Maternal speech predicts language outcomes in children with cochlear implants:

Results from a 10-year study

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- Dr. Laura Dilley is an Associate Professor, and Elizabeth Wieland is a Ph.D. student, at **Michigan State University**.
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A multi-university collaboration

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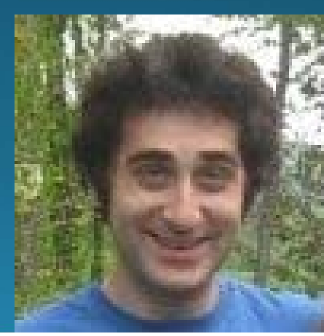
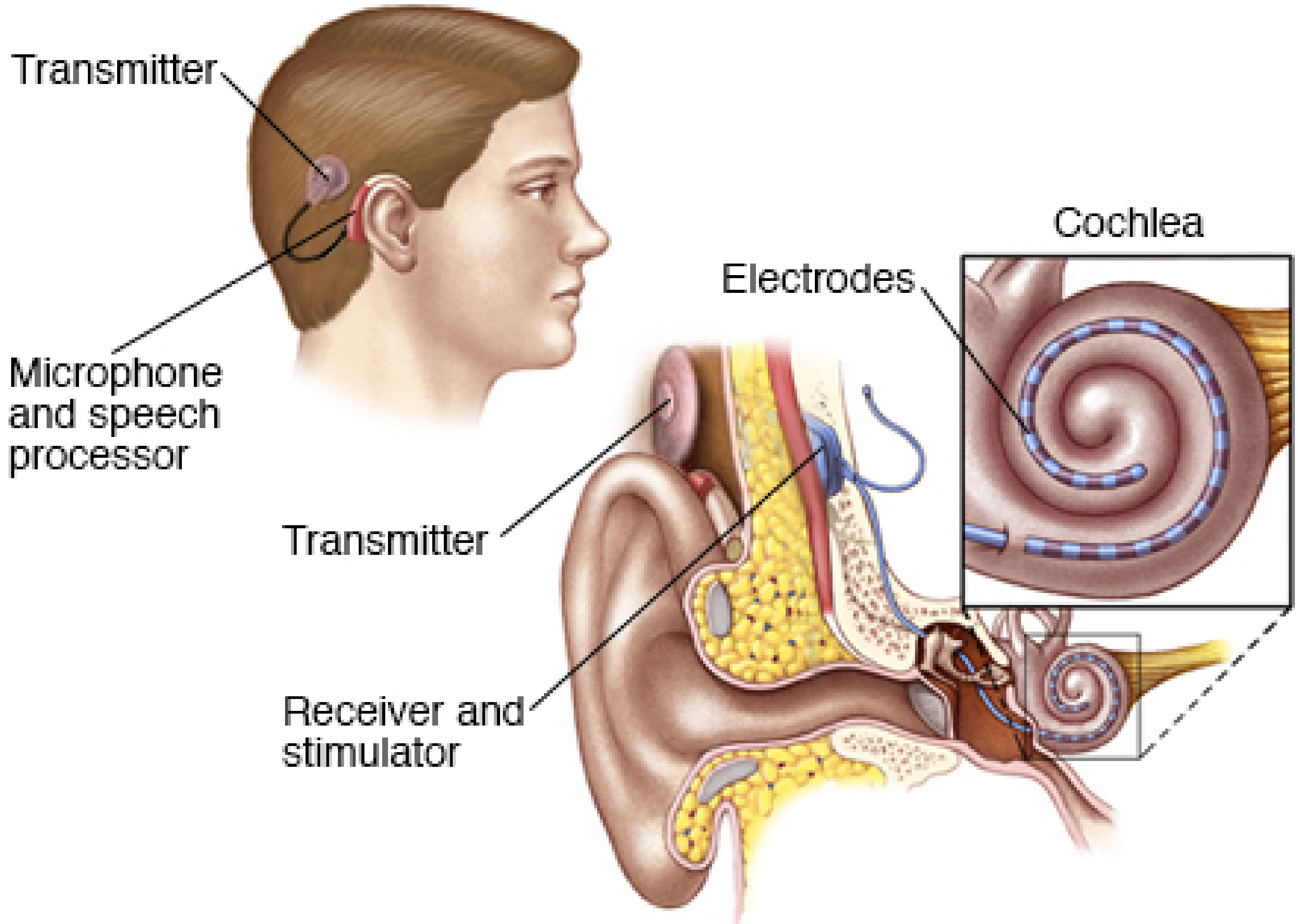


Dr. Matt Lehet

Children's learning of language

Children with cochlear implants


Transmitter
Microphone and speech processor
Cochlea
Electrodes
Transmitter
Receiver and stimulator

Infant directed (ID) speech draws infants' attention

- ID speech assists typical infants with word segmentation and word learning (Thiessen et al., 2005)
- This may ultimately drive word learning (Singh et al., 2009; Ma et al., 2011)

Preferential Attention to IDS → **Increased segmentation of words** → **Word learning**

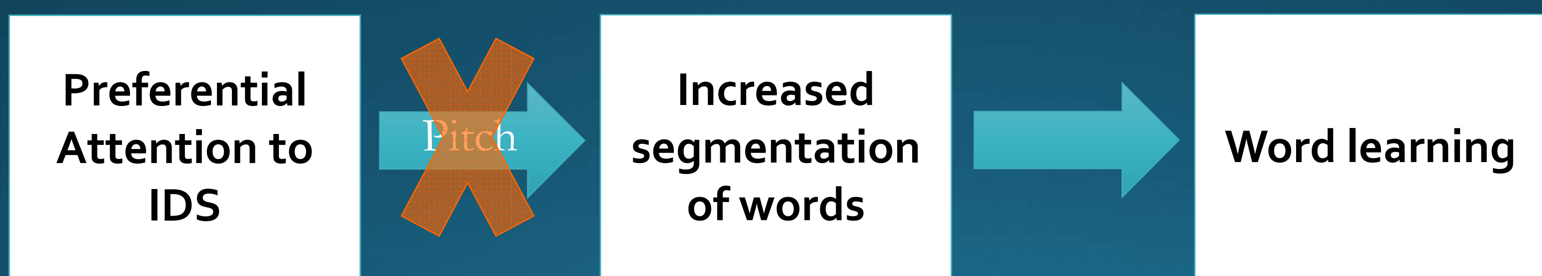
Children with CIs may not benefit from ID speech to the same extent…

- Prosodic cues – especially pitch cues and pitch variability – drive attention towards IDS (Fernald & Kuhl, 1987; Houston & Bergeson, 2014; Segal & Newman, 2015)

Preferential Attention to IDS $\xrightarrow{\text{Pitch}}$ **Increased segmentation of words** $\rightarrow$ **Word learning**

Children with CIs may not benefit from ID speech to the same extent…

- CI use impacts pitch perception particularly severely, and therefore possibly reduce attention to speech (McDermott, 2004; Oxenham, 2008; Wild et al., 2012
- Infants with CIs show reduced attention to speech, compared with normal-hearing children (Horn et al., 2007; Houston & Bergeson, 2014; Houston et al., 2003)



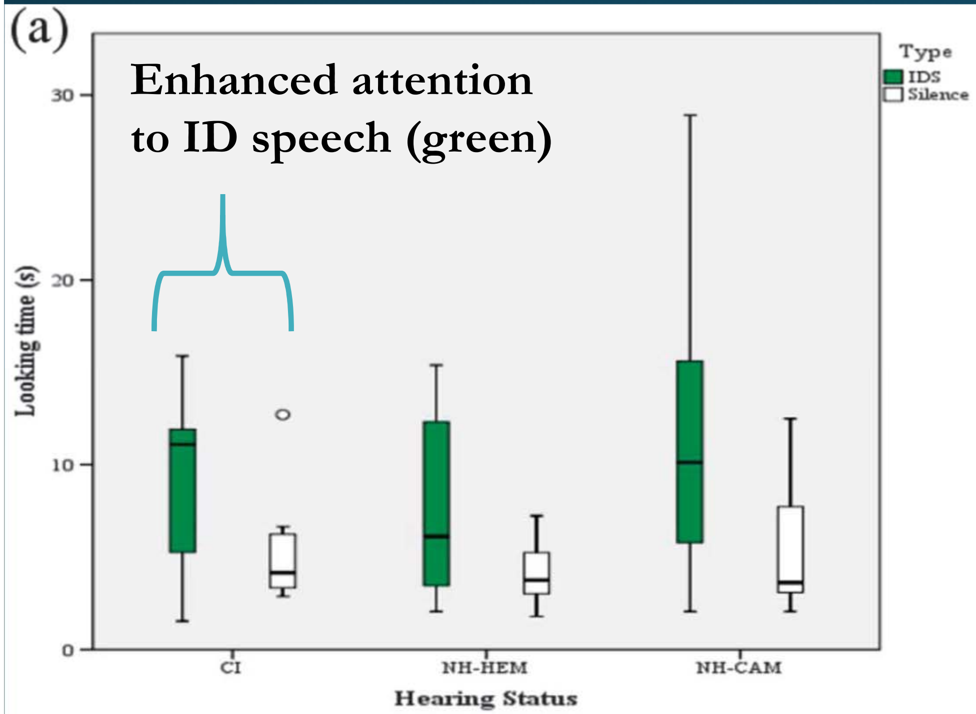
Other qualities of ID speech may still provide benefit to children with CIs

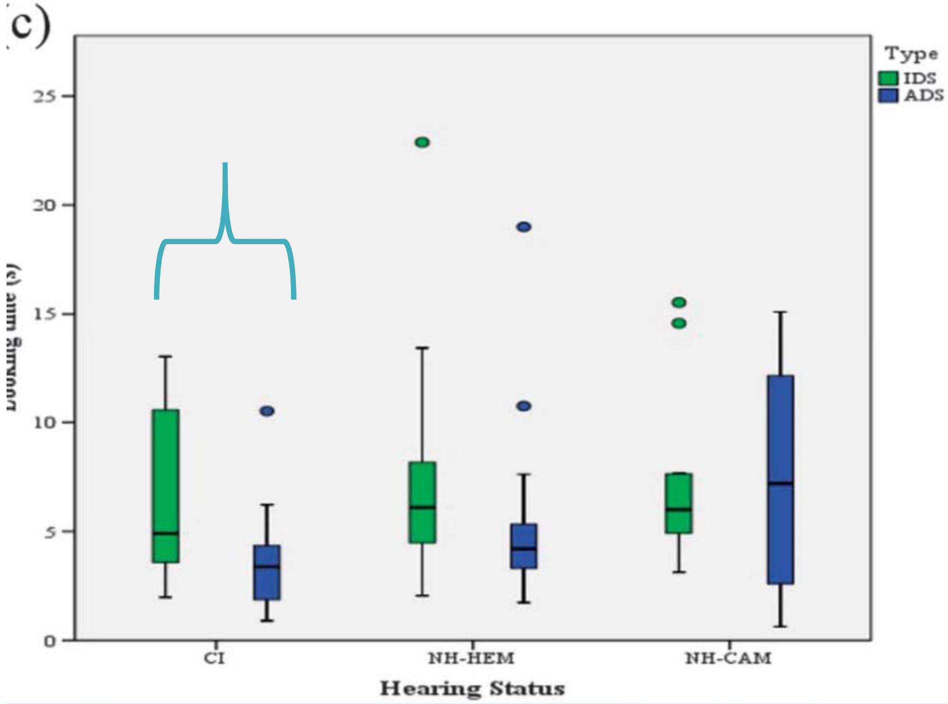
- **Vowel space area and vowel dispersion both distinguish IDS from ADS** (Kuhl et al., 1997; Burnham et al., 2002; Liu et al., 2003; Tsao et al., 2004; McMurray et al., 2013; Martin et al., 2015; Burnham et al., 2015; Wieland et al., 2015; Aadrians & Swingley, 2017)

- **Speech rate** (Fernald & Simon, 1984; Cooper & Aslin, 1990; Zangl et al., 2005; Song et al., 2010;)

Infants with CIs *prefer* ID speech

(Wang, Bergeson, & Houston, 2017, *JSLHR*)





History of the corpus

- ~10 years of maternal recordings and speech-language outcome measures collected at Indiana University Devault Otologic Research Lab
- Recordings and outcomes collected 2003 - 2012
- N =~ 65 dyads of children with CI's and mothers participated in part or all of study protocol
- **N = 40 dyads** had both recordings and clinical outcomes that could be included in the present analysis

Longitudinal visits

- Children and parent(s) visited the lab one or more times
- Visits at:
  - 6 months pre-implantation
  - At implantation (Time "0")
  - Every 6 months post-implantation
    - 0.5 yr, 1 yr, 1.5 yr, 2 yr, 2.5 yr, 3 yr, 3.5 yr, 4 yr … 9 yr
- At each, recordings made and/or measures taken

Clinical outcome measures

- Peabody Picture Vocabulary Test (**PPVT**)
- Preschool Language Scales (**PLS**)
- Reynell Developmental Language Scales (**RDLS**)
  - Receptive (“RDLS-r”)
  - Expressive (“RDLS-e”)
- Lots of missing data across participants makes this a complicated data set

Clinical outcome measures:
Challenges of missing data

	Post-implantation interval															
	1;0				1;6				2;0				2;6			
	PPVT	PLS	RDLS r	RDLS-e	PPVT	PLS	RDLS-r	RDLS-e	PPVT	PLS	RDLS-r	RDLS-e	PPVT	PLS	RDLS-r	RDLS-e
Child 1	53		23	29		79			86		17	25	89			
Child 2		87			54				73	71				81		
Child 3		67			69		27	39					89		32	45

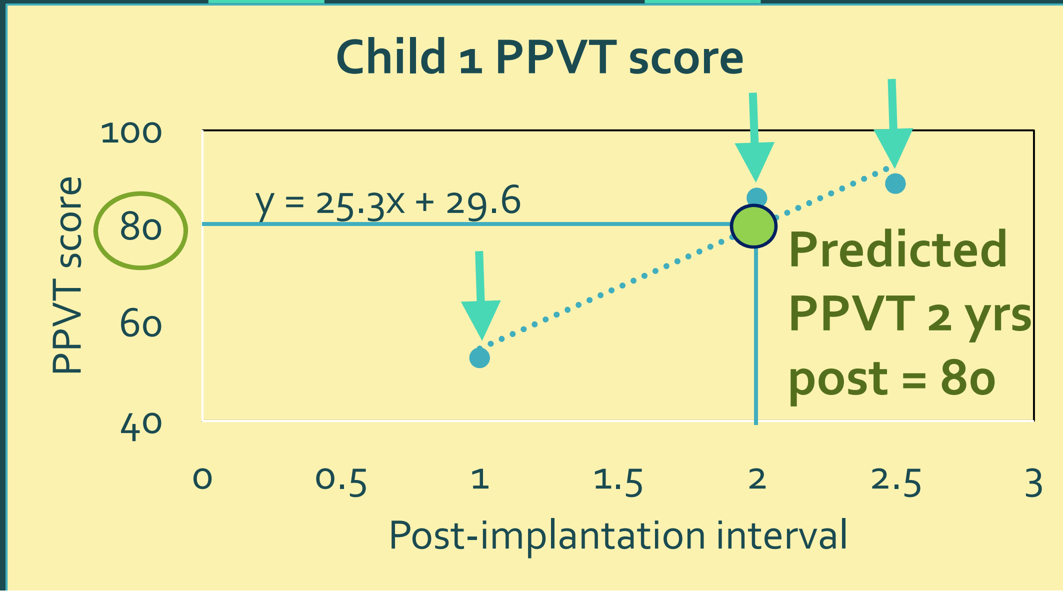
Clinical outcome measures: Challenges of missing data

	Post-implantation interval															
	1;0				1;6				2;0				2;6			
	PPVT	PLS	RDLS r	RDLS-e	PPVT	PLS	RDLS-r	RDLS-e	PPVT	PLS	RDLS-r	RDLS-e	PPVT	PLS	RDLS-r	RDLS-e
Child 1	53		23	29		79			86		17	25	89			

Clinical outcome measures:
Challenges of missing data

	Post-implantation interval															
	1;0				1;6				2;0				2;6			
	PPVT	PLS	RDLS r	RDLS-e	PPVT	PLS	RDLS-r	RDLS-e	PPVT	PLS	RDLS-r	RDLS-e	PPVT	PLS	RDLS-r	RDLS-e
Child 1	53		23	29		79			86		17	25	89			

Post-implantation interval	PPVT score
1;0	53
2;0	86
2;6	89



How does the acoustic measures predict clinical outcomes?

- Goal: Determine how well speech-related factors (segmental, suprasegmental) predict clinical outcome measures

Approach

- Calculate segmental and suprasegmental phonetic measures across 3, 6, and 12 month intervals after first CI stimulation
- Use these phonetic measures as predictors of outcomes at 2 years

Research *novelty* in examining how characteristics of speech input to children with cochlear implants influences their clinical outcomes.

Prior research has focused on CI device factors, communication mode, etc. (e.g., Geers et al., 2000; Kirk, Miyamoto, Ying, Perdew, & Zuganelis, 2003; Tomblin, Barker, Spencer, Zhang, & Gantz, 2005)

Quality vs. quantity of speech

Hypothesis: Individual differences in speech *input* to children with CIs affect speech-language *outcomes*.

How well does a mother's speech ***quality*** predict her child's speech-language outcomes? …***quantity***?

Quality and quantity: Hypotheses

Individual differences exist, such that mothers who produce…

*….*higher *quality* speech…

OR ….a higher *quantity* of speech…

…will have children who achieve better speech-language outcomes.

Predicted *correlations* between quality and quantity measures and outcome scores.

Quality and quantity measures

- Quality
  - Segmental (i.e., phonemic): *Vowel triangle area, vowel space dispersion*
  - Suprasegmental (i.e., prosodic): *Pitch median, variability, rate*
- Quantity
  - Estimated words per 1 minute of dyadic interaction

Quality measures: Acoustical analysis of pitch, rate and vowels

- Pitch (“fundamental frequency”) measurement was very accurate due to use of hand-analysis
- For pitch, *median* and (semi-interquartile) *range* were used since distributions were asymmetric
- Speech rate measured in syllables per second
- Vowel formant frequencies F1, F2 measured by hand

Quality measures: Acoustical analysis of vowels

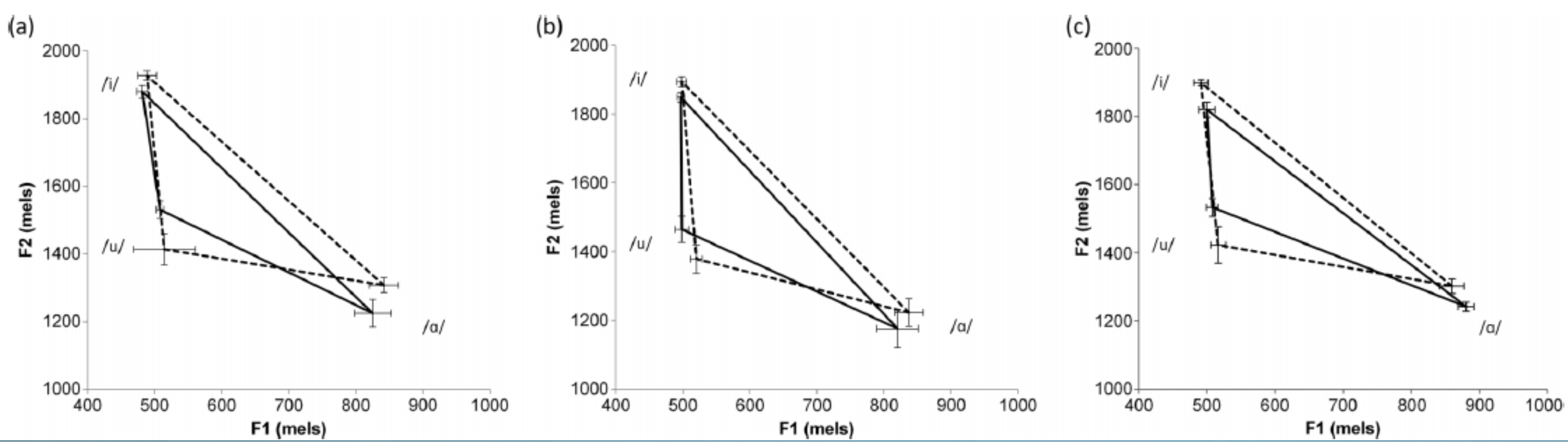
- Used spontaneous speech, so lexical items and token counts unpredictable
- Signal challenges (background noise, simultaneous infant vocalizations, etc.)
- Tokens must be reasonably “prominent” for good formant resolution
- Coarticulation with variable segmental contexts

Quality measures: Acoustical characterization of vowel *space*

- Vowel "triangle" areas in F1, F2 space
  - First (F1) and second (F2) formants for /i,ɑ,u/
  - Area difference (ID – AD) predicts perceptual sensitivity and language outcomes (Liu, Kuhl & Tsao; Hartman, Ratner & Newman, 2016)
- Vowel formant dispersion

Wieland, Burnham, Kondaurova, Bergeson & Dilley, 2015, *JSLHR*

Figure 1. Infant-directed (dashed line) and adult-directed (solid line) vowel space triangles that are based on average first formant (F1) and second formant (F2) values for speech to (a) participants with hearing impairment fitted with cochlear implants, (b) chronological-age matches with normal hearing, and (c) hearing-experience matches with normal hearing. Error bars show mean ± 1 *SEM*.



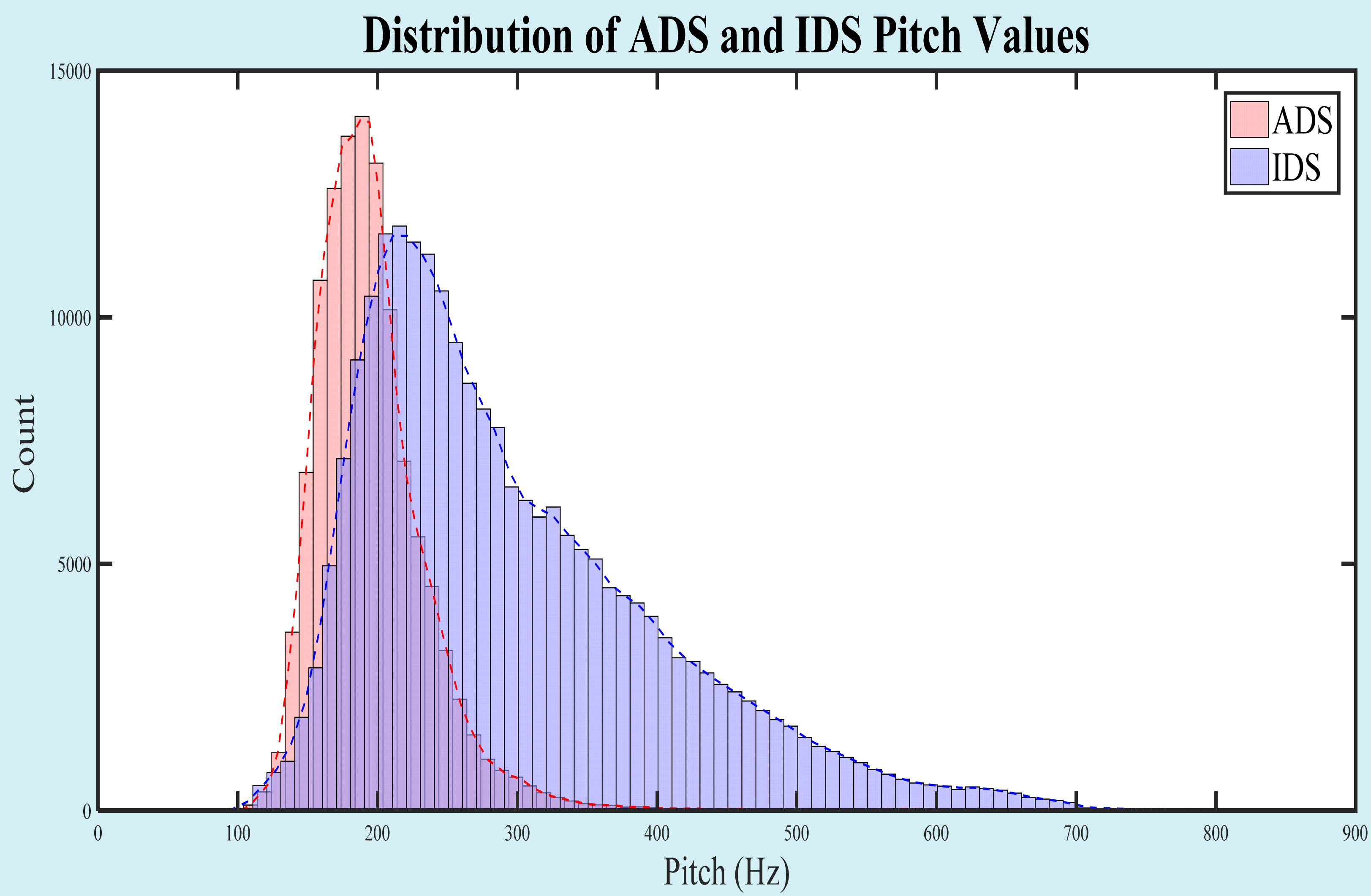
Quantity measure

- Mother-infant recording sessions varied in length
- Two minutes of audio analyzed for each mother at each clinical session
- Quantity measure = Estimated number of words produced per one minute of mother-infant interaction

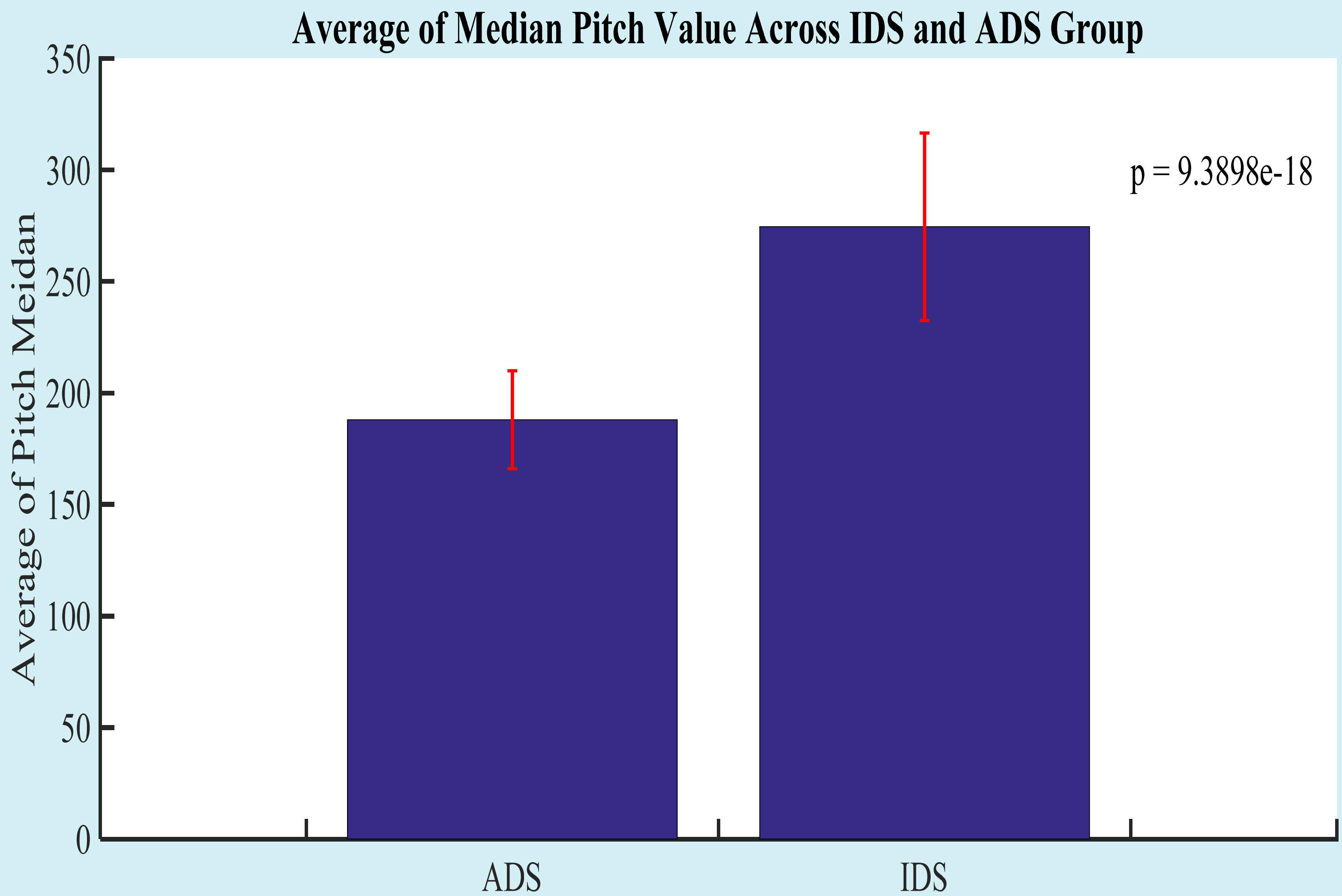
Results: Quality measures by addressee condition (ID vs. AD)

Mothers as a group produced acoustic-prosodic modifications in their speech to their children (ID speech) compared to how they talked to other adults (AD speech).

This is consistent with prior results.



Distribution of ADS and IDS Pitch Values
15000
10000
5000
0
Count
0
100
200
300
400
500
600
700
800
900
Pitch (Hz)
ADS
IDS


Average of Median Pitch Value Across IDS and ADS Group
Average of Pitch Meidan
350
300
250
200
150
100
50
0
p = 9.3898e-18
ADS
IDS

Quality measures: "Normalized" pitch parameters

- Size of person affects pitch
  - Shorter, smaller mothers have higher pitch than taller, larger mothers
- *Expressive variability* separated from variability due to size by comparing a mother's ID with her AD speech

Quality measures: "Normalized" pitch parameters

- **Pitch median** (ID median normalized by AD median)

  [Median in ID / Median in AD]

- **Pitch variability** ("normalized coefficient of variation")

  [(IQR of ID Fo values *normalized for AD median*) / ID median]

Quality measures: How well did they correlate with one another?

- ID speech compared to AD speech
  - Higher, more variable pitch in ID speech
  - Slower rate in ID speech
  - More “exaggerated” vowels in ID speech

Quality measures: How well did they correlate with one another?

- To what extent were different measures of ID speech /quality related?
  - Reframed: To what extent were there significant <u>*correlations*</u> *across mothers* of the various measures of ID speech "quality" with one another?
  - Or, did statistically reliable *individual differences* exist across mothers?

Quality measures: ID correlations

- Significantly ***correlated*** :
  - Pitch *median* and *variability* (strong effect, $r = -.67$, $^{**}p < .001$)
  - Pitch *median* and speech *rate* (strong effect, $r = .50$, $^{**}p < .001$)
  - Pitch *variability* and speech *rate* (moderate effect, $r = .32$, $^{**}p < .01$)
- Statistically ***uncorrelated***:
  - Suprasegmental (i.e., prosodic) measures and vowel measures ($|r| < .25$, p's $> .16$). Exception: pitch variability vs. vowel dispersion (moderate effect, $r = .36$, $^{*}p < .05$)
  - Vowel triangle area and vowel dispersion ($r = .01$, $p = .99$, ns)

Quality measures: ID correlations

- Suprasegmental measures of quality were *highly correlated*
  - Mothers producing greater difference in pitch to their child compared with AD speech sustained ID high pitch more consistently

Quality measures: ID correlations

- Segmental and suprasegmental measures of quality were largely *uncorrelated*
- Vowel triangle area and vowel dispersion (both segmental measures) were *uncorrelated*
  - Lack of correlation implies these are independent dimensions of individual variation

Hypotheses

Individual differences exist, such that mothers who produce…

….higher *quality* speech…

OR ….a higher *quantity* of speech…

…will have children who achieve *better speech-language outcomes*.

Predicted *correlations* between quality and quantity measures and outcome scores.

Individual differences in maternal speech

Predictors vs. predicted outcomes

- Correlation matrix showed which correlated quality measures explained the most variance; these were used as predictors
- Statistical approach:
  - Selected predictors of outcomes subjected to backward elimination in SPSS
  - Predictors surviving backward elimination were used for statistical modeling in R software

Predictors vs. predicted outcomes

- Quality measures
  - Pitch median (normalized)
  - Pitch variability (normalized coeff. of variation)
  - Speech rate (syls/second)
  - Vowel triangle area difference (ID – AD)
  - Vowel dispersion
- Quantity measure
  - Word quantity per minute of mother-infant interaction

To what extent does a caregiver's *quality* of ID speech statistically predict clinical outcomes in her child with a CI?

To what extent does a caregiver's *quality* of speech vs. her *quantity* of speech matter for her child's outcome?

A note about effect sizes

Pearson's *r* correlation coefficient: $0 \leq |r| \leq 1$

$|r| \cong 0$ no correlation / no predictive relationship

$|r| \cong .30$ *weak* correlation / *weakly* predictive

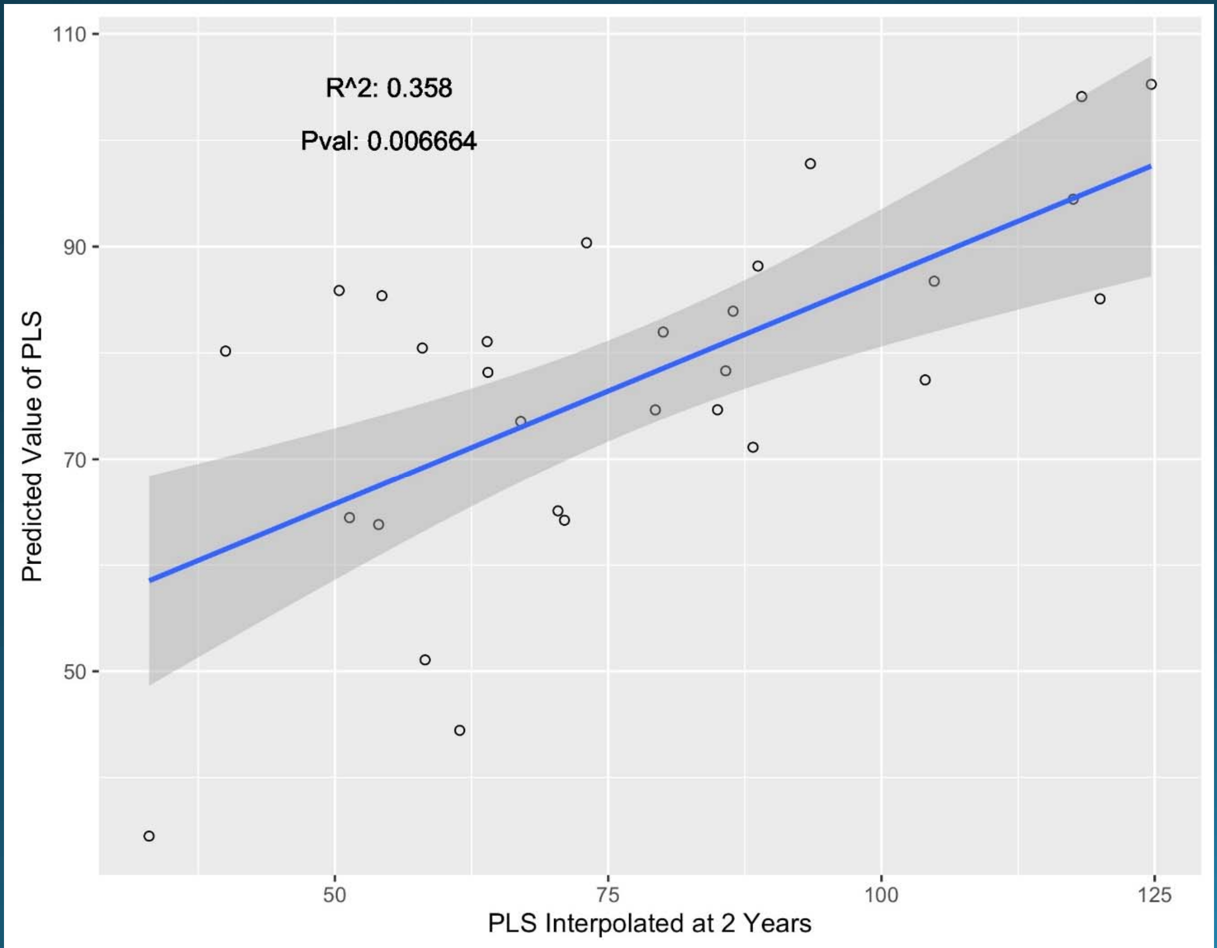
$|r| \cong .50$ *moderate* correlation / *moderately* predictive

$|r| \cong .70$ *strong* correlation / *strongly* predictive

PLS: Input vs. outcome measures

- Characteristics of mother's speech to her child with a CI spoken at 3 – 12 mos post-implantation ***significantly predicted child's PLS scores** at 2 years*!
- Speech predictor results:
  - *Quantity* of words in 1 minute (**p <.01)
  - ID speech rate (a *quality* measure) (*p < .05)
  - Vowel dispersion (a *quality* measure) (p = .13, NS)

Quantity of maternal speech and *quality* of speech (slower speech rate) between 3-12 mos post-implantation ***significantly predicted PLS scores*** in children with CIs at 2 years post.



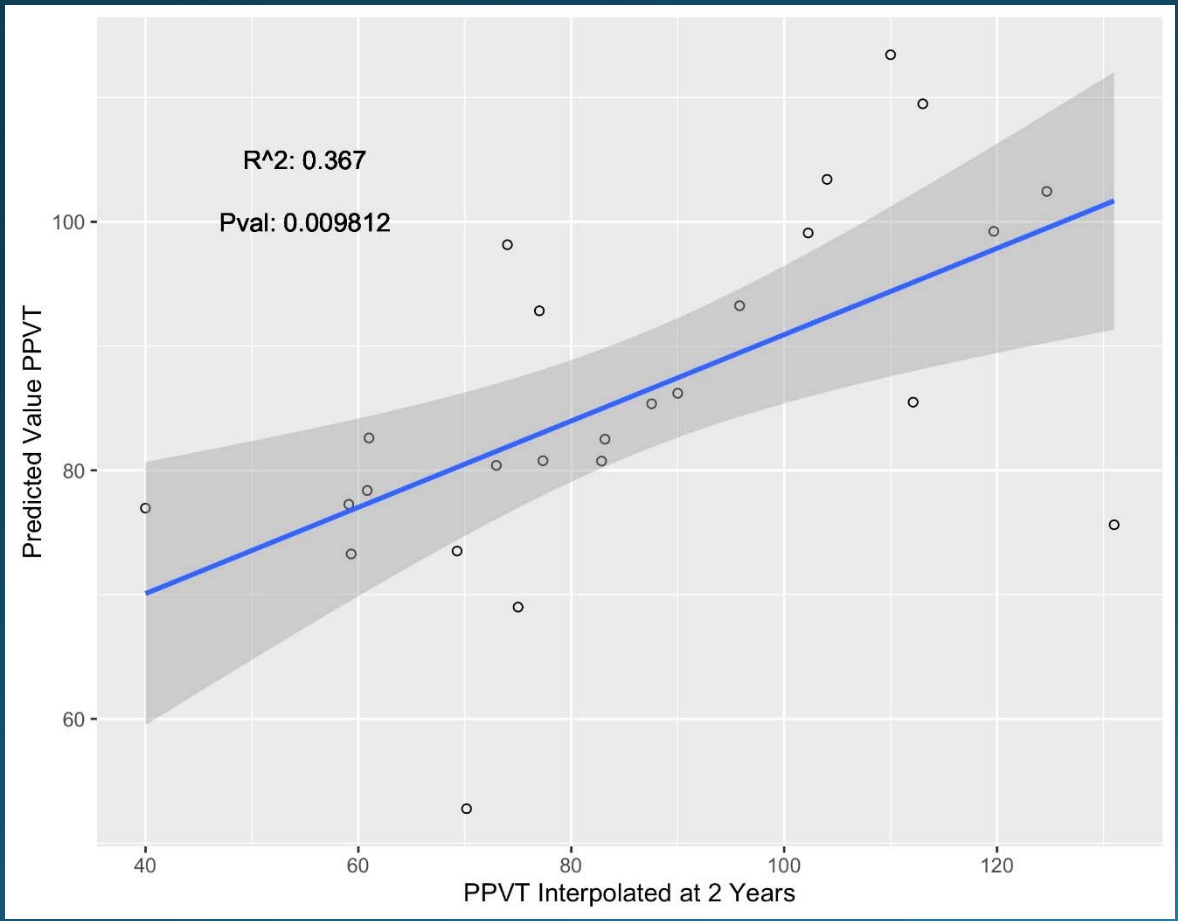
r = 0.60

-*Quality* and *quantity* of mother's speech were associated with ***moderately strong*** effects on PLS!

PPVT: Input vs. outcome measures

- Characteristics of mother's speech to her child with a CI spoken at 3 – 12 mos post-implantation <u>*significantly predicted child's PPVT*</u> *scores at 2 years*!
- Speech predictor results:
  - <u>*Quantity*</u> of words in 1 minute (***p* <.01)
  - Vowel dispersion (a <u>*quality*</u> measure) (*p* = .12, NS)

Quantity of maternal speech between 3-12 mos post-implantation ***significantly predicted PPVT scores*** in children with CIs at 2 years post.



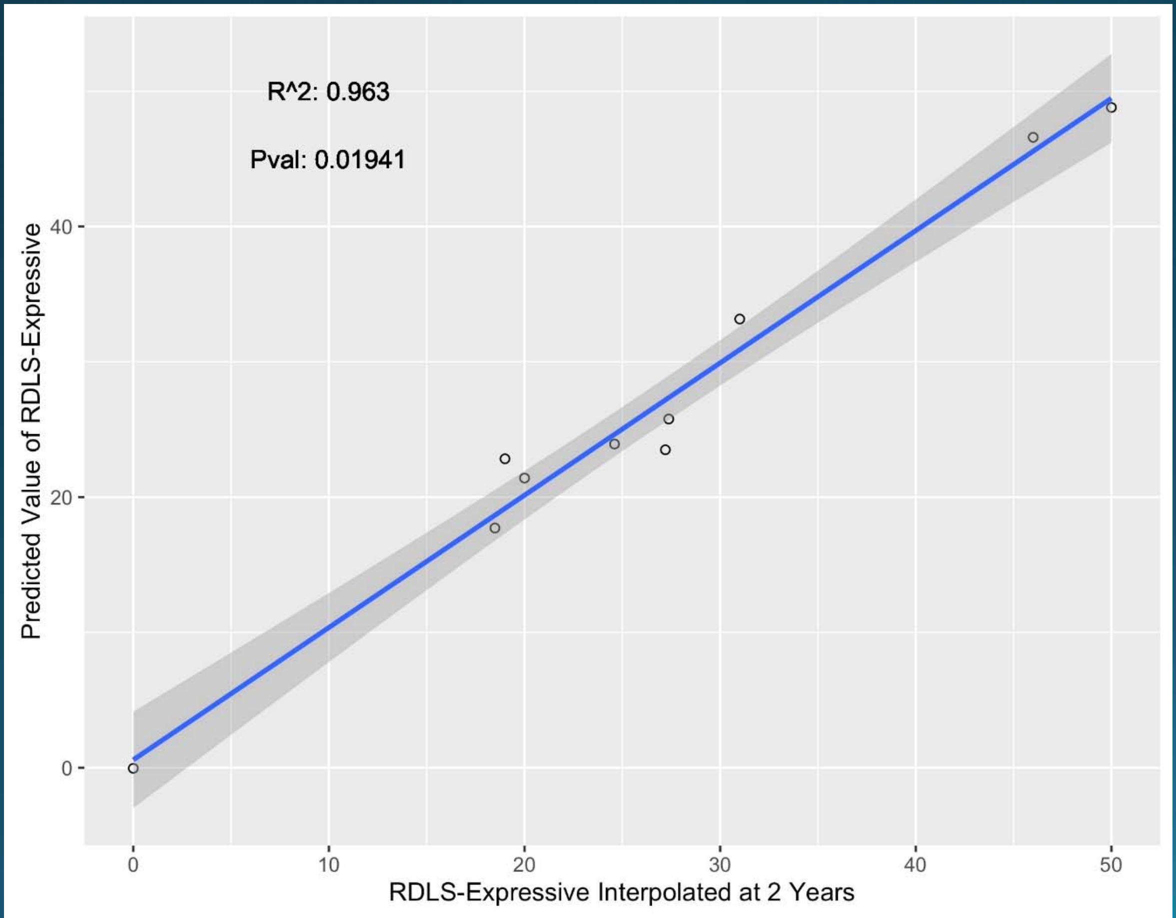
$r = 0.61$

-Quantity of mother's speech was associated with ***moderately strong*** effects on PPVT!

RDLS expressive: Input vs. outcome measures

- Characteristics of mother's speech to her child with a CI spoken at 3 – 12 mos post-implantation *significantly predicted child's RDLS expressive scores at 2 years*!
- Speech predictor results:
  - Vowel dispersion (a *quality* measure) (**p < .001)
  - *Quantity* of words in 1 minute (**p* <.02)
  - Pitch variability (a *quality* measure) (*p* = .26, NS)

Quality of maternal speech (vowel dispersion) and *quantity* of speech between 3-12 mos post-implantation ***significantly predicted RDLS expressive scores*** in children with CIs 2 years post.



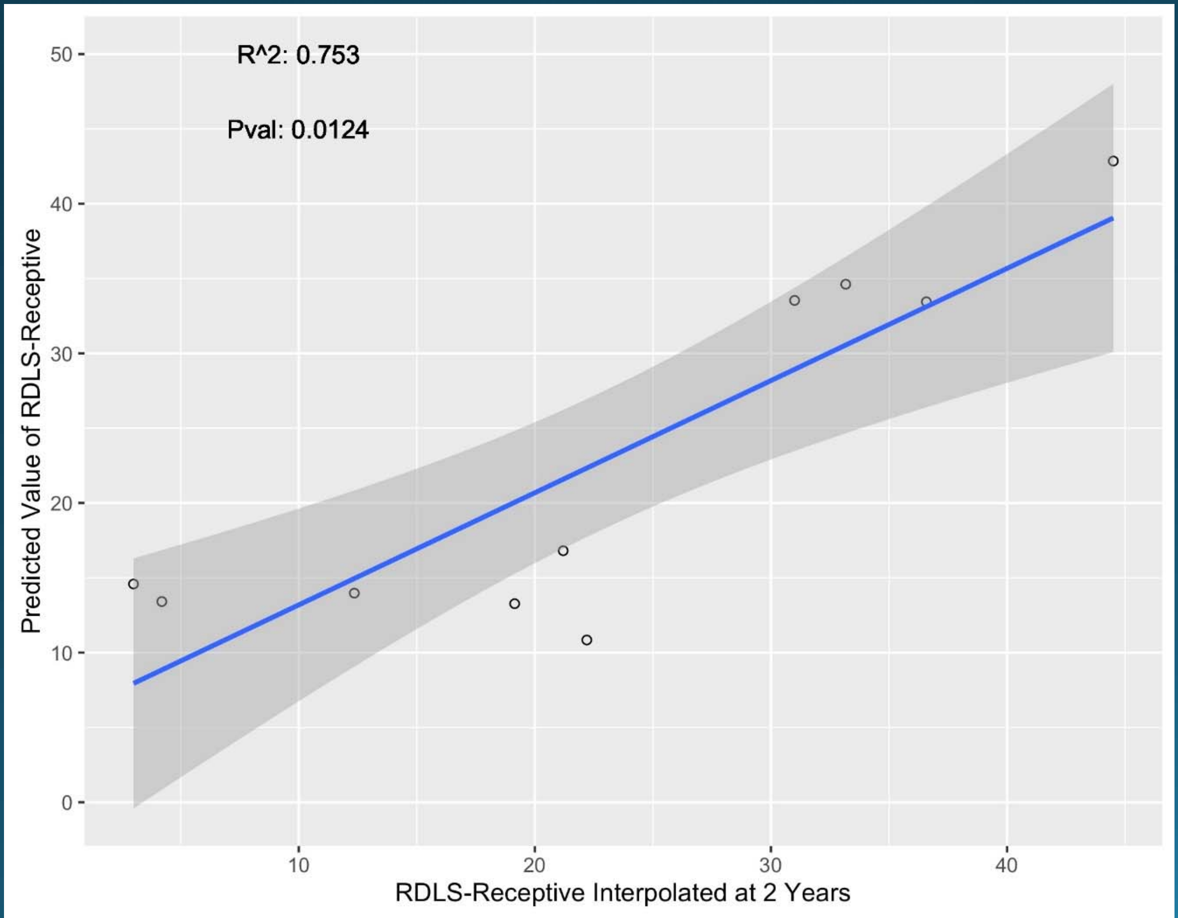
r = 0.98

-Quality and quantity variables of mother's speech were associated with ***very strong*** (i.e., whopping) effects on RDLS expressive scores.

RDLS receptive: Input vs. outcome measures

- Characteristics of mother's speech to her child with a CI spoken at 3 – 12 mos post-implantation *significantly predicted child's RDLS receptive scores at 2 years*!
- Speech predictor results:
  - Vowel triangle area (a *quality* measure) (*$p < .02$)
  - Pitch variability (a *quality* measure) ($p = .26$, NS)

Quality of speech (vowel triangle area difference) between 3-12 mos post-implantation *significantly predicted RDLS receptive scores* in children with CIs at 2 years post.



$r = 0.87$

-Quality of mother's speech was associated with a ***strong*** effect on RDLS receptive scores.

Summary

- Infant-directed (ID) speech has distinctive properties relative to adult-directed (AD) speech
  - Expanded, more dispersed vowel space; higher, more variable pitch; slower speech rate
- Infant-directed (ID) speech draws infants' attention and fosters language development in children with normal hearing
  - Quality and quantity of speech is important
- Unclear whether children with CIs would benefit from ID speech

Summary

- ~10 years worth of data from a multi-university, NIH-funded study
- Focus: To what extent does caregivers' speech to children with CIs statistically predict speech-language outcomes?
- Examined individual differences across mothers in how they talked to their child with a CI
  - Quality measures
  - Quantity measures

Summary

- Individual differences in how mothers talked to their child with a CI were highly predictive statistically of child's speech-language outcomes!
  - PPVT, PLS, *and* RDLS expressive/receptive!
- Both *quality* and *quantity* of ID speech statistically predicted child scores 2 yrs post
- Provides evidence for interventions with caregivers that by producing a lot of "high-quality" speech to their child with a CI, they will foster good outcomes!

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Pitch analysis methods

- Automatic measures of fundamental frequency (Fo) are unreliable, especially in ID speech
- Analysts examined pitch tracks for 2 minutes of ID speech at 3m and 6m post-implantation (~4 min total)
- Marked stretches of *modal* voicing in speech
  - Avoided voicing irregularity
- Specified Fo parameters to obtain good tracking
  - Min Fo of estimate, Max Fo of estimate, silence threshold, voicing threshold
- Finally, automatic extraction of Fo values

Measurement and analysis: Vowel space measures

$$\text{Area} = \frac{|(F1_i \times (F2_a - F2_u) + F1_a \times (F2_u - F2_i) + F1_u \times (F2_i - F2_a|)}{2}.$$

Appendix

Vowel Space Dispersion Calculations

First, the centroid (C) of each speaker-condition vowel space triangle was calculated using the formula:

$$\mathrm{C} = \left(\frac{F1_a + F1_i + F1_u}{3}, \frac{F2_a + F2_i + F2_u}{3}\right),$$

where /i/, /ɑ/, and /u/ were the corners of each vowel space triangle and $F1$ and $F2$ were the x and y coordinates of each of the corners.

Next, the Euclidean distance ($|d|$) of each token from the centroid was calculated using the formula:

$$|d| = \sqrt{(F1_C - F1_t)^2 + (F2_C - F2_t)^2},$$

where $F1_C$ and $F2_C$ were the x and y coordinates, respectively, of the centroid and $F1_t$ and $F2_t$ were the first and second formant values, respectively, for the token in question.

Last, the vowel space dispersion (D) was calculated as the ratio of the Euclidean distances ($|d|$) of each token from the centroid of the triangle to the number of tokens (n) using the formula:

$$D = \frac{\sum |d|}{n}.$$