, memory

RESULTS:
All toddlers with BICls can discriminate angles as small as 15° when using both CIs

With a single CI - Performance is either poor or they are unable to do the task

Example of 2 toddlers with Bilateral CIs

Example of 3 toddlers with BICls

NIH Toolbox Cognition Battery
• Measures the same constructs across the lifespan
• Standard set of measures that can be used across diverse study designs and settings
• Easy to administer and obtain assessment scores

www.nihtoolbox.org
Working Memory

• List Sorting Test

www.nihtoolbox.org

Inhibitory Control

www.nihtoolbox.org

Attention Shifting

• Dimensional Change Card Sort Test

www.nihtoolbox.org

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Peripheral Limitations in Bilateral CIs:

→ Independently operating speech processors minimize/remove binaural cues
→ Poor signal processing for representing ITDs
→ Neural Pathology?
→ Asymmetry in insertion depth and distance from neurons?

Approaches to restoring binaural inputs:

Bypass the microphones & clinical processors
Research Processor: Direct Electrical Stimulation

Pairs of electrodes
→ Pitch-matched
→ Loudness balanced

Task:
2-intervals / 2-alternatives

Trial type 1: Left ITD – Right ITD
Trial type 2: Right ITD – Left ITD

Threshold = smallest ITD that can be discriminated
Electrode arrays in the left and right cochleae

Stimulating 1 pair of pitch-matched electrodes

Bilaterally implanted children ages 8-12 showed ILD sensitivity, but only 3/10 showed ITD sensitivity

Lost hearing after age 3
Exposed to acoustic hearing early in life

Ehlers et al. (in revision)

Research in children, using research processors, shows that:

→ ITD sensitivity: highly "vulnerable" to acoustic deprivation early in life.
→ ILD sensitivity: more resilient to acoustic deprivation early in life.

Research to date with adults is consistent with the timing/level findings in children:

→ ITD (timing) sensitivity: highly "vulnerable" to acoustic deprivation early in life.

Litovsky et al. (2010)

Why don’t we abandon ITDs and focus on preserving ILDs in CI speech processors?

• Because data suggest that ITDs are superior
• ITDs provide the best outcomes for sound localization (e.g., Wighman and Kistler, 1992) and for spatial release from masking (e.g., Culling, Hawley, Litovsky, 2004)

• Many CI users are adults with late-onset of deafness OR congenitally deaf children;
• Motivation to restore ITDs as soon as patients are activated

Research to date with adults is consistent with the timing/level findings in children:

→ ILD (level) sensitivity: "maintained" or "recoverable" after long-term deafness.

Litovsky et al. (2010)
Cochlear Implant Processing:

- Time
- Frequency (Hz)

- Envelope
- Fine Structure

The Conundrum:
ITD sensitivity is best at low stimulation rates (< 300 pulses per second)
BUT
Speech processors typically operate at high rates (~1,000 pulses per second)

So, how can we restore ITD sensitivity without compromising good speech envelope representation?

The Plan: Mixed (hybrid) Rate Strategy

1. Find best places along the cochlea for each patient
2. Provide ITD stimuli at low rates to those places
3. Provide speech stimuli at high rates to other places along the cochlea
4. Test to see if the high-rate stimulation interferes with the low-rate ITD sensitivity

Sensitivity to ITDs varies: some places along the cochlea are better for each patient
(> due to neural health, electrode-neural interface, etc.)

Stimulating 5 pairs of electrodes along the electrode arrays

Thakkar, Kan, Jones, and Litovsky (under review)

Kan, Jones, and Litovsky (2015)
Novel Stimulation Strategies: ‘Hybrid’ Rates

Some electrode pairs at 100 pulses/sec (good for ITDs)
Others at 1000 pulses/sec (good for speech)

Re: All High → significant improvement in ITD JNDs with only 1 low-rate electrode

Positive results with hybrid-rate: Lateralization
With multi-electrode stimulation (needed for speech understanding)
Can preserve ITD sensitivity:
→ Low stimulation rates at 1 electrode
→ High stimulation rates at other electrodes

Across dozens and dozens of patients:
→ Variability in performance
Within individual patients:
→ Variability across place of stimulation in the cochlea
→ Depends on many variables including neural health at specific places of stimulation

How do we assess neural health, and choose best place to present ITD cues?

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Listening effort / cognitive load
1. Degraded signals such as CIs
2. Hearing with 1 vs. both ears

Patients report that these are very difficult listening conditions
In search of using our binaural strategies to improve localization as well as to improve speech understanding and release from cognitive load
Listening to patient reports: “it’s easier with two ears than one” [improvement not always seen in %correct scores]

Objective measures of "arousal"
Aka listening effort / cognitive load
using an eye tracker → quantify pupil dilation

Pupil dilation also related to arousal state (attend to environment; flight/fright; controlled by norepinephrine)

PROCEDURE:
Listen to & repeat sentences while fixating on the screen
→ Measure “real time” processing

Measuring listening effort / cognitive load using eye tracking: Effect of spectral resolution in speech

Correct Trials Only

Bilateral cochlear implant subjects (N=12)

Winn, Edwards, Litovsky (Ear Hearing, 2015)

Bilateral cochlear implant subjects (N=12)

Winn, Litovsky (in prep)

Winn, Litovsky (in prep)
Bilateral cochlear implant subjects (N=12)

- Bilateral listening mode produces reduced listening effort compared to either ear alone.
- Often, patient's subjective report re: which ear is 'better' or 'worse' is consistent with the amount of listening effort in each ear alone.

Future Directions: Optimizing Benefits

**Peripheral:** Lack of binaural inputs:
- No coordination between CIs
- Lacking fine structure

**Central:**
- Lack of perceptual map of space
- Executive Function?

**Goal:**
- Improve function of bilateral CIs → binaural
- Improve function in everyday noisy environments
- Reduce listening effort

**Engineering, signal processing...**
- What cues are worth preserving???

**Cognitive Measures:**
- Identify children at risk for lower performance?

**Training**
- ? Using Audio-visual integration

**Objective measures**
- Listening effort
- Peripheral limitations

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**Future Directions:**
- Optimizing Benefits
- Engineering, signal processing...
- What cues are worth preserving???
- Cognitive Measures: Identify children at risk for lower performance?
- Training: ? Using Audio-visual integration
- Objective measures: Listening effort, Peripheral limitations

**Thank you**