Clinical application of latest CI research

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Wilson BS, Dorman MF. (2008). J Rehabil Res Dev, 45(5): 695-730.

The cochlear implant:

"…the most successful of all neural prostheses developed to date"

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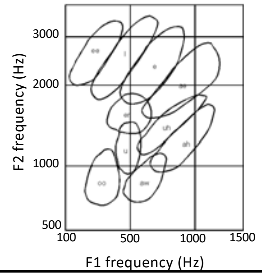
Wilson BS, Dorman MF. (2008). J Rehabil Res Dev, 45(5): 695-730.

The cochlear implant:

"…the most successful of all neural prostheses developed to date"



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One size fits all?

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One size fits all?

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One size fits all?

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CI programming: one size fits all?

- Cochlear implant programming: "one-size-fits-all" philosophy
- Default parameters & electrode arrays used for most recipients
    - stimulation rate
    - stimulation strategy
    - electrode-frequency allocation
    - max # of active electrodes
- Defaults are used despite differences in cochlear anatomy, electrode insertion depth, scalar/electrode location, an individual's listening environment(s), etc.

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CI programming: one size fits all?

ASSUMPTIONS:

- electrodes are in the **right place** with similar scalar location & depths across ears
- similar electrode-to-neural interface along the array
- bilateral recipients have similar insertion depths and placement across ears
- all electrodes in cochlea
    - 35 of 262 CI users had extracochlear electrodes—only 2 cases were identified in operative report (Holder et al., 2018. *Otol Neurotol, 39:e325–e331).*

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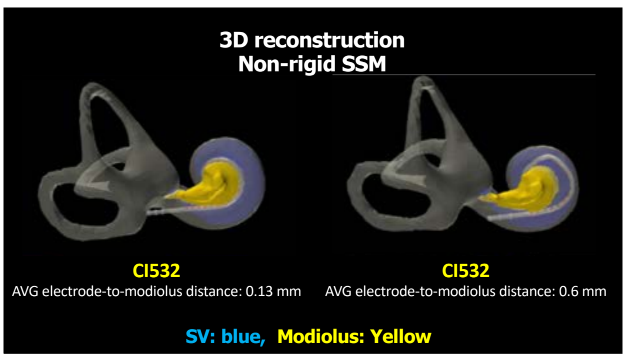

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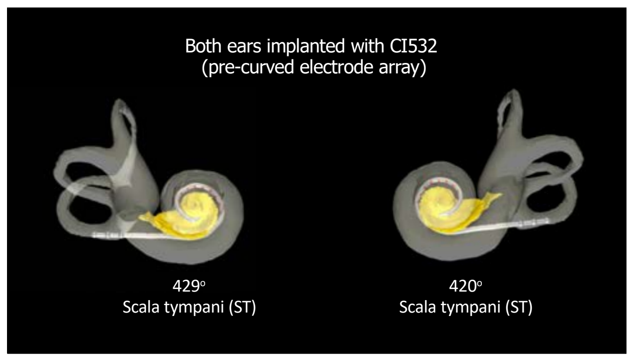

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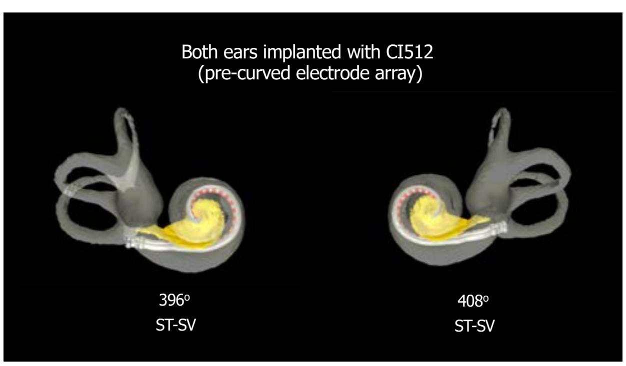

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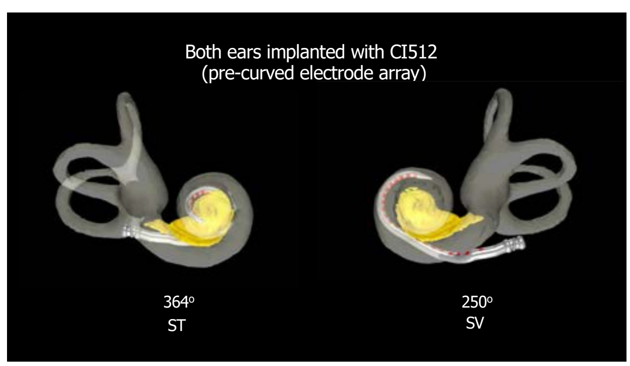

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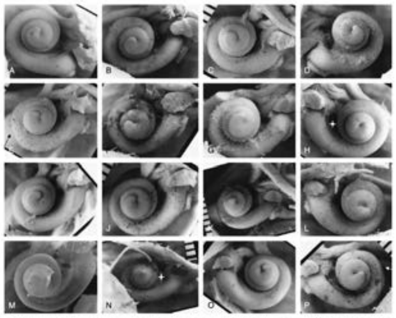

Erixon et al. (2009). *Otol Neurotol*, 30:14-22.

- n = 72 human cochleae
- Mean # turns: 2.6 (range 2.2 to 2.9)
- mean length of 1st turn = 22.6 mm (range 20.3 to 24.3 mm)
- Mean outer wall length: 42 mm (38.6 - 45.6 mm)

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How many electrodes do we need for maximum speech understanding?

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What do we know from past studies (with simulations & CI recipients)?

Above 4-8 channels, there were no additional gains for:

- Consonants
- Vowels
- Monosyllables
- Sentences in quiet
- Sentences in noise

Fishman et al., 1997; Dorman et al., 1997; Friesen et al., 2001; Shannon et al., 2011

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Classic literature: CI channel independence

- More traumatic electrodes & surgical approach
- Unknown scalar placement
  - Electrode position affects outcomes (Skinner et al., 2007;Finley et al., 2008;Holden et al., 2013; Wanna et al., 2014; O'Connell et al., 2016; Ramos Macias et al., 2017; Shaul et al., 2018; James et al., 2018; Chakravorti et al., 2019)
- Straight (lateral wall) electrodes
  - Electrode-to-modiolus distance → channel interaction (Litvak et al.,2007; Kang et al., 2015; Davis et al., 2016; Ramos Macias et al., 2017)
- Longer durations of deafness & poorer thresholds

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Why does electrode position matter?

- Electrode-to-modiolus distance correlated with charge for upper stim levels (e.g., Litvak et al., 2007; Kang et al., 2015; Davis et al., 2016)

Modiolus: yellow
Green: scala tympani

- Higher charge → greater channel interaction (e.g., Chatterjee & Shannon, 1998; Chatterjee et al., 2006)
- Greater channel interaction → poorer spectral resolution

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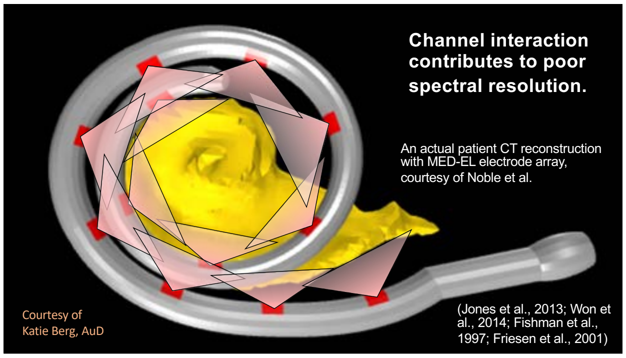

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Berg et al. (2019). *J Acoust Soc Am*, 145: 1556-1564

- 11 precurved electrode recipients
- 7 CI24RE(CA), 4 CI532
- Mean age = 67 years (24 to 87 years)
- Imaging and 3D reconstruction to determine scalar location
  - All completely in scala tympani (ST)

Examined speech recognition & sound quality for a number of spatially selective channel conditions per Friesen et al. (2001)

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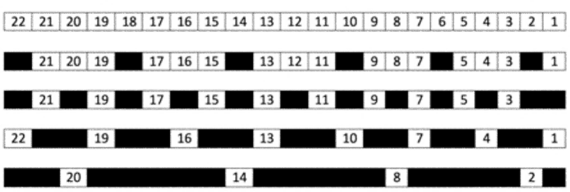
Spatially selective channel independence



Berg et al. (2019) Friesen et al. (2001)

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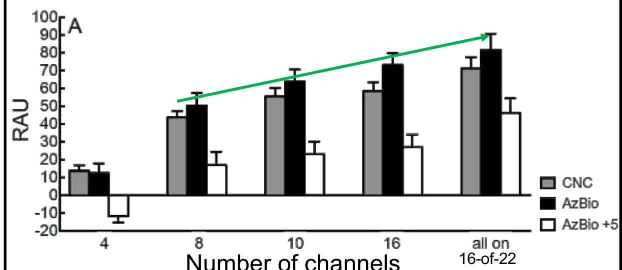
Berg et al. (2019). *J Acoust Soc Am*, 145: 1556-1564



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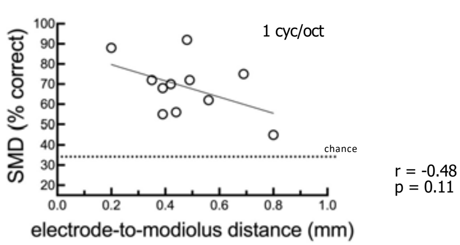

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Continuous Interleaved Sampling

Courtesy of MED-EL

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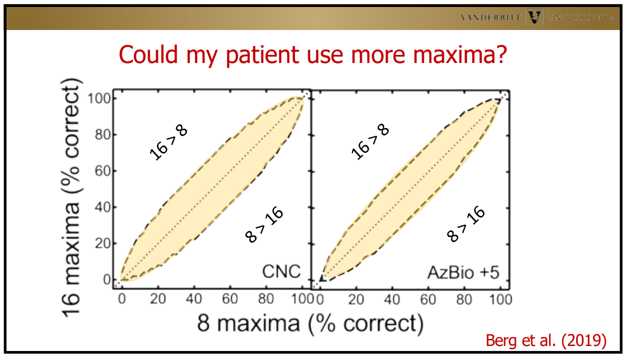

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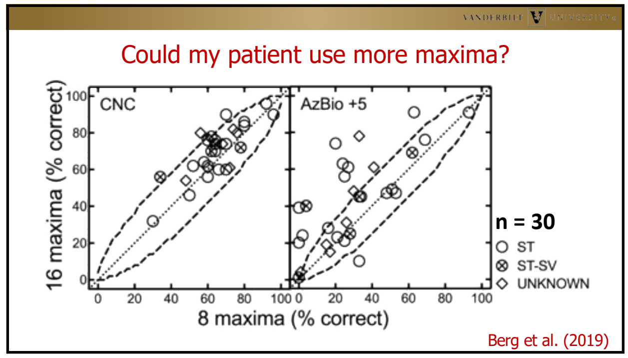

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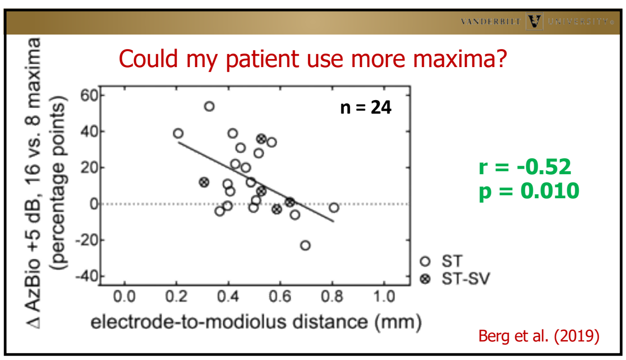

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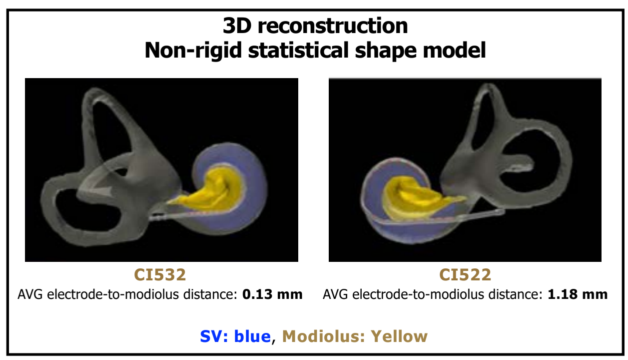

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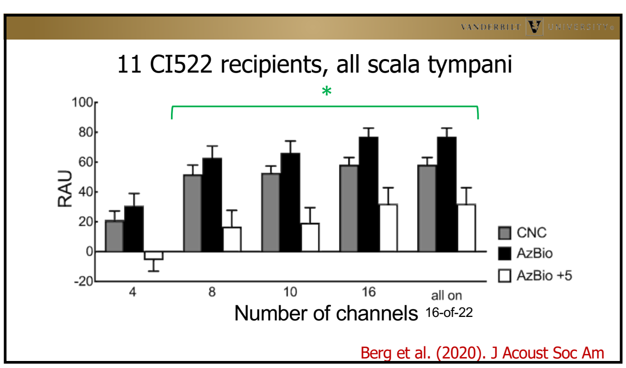

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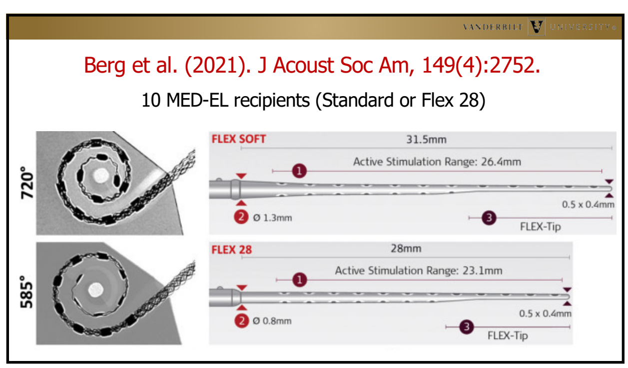

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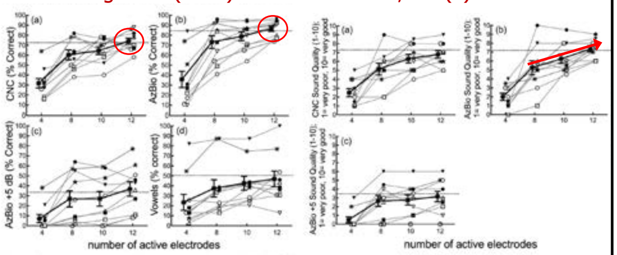
Berg et al. (2021). J Acoust Soc Am, 149(4):2752.



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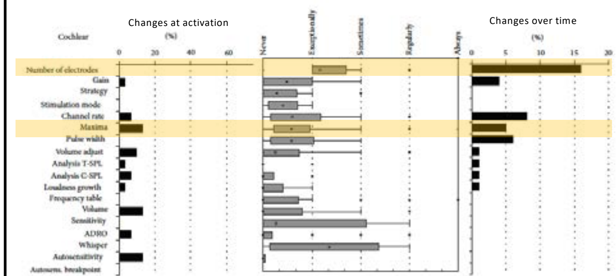
CI programming parameters: frequency of adjustment



Vaerenberg et al. (2014). Sci World J. 2014:646590.

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Summary

- Modern adult CI users w/ precurved electrodes are different from those studied in the classic literature
  - Adults: significant gains up to 16 channels (CIS) or 22 channels (n-of-m)
    - BUT…still no gains beyond 8 electrodes for straight arrays (Cochlear 522/422 or MED-EL Standard or Flex 28)

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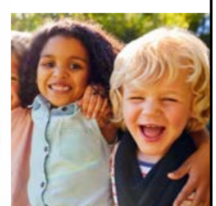

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Spectral resolution in children with NH: early peripheral maturation, but CAS continues to mature

By 3 months of age:

- Infants can discriminate complex pitch
  - Lau & Werner (2012). J Acoust Soc Am, 132: 3874–3882; He & Trainor (2009). J Neurosci, 29: 7718–7722; Spetner & Olsho (1990). Child Dev, 61: 632–652.
- Spectral resolution is mature (up to 1000 Hz)
  - Montgomery & Clarkson (1997). J Acoust Soc Am, 102:3665–3672; Folsom & Wynne (1987). J Acoust Soc Am, 81: 412-417.

By 6 months of age:

- Spectral resolution is mature (up to 4000 Hz)
  - Montgomery & Clarkson (1997). J Acoust Soc Am, 102:3665–3672; Schneider et al. (1990). J Exp Psychol Hum Percept Perform, 16: 642-652.

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Spectral resolution in children with normal hearing

Children with NH:

- *require more channels* for asymptotic speech recognition with sine-wave vocoder (Dorman et al., 2000) and noise-band vocoder (Eisenberg et al., 2000)
- vocoded speech recognition improves with age (Eisenberg et al., 2000, 2002; Roman et al., 2016; DiNino & Arenberg, 2019)
- poorer frequency discrimination (Halliday et al., 2008; Moore et al., 2008; Buss et al., 2014)
- Poorer spectral modulation detection (Sheffield et al., 2016; Gifford et al., 2018; Landsberger et al., 2018)
- Broader auditory filters (Irwin et al., 1986)
- Higher masked thresholds (Irwin et al., 1986; Allen et al., 1989; Hall & Grose, 1991)

Infants with NH:

- Spectrally degraded vowel recognition improved with up to 32 channels (Warner-Czyz et al., 2014)

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Gifford et al. (2022). JASA Express Lett, 2(9): 094403.

- n = 10 precurved electrode recipients
  - Mean age = 11.7 years (8.5 to 14.5 years)
- Imaging and 3D reconstruction to determine scalar location
  - 4 ST, 1 SV, 4 ST-SV, 1 SV, 1 without CT
    - 6 CI512, 1 CI532, 3 CI24RE(CA)
- Spatially selective CI programs were created per Friesen et al. (2001) using 4, 8, 12, 16, and 22 active electrodes

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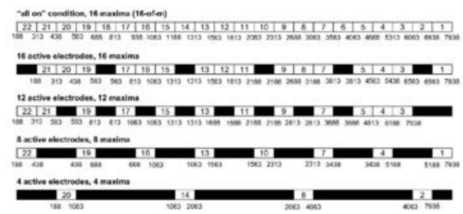
Gifford et al. (2022). JASA Express Lett, 2(9): 094403.



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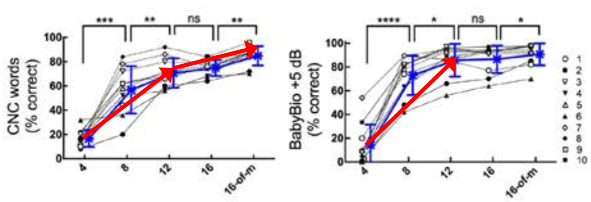

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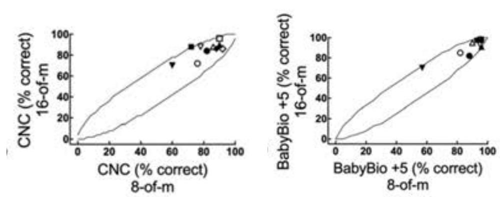

t(9) = 2.4, p.0.039

t(9) = 1.6, p = 0.14

Gifford et al. (2022). JASA Express Lett, 2(9): 094403.

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Summary

- Children with CI: performance gains up to 12 channels in a CIS strategy and up to 22 in an n-of-m (ACE) strategy.
  - increasing channels → greater overall stimulation rate
    - 900 pps, 8 ch = 7,200 pps
    - 900 pps, 12 ch = 10,800 pps
- Differential weighting of spectral and temporal information?
  - Investigation is ongoing!
- Clinical tip:
  - Adults & children using n-of-m, consider increasing maxima from 8 to 16 (particularly for adults' noise programs)

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Bimodal or Bilateral?

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Bilateral CI = standard of care for bilateral severe-to-profound SNHL

Balkany et al. 2008; BCIG, 2008; Papsin & Gordon, 2008; Peters et al., 2010; Ramsden et al., 2012

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Bimodal (CI+HA) vs. Bilateral CI (CI+CI)

Both hearing configurations provide significant benefit over 1 CI alone

Speech in quiet

Speech in noise

localization

music

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Clinical problem

Criteria for recommending bimodal vs. bilateral CI?

Bilateral CI = standard of care

But, potentially sacrificing acoustic hearing

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Bimodal stimulation → significant benefit *even if pursuing a 2nd CI*

Phonological processing: Moberly et al. 2016; Nittrouer et al. 2012, 2018

Lexical tone perception: Yeun et al. 2009; Luo et al. 2014; Zhang et al. 2020

Suprasegmental perception: Straatman et al. 2010; Hegarty & Faulkner, 2013; Davidson et al. 2019

Music emotion perception & sound quality: Sucher & McDermott, 2009; El Fata et al., 2009; Giannantonio et al., 2015; Shirvani et al., 2016; D'Onofrio et al., 2020; D'Onofrio & Gifford, 2021

Subjective reports of listening effort: Gifford et al., 2017

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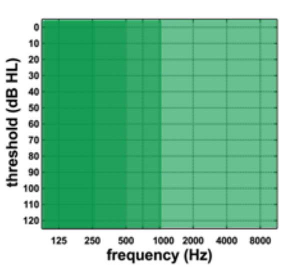
How much acoustic hearing adds benefit?



Sheffield & Gifford (2014). Audiol Neurotol, 19: 151-163
- 12 adults

Gifford et al. (2021). Otol Neurotol, 42:S19-S25.
- 10 children

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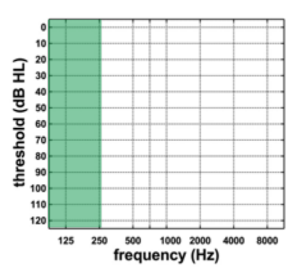
How much acoustic hearing adds benefit?



Sheffield & Gifford (2014). Audiol Neurotol, 19: 151-163
- 12 adults
- **CI+250 Hz** → significant benefit
- Continuous bimodal benefit with expanding acoustic bandwidth

Gifford et al. (2021). Otol Neurotol, 42:S19-S25.
- 10 children
- **CI+250 Hz** → significant benefit

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Bimodal Benefit

LF acoustic hearing → F_0 & temporal fine structure

- **Clinical implication:** we should always attempt to aid a non-implanted ear, but…

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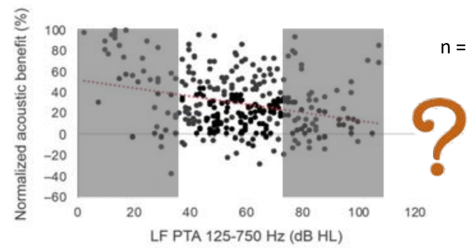
Kessler et al. (2020). JSLHR, 63:1561-1571.



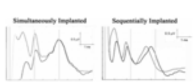
Kessler et al. (2020). Trends Hear

51

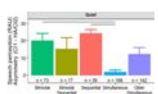
Bimodal Benefit

LF acoustic hearing → F_0 & temporal fine structure

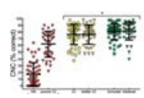
- **Clinical implication:** we should always attempt to aid a non-implanted ear, but…
- Consider impact of **aural preference syndrome**
  - Gordon et al. (2015). Pediatrics, 136(1):141-53.



Gordon et al. 2011. Cochlear Implant Intl



Polonenko et al. 2018. Sci Rep



Gifford & Dorman, 2019. Ear Hear.

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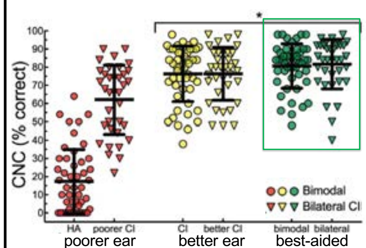
Bimodal Benefit



Gifford & Dorman, 2019. Ear Hear.

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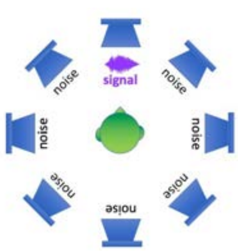
Bimodal Benefit



Do you need a 2nd CI?

100% HIT	**23% FALSE ALARM**
0% MISS	**77% CORRECT REJECT**

Gifford & Dorman, 2019. Ear Hear.

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Bimodal vs. bilateral CI: considerations

- Clinical measures of speech understanding → no difference
- Audiogram → lacks specificity
  - Adults: Ask your patient
- Bimodal with ***significant interaural asymmetry*** (HA < CI)
  - Poorer SRM (Gifford et al., 2014; D'Onfofrio et al., 2021)
  - Poorer speech rec in complex noise (D'Onofrio et al., 2021; Gifford et al., 2018; Gifford & Dorman, 2019)
  - Poorer localization (Dorman et al., 2016)
  - Poorer speech rec with roving talkers (Gifford et al., 2018)

RECOMMENDATION: If non-CI ear meets CI criteria → **2nd CI**

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Auditory perceptual learning (i.e. training)

- **Traditional aural rehabilitation:**
  - Significant benefit for speech recognition in noise (e.g., Sweetow and Sabes, 2006; Anderson et al., 2013; Humes et al., 2014; Schumann et al., 2014; Han et al., 2022)
    - No difference (Henshaw & Ferguson, 2013; Saunders et al., 2016; Reis et al., 2021; Henshaw et al., 2022)
- **Music-based training** (Strait & Kraus, 2014; Slater et al., 2015; Smith et al., 2017)
- **AR paired with pharmaceuticals** (Tobey et al., 2004)
- **Multisensory training**
  - Audiomotor training → improved speech recognition in noise (Whitton et al., 2017)
  - Speech + Vagal stimulation → greater A1 activation in rodents (Engineer et al., 2015)

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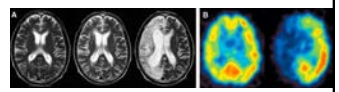
Training and pharmaceutical intervention

Tobey et al. (2005). *Ear Hear, 26*(4 Suppl): 45S-56S.

- single-photon emission computerized tomography (SPECT)
- Regional cerebral blood flow (rCBF)
- 8 postlingually-deafened adults
  - Placebo: 69 yrs (65-74 yrs)
  - Treatment: 52 yrs (44-59 yrs)
- cortical activation and speech tracking resulting from targeted intervention—in this case either AR alone or AR + amphetamine
  - AR: 8 weeks, two, 1.5 hour sessions/week



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Training and pharmaceutical intervention

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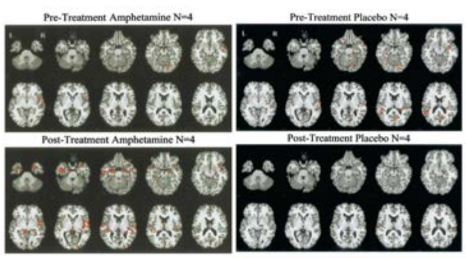

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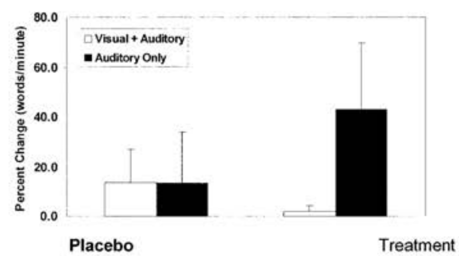
Training

Tobey et al. (2005). *Ear Hear, 26*(4 Suppl): 45S-56S.



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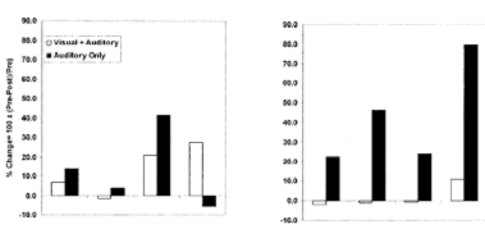
Training

Tobey et al. (2005). *Ear Hear, 26*(4 Suppl): 45S-56S.



Individual participant data: speech tracking

Placebo **Treatment**

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Cognition-enhancing medications

- Most are working on the cholinergic system
  - Donepezil (Aricept)
  - Nicotine
  - Caffeine
  - Amphetamine
  - Methylphenidate (Ritalin)
  - Modafinil—unknown mechanism (may or may not affect cholinergic neurotransmission)

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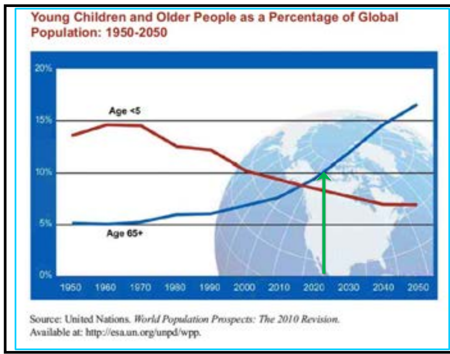

Figure 10-1

Gifford (2020)

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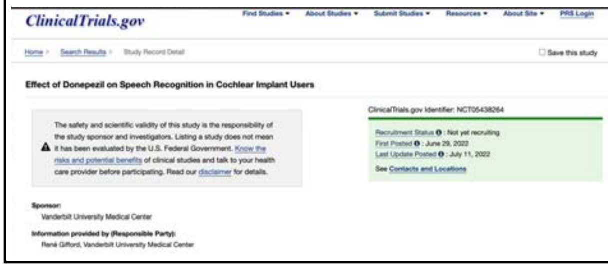
Effect of Donepezil on Speech Recognition in Cochlear Implant Users

Clinical trial at Vanderbilt for new CI recipients (adults)
ClinicalTrials.gov Identifier: NCT05438264



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CI programming

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Upper and lower stimulation levels

What's our target?

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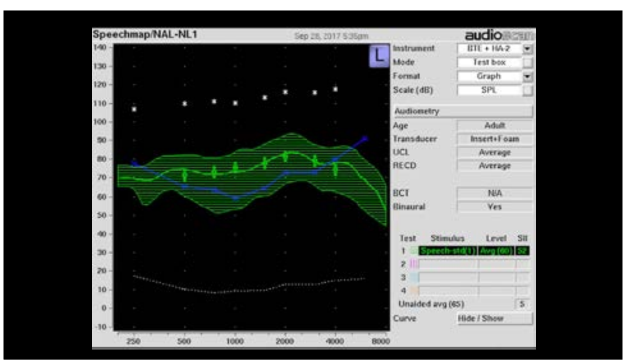

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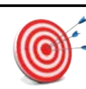

What's our target?

CI outcomes are impacted by stimulation levels & CI parameters

- Hodges et al. (1997). Otolaryngol Head Neck Surg, 117(3 Pt 1), 255–261.
- Skinner et al. (1999). *J Speech Lang Hear Res*, 42: 814–828.
- Geers et al. (2003). Ear Hear, 24(1 Suppl), 24S–35S.
- Boyd (2006). Ear Hear. 27(6):608-18.
- Wolfe & Kasulis (2008). Cochlear Implants Intl, 9, 70–81.
- Davidson et al. (2010). *Otol Neurotol*, 31(8):1310-4
- Holden et al. (2011). Intl J Audiol, 50(4): 255–269
- Baudhuin et al. (2012). J Am Acad Audiol, 23, 302–312.
- Holden et al. (2013). Ear Hear, 34, 342–360.
- Buechner et al. (2015). Cochlear Implants Intl, 16(1):39-46.
- Martins et al. (2021). Hear Res, 404: 108206

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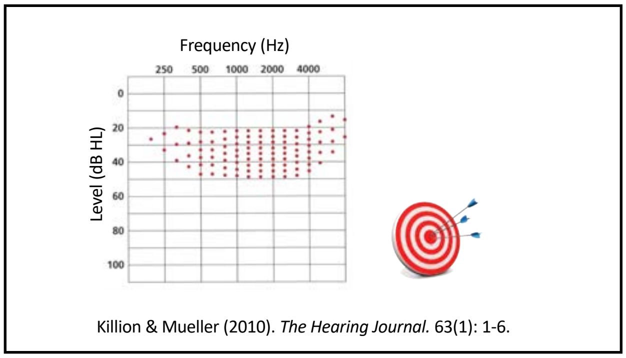

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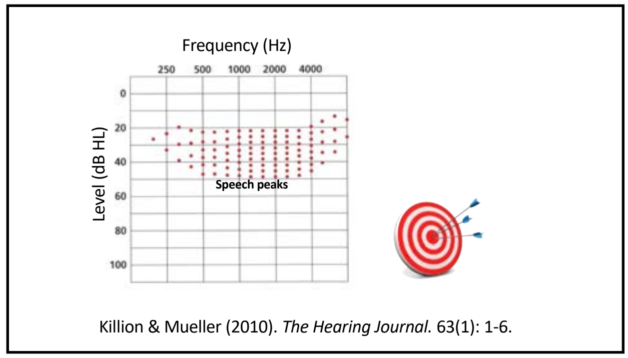

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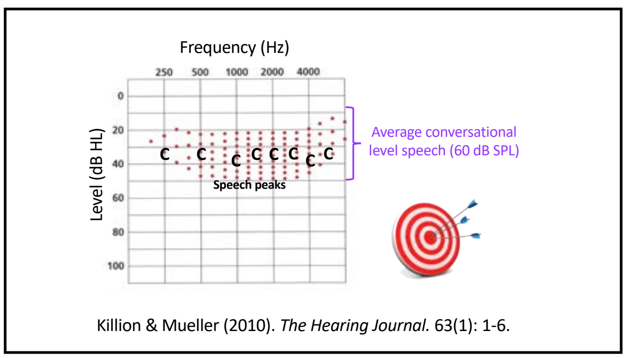

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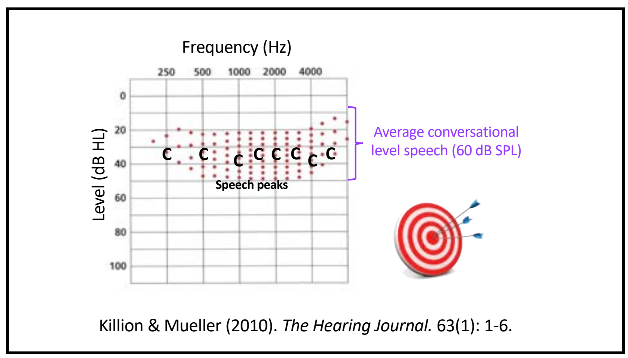

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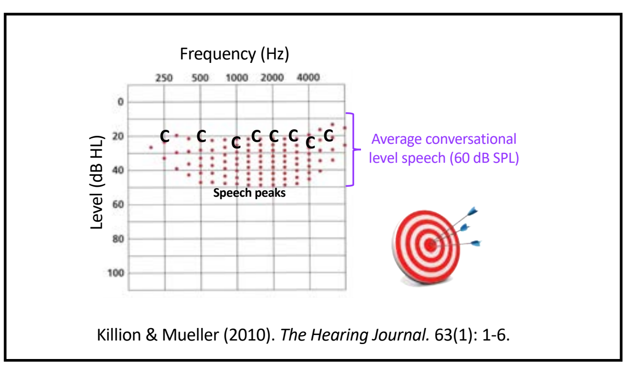

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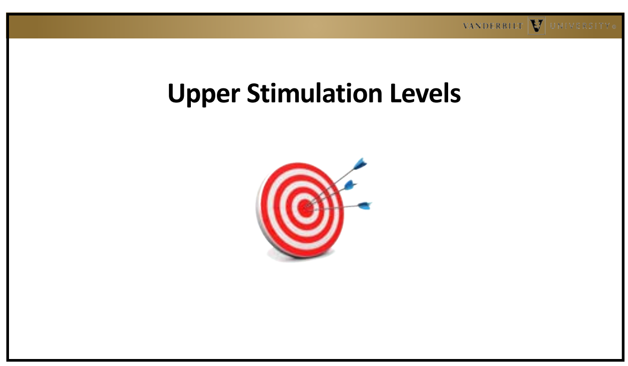

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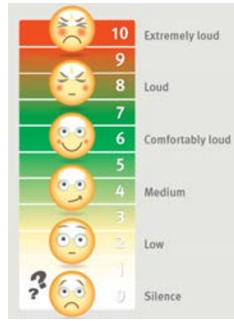
Upper Stimulation Levels

Different terminology and definition across manufacturers

- **AB**: "M" levels → **M**ost comfortable level
  - 65 dB SPL mapped to M level
  - 12:1 compression for inputs above 65 dB SPL
  - M levels are adjusted up & down with volume
- **Cochlear:** "C" levels → Loud, but **C**omfortable
  - 65 dB SPL mapped to C level in quiet
  - Inputs above CSPL → infinite compression
- **MED-EL:** "MCL" levels → **M**aximum **C**omfort **L**evel
  - 100 dB SPL is mapped to MCL
  - Input levels above 100 dB SPL → infinite compression

74



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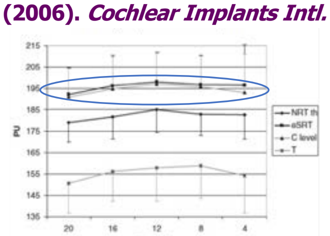
77

Problems with behavioral loudness scaling:

- Behavioral loudness scaling → difficult concept to conceptualize and communicate
  - Polak et al. (2006). Cochlear Implants Intl, 7: 125-41.
  - Willeboer & Smoorenburg (2006). Ear Hear, 27: 789-98.
- Loudness scaling for individuals with hearing loss → large variability depending on the method used
  - Marozeau & Florentine (2007). JASA, 122(3): EL81-EL87.

78

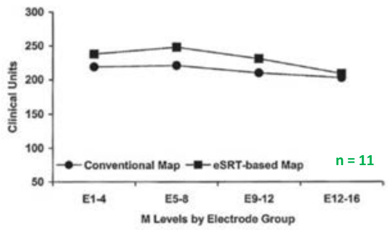
Polak et al. (2006). *Cochlear Implants Intl.* 7:125-141.



- Note agreement between behavioral Cs and ESRTs
- ECAP thresholds tend to undershoot behavioral Cs
  - But they can be anywhere in the audible dynamic range

79

Wolfe & Kausalis (2008). Cochlear Implants Intl, 9(2): 70-81



80

Wolfe & Kausalis (2008). Cochlear Implants Intl, 9(2): 70-81

Table 1: Speech perception scores (percentage correct) for 11 subjects using conventional behavioural programming techniques and after reprogramming with eSRT-based parameters

		HINT in noise 60 dB SPL SNR = 8 dB (%)	CNC words 50 dB SPL (%)	CNC words 60 dB SPL (%)	CNC words 70 db SPL (%)	
Conventional program	Mean	75	35	56	60	BEH
	Standard deviation	17	20	19	22	
eSRT-based program	Mean	78	42	62	70	ESRT
	Standard deviation	16	21	19	15	

81

Probe Tone		
226 Hz	678 Hz	1000 Hz
170	170	154
274	268	260
162	162	154
154	162	138
178	162	154
162	154	170
194	186	186
242	210	218
114	106	106
202	170	146
NR@162	138	146
202	202	210
146	146	154
136	127	118
NR@146	138	138
170	186	178
138	122	122
176	168	168
NR@194	186	186
234	202	202
178	162	178
NR@282	242	242
82	74	82

Numbers are in clinical units.
NR, no response.

Wolfe et al. (2017). Ear Hear, 38: 255-261.

23 adult CI recipients

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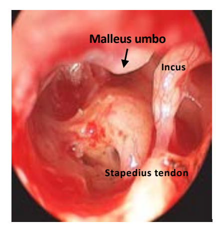

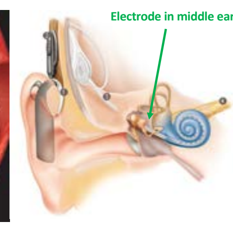

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Speech perception with behavioral and ESRT maps

- 20 adult CI recipients
- 12+ months of CI experience
- 19-89 years (mean = 61)
- 6 patients had long-term experience with ESRT-based map
  - ESRTs re-measured to verify upper stim level profile for existing ESRT maps
  - Behavioral maps measured
  - CI-aided thresholds 20-30 dB HL for all prior to testing
- CNC and AzBio +5 dB SNR
  - Testing was acute following programming and *double blinded*

Holder, Gifford, Sunderhaus (in prep)

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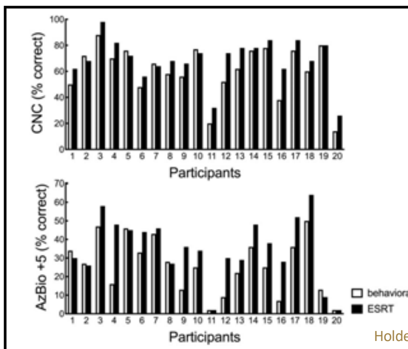
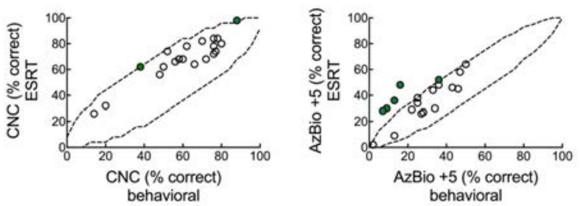


Mean CNC scores
Behavioral: 60.9%
ESRT: 68.8%

Mean AzBio +5 scores
Behavioral: 25.7%
ESRT: 34.8%

Holder, Gifford, Sunderhaus (in prep)

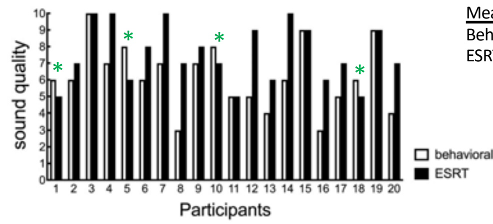
85



16 preferred ESRT, 3 preferred behavioral, 1 had no preference

Holder, Gifford, Sunderhaus (in prep)

86



Mean quality
Behavioral: 6.2
ESRT: 7.6

* long-term behavioral map

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Summary

- Upper and lower stimulation levels impact outcomes
- Loudness scaling is difficult
  - many patients reject HF stimuli
- Lower stimulation levels (T/THR)
  - CI-aided detection in the range of 20-30 dB HL (20-25 dB HL for children) yields better performance
- Upper stimulation levels (C/M/MCL)
  - ESRT-guided upper stimulation levels → patient preference and performance benefits
    - **AB**: ~ 10-15% below ESRTs
    - **Cochlear**: ~ 20 CL below ESRTs
    - **MED-EL**: close to 1:1 relationship

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Additional clinical tips & tools to improve outcomes

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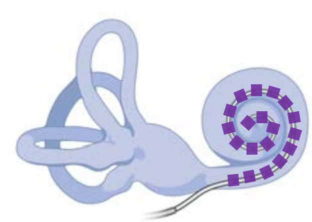
Advanced Bionics (AB)

Sequential or Paired?

90

Sequential stimulation (Optima-S)



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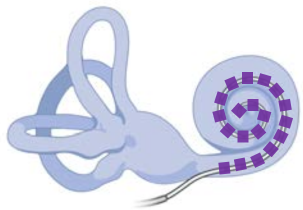
Paired stimulation (Optima-P)



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AB: switch to sequential stimulation

Reynolds & Gifford (2019). Int J Audiol, 58(6): 363-372.

- n = 10, within-subjects, repeated-measures design
  - Effect of strategy (HiRes, Fidelity120, and Optima)
  - Sequential vs. paired
- RESULTS: *For all strategies, sequential → significantly higher speech recognition in quiet, noise, and better sound quality.*

Holcomb et al. (2021). Audiol Neurotol. 2021 Jan 18;1-7.

- n= 17, within-subjects, repeated-measures design
- Significantly higher outcomes with sequential vs. paired
- All patients preferred Optima-S over Optima-P

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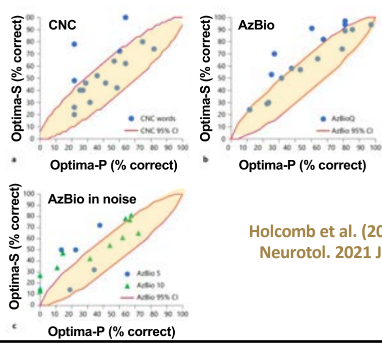


Holcomb et al. (2021). Audiol Neurotol. 2021 Jan 18;1-7.

94

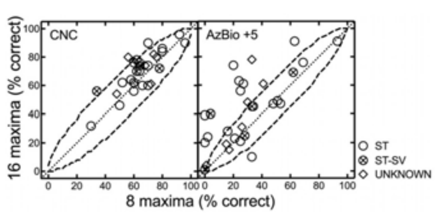
Cochlear

Increase # spectral maxima (n-of-m)

95

Cochlear: Try increasing maxima

Particularly for pre-curved electrode arrays



Berg et al. (2019). J Acoust Soc Am, 145(3): 1556-1564.

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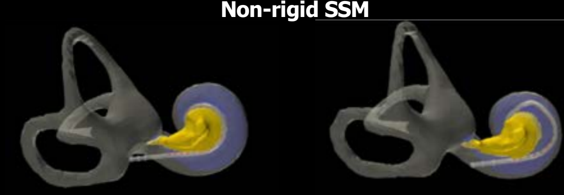
3D reconstruction
Non-rigid SSM



CI532
AVG electrode-to-modiolus distance: 0.13 mm

CI532
AVG electrode-to-modiolus distance: 0.6 mm

SV: blue, Modiolus: Yellow

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MED-EL

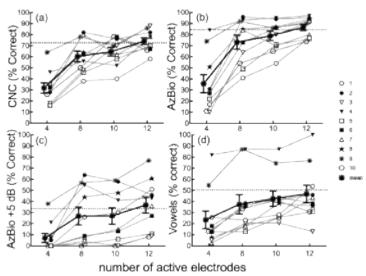
98

MED-EL: programming recommendations

- MCL levels → ESRTs
  - close to 1:1 relationship
- THR levels → aided thresholds ~25-30 dB HL
  - May need to adjust THR levels
  - Maplaw = 1000
- Volume default = 100%
  - Limited volume range: 90 to 100%
- If patient is still struggling, perhaps try switching to HDCIS

99

Berg et al. (2021). J Acoust Soc Am, 149(4): 2752–2763.



100

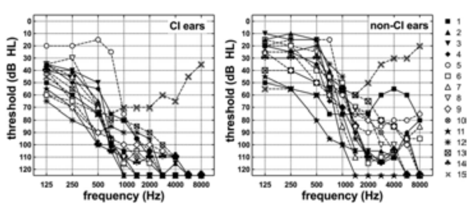
All devices

101

Manipulating CI bandwidth

Gifford et al. (2022). Hear Res, 2022 Jul 28, 108584, online ahead of print.

Investigated effects of CI bandwidth on speech recognition in 15 adult CI recipients with acoustic hearing preservation.



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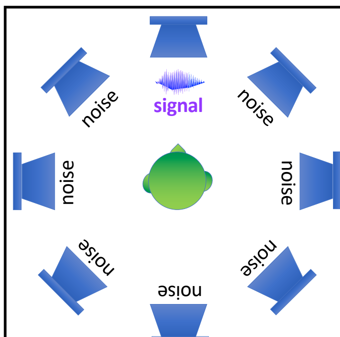


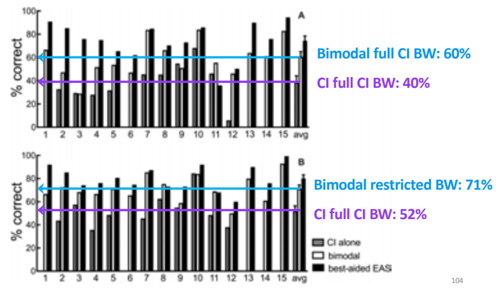
AzBio sentence recognition in noise (+5 dB SNR) $S_0N_{45\text{-}315}$

- CI alone
- Bimodal (CI + contra HA)
- Best-aided EAS (CI + bilateral HA)
  - Percent correct
  - Listening difficulty (VAS)

Gifford et al. (2022). Hear Res, 2022 Jul 28, 108584, online ahead of print.

103

Manipulating CI bandwidth



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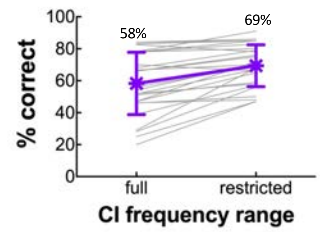
Bimodal listening condition



Gifford et al. (2017). Ear Hear, 38(5): 539-553.

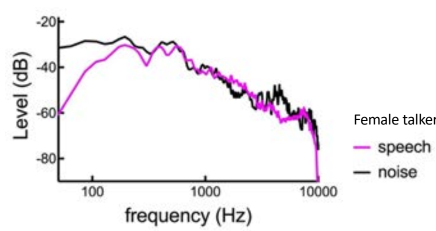
Gifford et al. (2022). Hear Res, 2022 Jul 28:108584.

105

Manipulating CI bandwidth

- For all manufacturers, if noise is highly problematic, try the following:
  - increase LF edge for E1
    - **AB:** 333 to 383 Hz for AB
    - **Cochlear:** 188 to 313 Hz (custom "FAT")
    - **MED-EL:** 100 to 150 (or 200) Hz
      - Gifford et al. (2017). Ear Hear, 38(5): 539-553.
      - Gifford et al. (2022). Hear Res, 2022 Jul 28:108584.
      - Fowler et al. (2016). J Speech Lang Hear Res, 59(1): 99-109.

106



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Assessing CI outcomes

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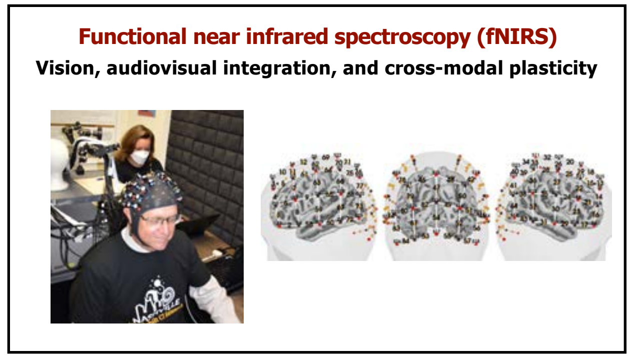

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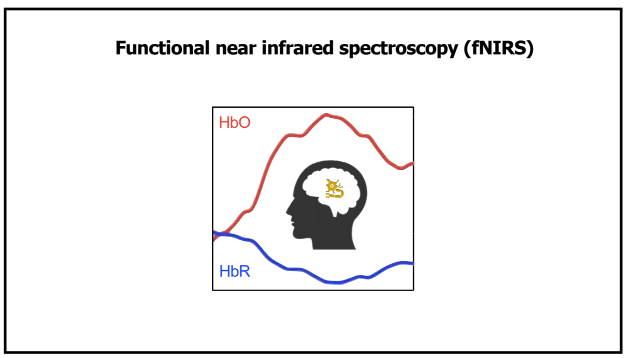

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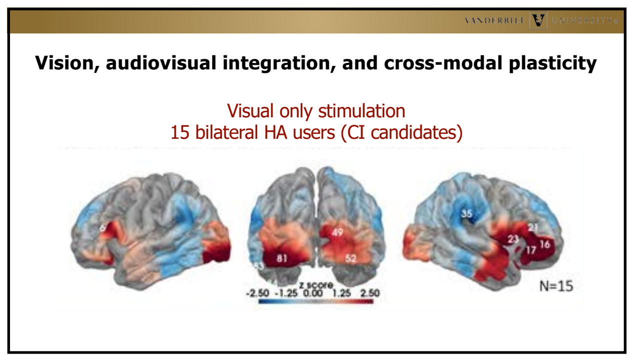

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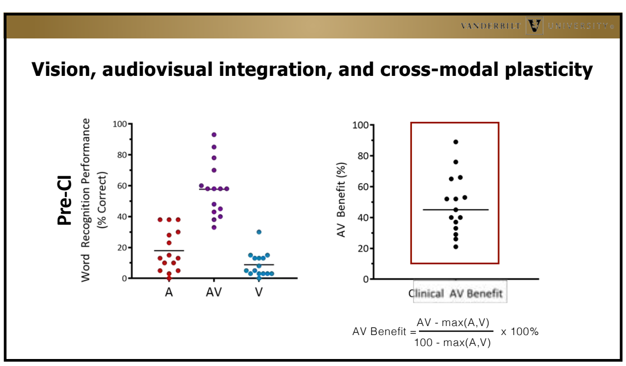

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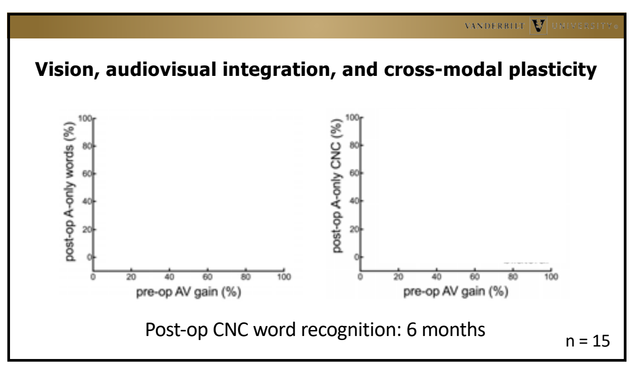

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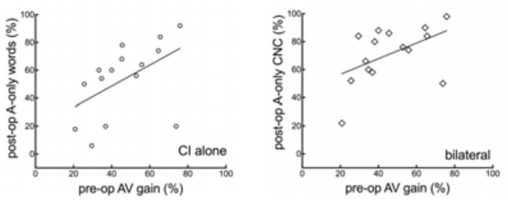
Vision, audiovisual integration, and cross-modal plasticity



r = 0.50, p = 0.06

r = 0.49, p = 0.06

n = 15

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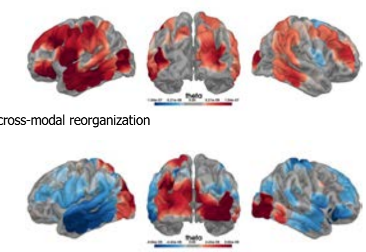

n = 1

cross-modal reorganization

n = 1

NO cross-modal reorganization

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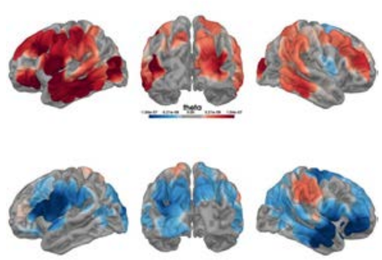
pre-op



post-op
3 months

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Summary

- **CIs are highly effective, but highly variable outcomes**
  - So many variables and CI parameters can impact outcomes
    - Easiest & "free" way to improve outcomes across lifespan
      → *increase CI wear time*
- **Current clinical practices = auditory only measures**
  - Pre-op auditory scores offer limited prognostic value
    - Additional factors having potential for clinical value
      - V & AV processing
      - crossmodal plasticity (pre- and post-op)
- **Otology & audiology: *one-size-fits-all* approach to device selection, surgical insertion, & programming**
  - *IGCIP & development changes (children) → significant improvement over time*
  - Improvement in spectral resolution correlated with downstream effects on speech perception, speech production, phonological processing, and literacy

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Future Considerations

- **Additional or different pre- and post-op assessments (e.g., AV, cross-modal reorganization)**
  - Better understanding of overall outcomes & variability
  - Ecological validity
  - *Possible prognostic value*
- **Individualized CI programming based on scalar electrode location and possibly baseline auditory perception on tasks of spectral resolution**
  - Significant improvements for auditory, speech, and literacy
  - Parent reports

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Questions? Comments?

rene.gifford@Vanderbilt.edu

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