Maternal speech predicts language outcomes in children with cochlear implants: Results from a 10-year study

Laura Dilley\textsuperscript{1}, Ph.D.
Elizabeth Wieland\textsuperscript{1}, M.S.
Yuanyuan Wang\textsuperscript{2}, Ph.D.
Jessa Reed\textsuperscript{2}, Ph.D.
Tonya Bergeson\textsuperscript{3}, Ph.D.
Derek Houston\textsuperscript{2}, Ph.D.

\textsuperscript{1}Michigan State University \textsuperscript{2}Ohio State University \textsuperscript{3}Butler University
Disclosures

• Dr. Laura Dilley and Dr. Derek Houston gratefully acknowledge research funding from the National Institutes of Health.
• Dr. Laura Dilley gratefully acknowledges research funding from the National Science Foundation.
• Dr. Laura Dilley is an Associate Professor, and Elizabeth Wieland is a Ph.D. student, at Michigan State University.
• Dr. Tonya Bergeson is Assistant Professor at Butler University.
• Dr. Derek Houston is an Associate Professor and Dr. Yuanyuan Wang and Dr. Jessa Reed are post-doctoral research associates at the Ohio State University.
A multi-university collaboration

Dr. Tonya Bergeson

Elizabeth Wieland, M.S.

Dr. Derek Houston

Dr. Yuanyuan Wang

Dr. Jessa Reed

Meisam K. Arjmandi, M.S.

Dr. Matt Lehet
Children’s learning of language
Children with cochlear implants
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)
Children with CIs may not benefit from ID speech to the same extent...

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)

Enhanced attention to ID speech (green)
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

<table>
<thead>
<tr>
<th></th>
<th>Post-implantation interval</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1;0</td>
<td>1;6</td>
<td>2;0</td>
<td>2;6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPVT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PLS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDLS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDLS-e</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Child 1</td>
<td>53</td>
<td>79</td>
<td>86</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Child 2</td>
<td>87</td>
<td>54</td>
<td>73</td>
<td>81</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Child 3</td>
<td>67</td>
<td>69</td>
<td>71</td>
<td>32</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Clinical outcome measures: Challenges of missing data

<table>
<thead>
<tr>
<th>Child 1</th>
<th>PPVT</th>
<th>PLS</th>
<th>RDLS</th>
<th>RDLS-e</th>
<th>PPVT</th>
<th>PLS</th>
<th>RDLS</th>
<th>RDLS-e</th>
<th>PPVT</th>
<th>PLS</th>
<th>RDLS</th>
<th>RDLS-e</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>53</td>
<td>23</td>
<td>29</td>
<td></td>
<td>79</td>
<td></td>
<td></td>
<td></td>
<td>86</td>
<td>17</td>
<td>25</td>
<td>89</td>
</tr>
</tbody>
</table>
# Clinical outcome measures: Challenges of missing data

<table>
<thead>
<tr>
<th>Post-implantation interval</th>
<th>1;0</th>
<th>1;6</th>
<th>2;0</th>
<th>2;6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PPVT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PLS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RDLS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RDLS-e</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Child 1</strong></td>
<td>53</td>
<td>23</td>
<td>29</td>
<td>79</td>
</tr>
</tbody>
</table>

### Predicted PPVT Score

\[ y = 25.3x + 29.6 \]

**Predicted PPVT 2 yrs post = 80**
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, a, 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
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

- ADS
- IDS

Pitch (Hz)

Count
Average of Median Pitch Value Across IDS and ADS Group

p = 9.3898e-18
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 *correlations 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 variablity (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: $0 \leq |r| \leq 1$

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

$|r| \approx .30$ weak correlation / weakly predictive

$|r| \approx .50$ moderate correlation / moderately predictive

$|r| \approx .70$ 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 *significantly predicted* child’s PPVT scores at 2 years!

• Speech predictor results:
  • *Quantity* of words in 1 minute (**p < .01)
  • Vowel dispersion (a *quality* 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!
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

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

Appendix
Vowel Space Dispersion Calculations

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

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

where /i/, /a/, 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:

\[
D = \frac{\sum|d|}{n}.
\]