JSLHR

Research Article

Individual Differences in Mothers' Spontaneous Infant-Directed Speech Predict Language Attainment in Children With Cochlear Implants

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Purpose: Differences across language environments of prelingually deaf children who receive cochlear implants (CIs) may affect language acquisition; yet, whether mothers show individual differences in how they modify infant-directed (ID) compared with adult-directed (AD) speech has seldom been studied. This study assessed individual differences in how mothers realized speech modifications in ID register and whether these predicted differences in language outcomes for children with CIs.
Method: Participants were 36 dyads of mothers and their children aged 0;8–2;5 (years;months) at the time of CI implantation. Mothers' spontaneous speech was recorded in a lab setting in ID or AD conditions before ~15 months postimplantation. Mothers' speech samples were characterized for acoustic–phonetic and lexical properties established as canonical indices of ID speech to typically hearing infants, such as vowel space area differences, fundamental frequency variability, and speech rate. Children with CIs completed longitudinal administrations of one or more standardized language assessment instruments at variable intervals from 6 months to 9.5 years postimplantation. Standardized scores on assessments administered longitudinally were used to calculate linear regressions, which gave rise to predicted language scores for children at 2 years postimplantation and language growth over 2-year intervals.
Results: Mothers showed individual differences in how they modified speech in ID versus AD registers. Crucially, these individual differences significantly predicted differences in estimated language outcomes at 2 years postimplantation in children with CIs. Maternal speech variation in lexical quantity and vowel space area differences across ID and AD registers most frequently predicted estimates of language attainment in children with CIs, whereas prosodic differences played a minor role.
Conclusion: Results support that caregiver language behaviors play a substantial role in explaining variability in language attainment in children receiving CIs.
Supplemental Material: https://doi.org/10.23641/asha.12560147

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Editor-in-Chief: Frederick (Erick) Gallun
Editor: Lori J. Leibold

Received September 21, 2019
Revision received January 17, 2020
Accepted April 1, 2020
https://doi.org/10.1044/2020_JSLHR-19-00229

In the last two decades, technological progress with cochlear implant (CI) devices has led to remarkable success in auditory restoration, providing access for many infants afflicted with severe-to-profound hearing loss to sound and spoken language. Yet, linguistic and scholastic outcomes continue to vary widely for these children (Geers et al., 2011; Holt et al., 2012; Houston & Bergeson, 2014). However, only a small fraction of variability in language outcomes in this population can be accounted for, with a great many children with CIs continuing to suffer language delays and lag in scholastic performance (Boons et al., 2012; Geers et al., 2011).

Early language environment is heavily implicated for normal-hearing children as an influential factor in language

Disclosure: The authors have declared that no competing interests existed at the time of publication.

acquisition (Cartmill et al., 2013; Hart & Risley, 1995; Hartman et al., 2017; Hirsh-Pasek et al., 2015; Newman et al., 2015; Romeo et al., 2018; Rowe, 2008, 2012; Schwab & Lew-Williams, 2016; Weisleder & Fernald, 2013). The quantity and quality of infant-directed (ID) speech—a speech style often used when interacting with infants and young children (Fernald, 1993)—in particular, has been shown to predict individual differences in language acquisition in normal-hearing children (Romeo et al., 2018; Rowe, 2012; Weisleder & Fernald, 2013; Weizman & Snow, 2001). Overall, the influence of variability in language environment on language attainment in children with CIs remains little studied (DesJardin & Eisenberg, 2007; Fagan et al., 2014; Szagun & Schramm, 2016; Szagun & Stumper, 2012). No studies thus far have examined whether variability in usage of an ID register by caregivers could help account for the wide range of language outcomes in children with CIs.

In this study, we aim to close this gap by examining how the quality and quantity of ID speech experienced by children receiving CIs early in life might predict their language development. Previewing the results presented here of a 10-year correlational study, we find evidence supporting significant impacts of language environment on linguistic attainment in children with CIs, in particular, evidence supporting the importance of usage of high-quality, ID speech as fostering these children's language development. The findings provide support for theories of language development emphasizing the importance of experiencing high-quality exemplars of the target language. They further suggest speech and language intervention strategies for caregivers and child language specialists targeting ID speech usage.

The Role of ID Speech in Language Development in Infants and Toddlers With Normative Hearing

Numerous studies suggest that ID speech enhances typically hearing infants' processing of language input, as well as linguistic development. Compared with hearing adult directed (AD) speech, when hearing ID speech, normal-hearing infants show better sound discrimination (Karzon, 1985), word recognition (Singh et al., 2009), and word learning (Ma et al., 2011). Furthermore, prior research has demonstrated that both the quantity and quality of ID speech predict speech, language, and cognitive development in normal-hearing children (Romeo et al., 2018; Rowe, 2012; Weisleder & Fernald, 2013; Weizman & Snow, 2001). For example, infants who experience more ID speech become more efficient in word recognition and have larger expressive vocabularies by 24 months of age, whereas overheard speech does not predict later vocabulary (Weisleder & Fernald, 2013). The degree of variability in lexical items (specifically lower type–token ratios indicating more repetition) within ID speech input at 7 months predicts infants' vocabulary outcomes at 2 years of age (Newman et al., 2015).

Importantly, the specific pronunciation properties of ID speech have also been shown to be predictive of outcomes and language competency in children with typical hearing. For example, expanded and more dispersed maternal pronunciation of vowels significantly predicts later receptive and expressive vocabulary (Hartman et al., 2017; Kalashnikova & Burnham, 2018) and phonetic perception (Liu et al., 2003). For young infants, vowel discrimination was improved by large fundamental frequency (F0) variability (Trainor & Desjardins, 2002), and phonetic perception was better for ID rather than AD speech, characterized by higher F0 and slower syllable rate (Karzon, 1985). Thus, in addition to the quantity of speech experienced, the prototypical qualities of ID speech provide young children with meaningful benefits to their language skills and development.

ID Speech and Its Role in Language Development in Infants With CIs

Although acoustic characteristics of ID speech to typically hearing children has been the focus of many studies, there has comparatively little work on ID speech properties to infants with CIs, who might benefit from an enriched speech signal more than children with typical hearing, due to their partial access to spectrotemporal cues (Bergeson, 2011; Bergeson et al., 2006; Kondaurova & Bergeson, 2011; Wieland et al., 2015). Previous findings suggest that caregivers modify prosodic characteristics of speech to infants with hearing loss compared to adult-directed speech (Kondaurova & Bergeson, 2011; Kondaurova et al., 2013). Furthermore, Wieland et al. (2015) found larger vowel spaces and vowel dispersion in both ID speech directed to infants with CIs and with normal hearing, compared to AD speech (although see Cristia & Seidl, 2013).

Infants with hearing loss seem to be sensitive to style-related variation in properties of the linguistic input and show a perceptual preference for ID speech over AD speech and silence (Segal & Kishon-Rabin, 2011; Wang et al., 2017). For example, Wang et al. (2017) found that infants with 12 months' experience with CIs showed a significant preference for ID speech over AD speech that was similar to a matched normal-hearing cohort with a comparable amount of hearing experience. In addition, the degree of ID speech over AD speech preference demonstrated by infants with CIs was associated with both their receptive and their expressive language measures 2 years postimplantation. Although F0 is the main acoustic attribute that drives attentional preferences to ID speech for normal-hearing infants (Fernald & Kuhl, 1987), CI devices transmit pitch cues poorly (Zeng et al., 2014); thus, it remains presently unknown which acoustic cues of ID speech may drive attentional preferences to ID speech for infants with CIs. Furthermore, it is unclear whether infants with CIs may benefit from ID speech, as normal-hearing infants have been shown to.

This Study: Goals and Predictions

The above review indicates that ID speech is a complex construct assumed to involve changes to several acoustic variables. In particular, ID speech canonically has (a) higher F0 central tendency, (b) greater F0 variability, (c) slower speech rate, and (d) more expanded "corner" vowels (/i/, /ɑ/, and /u/; in F1–F2 space), relative to AD speech. However, these acoustic properties do not all always reliably occur in ID speech (Burnham et al., 2015; Cristia & Seidl, 2013; Hartman et al., 2017), which has proven challenging to explain (McMurray et al., 2013). We hypothesized that mothers draw differentially on these cues in producing their own "signature" variety of ID speech; for instance, some mothers may modify F0 more, and modify vowels less, than other mothers in ID compared with AD speech, who might, in turn, show a reverse pattern. Individual variability across maternal caregivers in their ID speech acoustic modifications has seldom been investigated (Dilley et al., 2014; Ikeda & Masataka, 1999; Kitamura et al., 2002). In the context of studies of children with CIs, however, considering such variability is important, since some ID acoustic modifications might better facilitate language acquisition in infants with CIs than others. For instance, F0 modifications might not facilitate improved language outcomes in infants with CIs, due to notoriously poor pitch transmission by these devices (Oxenham, 2008).

Prior research has further identified lexical dimensions of variability in ID speech, which reliably influence language outcomes in typically hearing children. For instance, hearing a greater quantity of speech, or a greater diversity of words in speech, may each facilitate language development (Hoff & Naigles, 2002; Montag et al., 2018). This study filled these knowledge gaps by assessing distinct dimensions of acoustic and lexical variation in ID speech across individual mothers, to assess the possibility that mothers drew differently on these modifications in their ID speech. This in turn allowed us to investigate how attested dimensions of individual variability across mothers predicted language outcomes in infants with hearing loss who received a CI early in life, that is, before 25 months of age. Specifically, we examined whether differences in quality and quantity of ID speech might account for some of the variability in speech-language outcomes in later development. This study focused on individual differences in mothers' speech behaviors with their infants with CIs, as observed in a laboratory setting, and how those differences might differentially facilitate language development. Our study, which was conducted over a period of about 10 years, involved collecting audio recordings of mothers interacting with their infant with a CI (ID condition) or engaging in a semi-structured interview with an experimenter (AD condition). These recordings were examined to extract measures of ID speech quality (e.g., speech rate, F0, and vowel formant measures), as well as ID speech quantity. In addition, measures of the infants' language abilities (e.g., receptive and expressive language skills and vocabulary) were collected using a variety of well-established standardized tests.

At the outset of our study, two possibilities regarding outcomes were conceivable. One possibility was that ID speech provides similar benefits to infants with CIs as what has been shown with normal-hearing infants in terms of language processing and development. Alternatively, ID speech might not provide similar benefits to infants with CIs, either because CIs deliver degraded versions of ID speech (Geers et al., 2008; Houston et al., 2012; Houston & Bergeson, 2014; Kirk & Hudgins, 2016) or because early auditory deprivation reduces the ability of infants with CIs to utilize ID speech cues in support of language development (Conway et al., 2011; Houston et al., 2003; Wang et al., 2018). Previewing our findings, the results of our study firmly supported the first hypothesis, in that variability in the quality and quantity of mothers' ID speech recorded in the lab predicted their infant's speech-language development at 2 years postimplantation on a variety of standardized clinical measures.

Method

General Protocol and Participant Inclusion Criteria

This study involved analysis of speech samples collected in the lab from mothers of $N = 36$ infants (11 girls, 25 boys) who received CI surgical implantation as an intervention for deafness as part of a study from 2002 to 2013 at Indiana University School of Medicine (see Supplemental Material S1 for details of dyads enrolled in the study but who were excluded from this analysis). All infants were early implanted and had a mean age of activation of mean = 15.64 months ($SD = 4.57$ months; range: 8.28–24.26 months); Table S1 in Supplemental Material S1 provides information on deafness etiology, CI device characteristics, and age at implantation for each child in this sample.

The general protocol called for the collection of recordings of mothers' speech during several scheduled lab visits, including at pre-implantation and at 3, 6, and 12 months postimplantation. To reduce subject attrition, some recordings took place 2–3 months after the target postimplantation interval (see Table S2, Supplemental Material S1). Moreover, the protocol called for the administration of speech-language assessments to the child during longitudinal clinical visits at 6 months postimplantation, with additional longitudinal clinical visits targeted for collection approximately every 6–12 months thereafter. Due to participant attrition, infant fussiness, and other factors, the number of recordings per mother and the number of completed postimplantation assessments per child varied across dyads; see below and Supplemental Material S1 for details. Dyads were selected for this study based on the following inclusion criteria: (a) *Native English environment*. The mother was a native speaker of English, and the child was being raised in a monolingual English-speaking environment; (b) *maternal speech recordings*. The mother participated in both spontaneous ID and AD condition recordings by not later than 15 months after the child received the CI; (c) *available child clinical data*. The child completed the same assessment during at least two postimplantation visits to the lab. Data were combined and analyzed as described below.

Recording Procedures and Selection of Maternal Recordings

This study was based entirely on mothers' ID and AD spontaneous speech recordings from lab visits ranging from pre-implantation through 12–15 months postimplantation (with all ID recordings taking place 3–15 months postimplantation; see Table S2, in Supplemental Material S1). From 2002 to 2008, the protocol called for mothers to participate during recording sessions in four conditions: a spontaneous ID condition, a spontaneous AD condition, a mother–infant singing condition, and a mother singing condition; the order of conditions was always counterbalanced. For the spontaneous ID condition, the mother sat with her child on a chair or blanket on the floor and was instructed to speak to her child as she normally would do at home. In the spontaneous AD condition, each mother gave responses in a semistructured short interview led by an adult experimenter using open-ended questions about the child's daily routine and favorite activities; children were not present. From 2008 to 2013, the protocol called for mothers to participate during recording sessions in five counterbalanced speech conditions. Two of these comprised the same spontaneous ID and AD speech conditions using identical experimenter procedures as collected previously. For remaining conditions, the singing conditions were replaced with three different speech conditions. The first of these was a "spontaneous ID play condition"; it was identical to the spontaneous ID condition, except that mothers were provided with quiet toys whose labels included phonetic sounds of interest (i.e., a green key, pink ball, green turtle, brown dog, blue button, and black cat), and the experimenter instructed the mother to name the provided toys while playing with her infant. The other two conditions involved each mother reading a storybook when the infant was inside or out of the room, respectively (see Burnham et al., 2015, for more details).

Mothers completed an average of mean = 2.6 recording sessions postimplantation (*SD* = 0.7, range: 1–3). ID spontaneous recordings had a mean duration of mean = 5.05 min (*SD* = 1.12 min, range: 2.1–9.6 min), whereas AD spontaneous recordings had a mean duration of mean = 5.02 min (*SD* = 2.95 min, range: 1.5–20.5 min; see Supplemental Material S1 for additional details). Recordings were made with a 16-bit quantization rate at a sampling rate of at least 22.05 kHz in a double-walled, copper-shielded sound booth (Industrial Acoustics Company) at the DeVault Otologic Research Lab. Technical equipment for the first phase of the project consisted of a hypercardioid microphone (Audio-Technica ES933/H) at a fixed location in the sound booth powered by a phantom power source and linked to an amplifier (DSC 240) and digital audio tape recorder (Sony DTC-690). The equipment was updated part way through the longitudinal project to an SLX Wireless Microphone System (Shure). This system included an SLX1 Bodypack transmitter affixed to the child with a special vest with a built-in microphone and a wireless receiver SLX4 connected to a Canon 3CCD Digital Video Camcorder GL2, NTSC, which recorded the speech samples directly onto a Mac computer (Apple, Inc. OSX Version 10.4.10) via Hack TV (Version 1.11) software.

Measures of Maternal Speech and Language

The purpose of this study was to characterize individual differences in mothers' implementations of ID speech—a complex construct—as a means of assessing the potential of any attested ID speech individual differences to predict distinct patterns of language attainment in children receiving CIs as a treatment for deafness. This individual-differences approach was central to the study; it could not be assumed that acoustic or lexical properties canonically associated with ID speech to infants with typical hearing would advantage infants with CIs to the same extent, due to the degraded nature of signals delivered by these devices.

Acoustic–Phonetic Properties

To assess possible individual differences across mothers in the nature of acoustic modifications made to ID speech, we measured several ID acoustic–phonetic features—both suprasegmental and segmental—that are considered canonical features of ID speech in studies with typically hearing infants. We first assessed, for each mother, suprasegmental properties of F0 central tendency, F0 variability, and speech rate from samples of all ID and/or AD spontaneous recordings made during the first three scheduled post-implantation intervals (3–15 months postimplantation).[1] F0 measurements were based on rigorous hand analysis of 1- to 2-min samples drawn from each ID or AD file (see Supplemental Material S1 for more information). F0 measurements were based on approximately the first 2 out of 5 min, that is, ~40%, of each file (*M* = 116.3 s, *SD* = 6.9 s) for ID files and, approximately, the first 1 out of 5 min, that is, ~20% of each file (*M* = 50.3 s, *SD* = 7.5 s) for AD files; the greater duration of ID samples was appropriate given the greater F0 variability typical of ID compared with AD speech styles. F0 central tendency was calculated as a "normalized median F0" based on the ratio of median F0 in ID to median F0 in AD conditions (to normalize for extraneous effects of talker size on F0), whereas F0 variability was calculated as "normalized F0 variability," defined as the interquartile range of F0 in the ID condition, normalized by the median F0 in the AD condition. Furthermore, *speech* rate was calculated for each mother as the average across ID files of the total number of syllables in each ID file, divided by the summed duration of mother's utterances in that file (excluding pauses of 250 ms or longer).

To investigate segmental properties, we measured the first (F1) and second (F2) formants (i.e., spectral resonances) for the three "corner" vowels (/i/, /ɑ/, and /u/),

[1]For one mother (Dyad 24), no AD spontaneous recording was available 3–15 months postimplantation, so an AD spontaneous recording made during the pre-implantation interval was used for this participant for the AD condition.

which involve spatially extreme articulations in the oral cavity (Kuhl et al., 1997) in both ID and AD conditions. F1 and F2 values were used to calculate well-validated measures of ID (vs. AD) pronunciation differences: (a) vowel space area (i.e., the percent change, for each mother, in areas of triangles formed by mean F1 and F2 values for each corner vowel in ID and AD speech; Kuhl et al., 1997), and (b) vowel dispersion (i.e., the percent change, for each mother, in mean Euclidean distance of vowel tokens from the centroid of the vowel triangle in ID and AD speech; Bradlow et al., 1996). Due to the fact that vowels of interest were relatively more sparsely distributed within and across files than data for other analyses, we tailored token and file selection procedures around prioritizing identification of desired "quotas" of vowel tokens needed for calculations of reliable vowel triangle area estimates of mothers' ID and AD speech. In particular, we established a criterion that at least three vowel tokens were needed for each of six cell means per mother (based on three corner vowels, /i/, /ɑ/, or /u/, in two elicitation conditions, ID or AD; $3 \times 2 = 6$ cells); falling below this threshold in any cell constituted insufficient data for calculating a reliable area estimate, necessitating exclusion of a mother from the analysis. File analysis began by default with an examination of extant ID and AD recordings made at 3 and 6 months, with the goal of identifying sufficient numbers of vowel tokens in each cell that met phonetic criteria for inclusion and exclusion (see Supplemental Material S1 for a description of criteria and formant measurement procedures). In order to establish roughly comparable granularity across analyses by not unduly oversampling tokens for cell means (given juxtaposition with occasionally unavoidably low cell token counts of $N = 3$ or 4 for some mothers), we therefore capped at 18 the number of vowel tokens included for each cell. If more than 18 tokens of vowels for a given cell were identified within files under consideration for analysis, this triggered a process of iterative random selection of vowels from within analyzed files, until a final set of 18 could be identified that met phonetic criteria (see Supplemental Material S1 for additional details). If analysis of extant 3- and/or 6-month recordings did not result in minimum counts of vowel tokens in all cells that met phonetic criteria, one or more additional recordings were successively analyzed solely to add vowel tokens to cells with counts of $N < 3$; this was required for five mothers. One mother produced fewer than three measurable tokens of a corner vowel for a cell, despite exhaustive searches of all available files, necessitating exclusion of that mother for vowel-related dependent measures. This selection procedure resulted in mean = 12.7 tokens ($SD = 5.0$) overall per cell (i.e., per corner vowel per elicitation condition), with mean = 13.6 per cell for AD speech ($SD = 4.7$, range: 3–18) and mean = 11.9 tokens per cell for ID speech ($SD = 5.2$, range: 3–18).

Lexical Properties

In addition, two lexical properties were calculated for each mother's ID speech; lexical properties were calculated from the same set of ID files and samples selected for F0 analyses, above. First, we calculated each mother's lexical quantity, defined as the "average number of words spoken by that mother per minute of sampled speech," which was calculated by counting words in sampled portions of each recording and dividing by the duration of the sample and then averaging across files. Second, we calculated a measure of lexical diversity, defined here as the type–token ratio, that is, the ratio of count of word types (i.e., the number of different words) to word tokens (i.e., the number of total words) in the transcriptions of ID condition samples. This was an index of diversity of morphemes (based on Guidelines 1–6 in Richards, 1987). Strengths and weaknesses of type–token ratio as a measure of lexical information content have been amply discussed in the literature (see, e.g., Montag et al., 2018).

Child Speech-Language Assessments and Modeling

Children completed mean = 5.8 ($SD = 2.5$, range: 2–12) longitudinal visits to the lab during which they completed one or more standardized speech-language assessments, including the Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4; Dunn & Dunn, 2007), the Preschool Language Scales (PLS) total language score (Zimmerman et al., 2002), and/or the Reynell Developmental Language Scales (RDLS; Edwards et al., 1997). Children given the RDLS were administered both the receptive and expressive scales; due to administrative changes in the clinic, the RDLS was discontinued in 2011, partway through the study. Due to variability in numbers and timing of administrations of these standardized assessments, it was not possible to combine all assessment scores for each child to a single value for valid comparisons across children. We therefore considered as a group those children who had completed a given assessment two or more times for purposes of modeling their performance on that assessment. The number of children completing a given assessment two or more times was $N = 33$ for the PLS (with $M = 3.8$ administrations, $SD = 1.7$, range: 2–8), $N = 25$ for the PPVT (with $M = 3.8$ administrations, $SD = 1.8$, range: 2–10), and $N = 10$ for the RDLS-Expressive and Receptive (with $M = 3.8$ administrations, $SD = 1.4$, range: 2–5). Children had a mean amount of hearing experience (i.e., postimplantation time elapsed) at the time of assessment of mean = 4.2 years ($SD = 1.2$ years; range: 1.0–9.5 years) for the PPVT, mean = 2.4 years ($SD = 0.8$ years; range: 0.75–4.5 years) for the PLS, and mean = 2.0 years ($SD = 0.4$ years) for the RDLS. Collapsing across assessments, children's mean hearing experience at the time of assessments was mean = 2.6 years overall ($SD = 1.1$ years; range: 6 months to 9.5 years; see Table S4, in Supplemental Material S1, for assessment administration details for each child). The mean timing of maternal recordings used in the study was largely uncorrelated with the mean timing of child language assessments (see Supplemental Material S1).

To characterize language outcomes and growth over time for each longitudinally administered assessment for each child, a simple linear regression was fitted to available longitudinal scores as a function of postimplantation time elapsed for each child. All available scores were used to calculate linear regressions. Since each line of regression is characterized by two independent parameters, a point of intersection and a slope (rise over run), linear regressions therefore gave rise to two independent measures of predicted attainment: (a) the child's predicted outcome score at 2 years, corresponding to the value of the ordinate from the linear regression equation at $x = 2$ years postimplantation (cf. a point of intersection), and (b) the child's predicted language score changes over 2 years, corresponding to the change in the ordinate over a 2-year span (cf. the slope; see Table S3, in Supplemental Material S1, for bivariate correlations across children for language outcome and change scores).

General Statistical Modeling Approach

We first tested the prediction that mothers would show individual differences in their realizations of ID and AD speech across acoustic–phonetic and/or lexical dimensions. Under an individual differences hypothesis, changes to one or more variables should not be statistically predictable from changes to other variables. Bivariate correlation analyses were used to assess whether any of the seven dimensions were significantly correlated with one another at $\alpha = .05$.

Having identified factors indexing ID maternal speech variation that were not correlated across mothers—thereby confirming individual differences—we conducted statistical modeling using these factors to test our main prediction: that individual differences in maternal ID speech would predict differences in language outcomes and attainment across children with CIs. The independent estimates for each child of outcome scores (derived from linear regression points of intersection) and language growth (derived from linear regression slopes) were used respectively to construct independent statistical models—one model for each independent language estimate (outcome scores, change scores) for each of the four assessments (PLS, PPVT-4, RDLS-Expressive, and RDLS-Receptive). This gave rise to a total of eight models. To test for statistical relationships between maternal ID speech properties and the independent indices of language attainment for each assessment, we used backward elimination of maternal speech predictors in SPSS and by hand in R (R Development Core Team, 2015). Using both R and SPSS ensured that one mother who did not have vowel predictors would be included in models without those factors. This process permitted determination, for each assessment, of whether any of the ID maternal speech indices significantly predicted language outcome and/or change scores. Statistical models used an α set at .05 and included factors which contributed significantly to model fit with $\alpha = .10$, a log-likelihood ratio test to remove variables that were not significantly predictive at each step.

Results

Individual and Group Characteristics in Mothers' Implementation of ID and AD Speech

A bivariate correlation analysis across mothers for each pair of sampled variables reflecting canonical ID and AD attributes is shown in Table 1. Consistent with the prediction that mothers would show individual differences in implementing ID speech compared with AD speech, our measured variables showed distinctive pairwise patterns of statistical significance in bivariate correlation analyses. Only three pairs of variables showed significant correlations. First, normalized median F0 was significantly correlated with normalized F0 variability, $r = -.70$, $df = 34$, $p < .001$. Second, normalized median F0 was also significantly correlated with speech rate, $r = -.53$, $df = 34$, $p = .001$. Third, and finally, lexical diversity was significantly correlated with lexical quantity, $r = -.43$, $df = 34$, $p = .009$, as anticipated by recent analyses of the relationship of these two language properties (Montag et al., 2018). All other pairs of predictors were not significantly correlated with one another, consistent with these being statistically independent dimensions of ID and AD variation across mothers.

We also asked whether mothers, as a group, produced statistically reliable within-subject differentiation between ID and AD speech conditions on the various canonical ID dimensions. Table 2 shows that mothers as a group reliably distinguished between ID and AD speech in lexical properties, including lexical quantity and lexical diversity, and in suprasegmental properties, including speech rate, median F0, and F0 variability. However, there was no statistically reliable difference as a group by mothers between ID and AD speech conditions for segmental properties (cf. vowel space and dispersion), indicating that this was a substantial dimension of individual variability in this sample.

Individual Variation in Mothers' ID Speech Predicted Children's Estimated Language Outcome Scores at 2 Years Postimplantation

Since two factors—normalized median F0 and lexical diversity—were significantly correlated with other dimensions of ID speech variation (cf. Table 1), we first excluded these two factors as predictors from subsequent statistical models relating maternal speech to child language outcomes, thereby enhancing model reliability and validity through reducing multicollinearity of predictors. Based on the remaining five predictors (vowel space area, vowel dispersion, speech rate, normalized F0 variability, and lexical quantity), we then constructed a single model each for the two independent, predicted child outcome scores for each of the four assessments (see Method section). Results showed that individual differences in mothers' spontaneous ID speech significantly predicted outcome scores for multiple speech-language assessments for children with CIs, as follows.

Table 1. Correlation of maternal speech segmental, suprasegmental, and lexical properties.

Variable	Vowel space area	Vowel dispersion	Speech rate	Normalized median F0	Normalized F0 variability	Lexical quantity	Lexical diversity
Vowel space area	1.0						
Vowel dispersion	.05	1.0					
Speech rate	–.07	.22	1.0				
Normalized median F0	.02	–.11	–.53**	1.0			
Normalized F0 variability	–.10	.30	.32	–.70***	1.0		
Lexical quantity	.14	–.12	.17	.12	–.09	1.0	
Lexical diversity	.03	.11	.22	–.27	.09	–.43**	1.0

Note. F0 = fundamental frequency.
**$p < .01$. ***$p < .001$.

PLS

PLS scores for children with CIs 2 years postimplantation were significantly predicted by a combination of two maternal speech variables: (a) lexical quantity in mothers' ID speech ($p = .017$) and (b) ID speech rate ($p = .053$). Statistical modeling showed a large effect size, $R = .481$, $F(2, 30) = 4.51$, $p = .019$ (see Figure 1A.).

PPVT

PPVT scores for children with CIs 2 years postimplantation were significantly predicted by a combination of two maternal speech variables: (a) lexical quantity in their mothers' ID speech ($p = .003$) and (b) mothers' vowel dispersion in ID versus AD speech ($p < .042$). Statistical modeling showed a large effect size, $R = .634$, $F(2, 21) = 7.07$, $p = .004$ (see Figure 1B).

RDLS-Receptive

RDLS-Receptive subtest scores in children with CIs 2 years postimplantation were marginally significantly predicted by individual differences in mothers' ID speech, as indexed by the variable of mothers' vowel space area in ID compared with AD speech, $p = .064$, $F(1, 7) = 4.845$. There was a large effect size, $R = .64$ (see Figure 1C).

RDLS-Expressive

RDLS-Expressive subtest scores were significantly predicted by individual differences in mothers' ID speech, $p < .001$, $F(3, 5) = 35.66$, as indexed by a combination of three maternal speech variables: (a) lexical quantity in mothers' ID speech ($p = .004$), (b) mothers' vowel dispersion in ID versus AD speech ($p < .001$), and (c) mothers' normalized F0 variability ($p = .038$). Statistical modeling showed a large effect size, $R = .977$ (see Figure 1D).

Mothers' ID Speech Predicted Children's Estimated Language Change Scores Over 2 Years Postimplantation

Individual differences in mothers' speech quantity and quality were also significant predictors of change scores across multiple speech-language assessments over 2 years postimplantation for children with CIs, as follows.

PLS

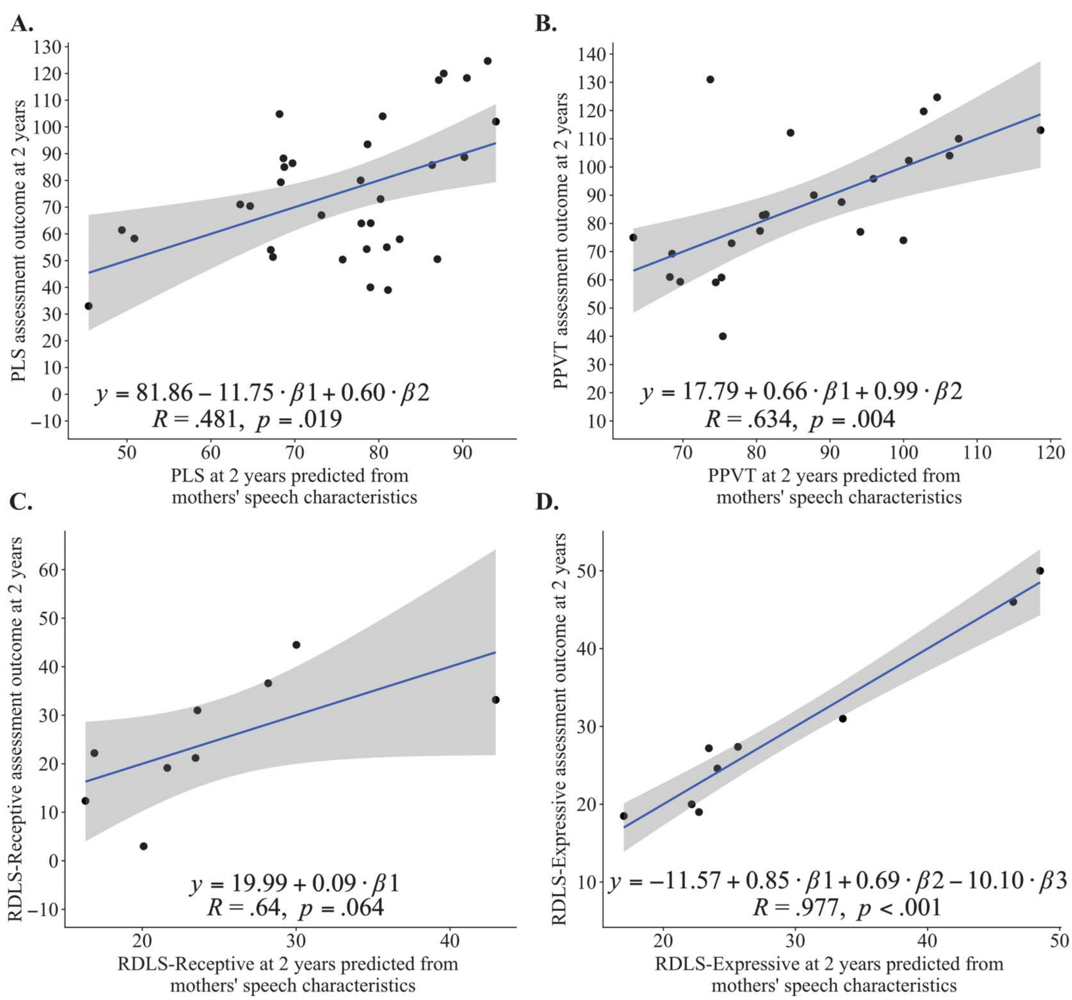
PLS score change for children with CIs over 2 years postimplantation was significantly predicted by the variable of difference in mothers' vowel space areas for ID versus AD speech with a moderate effect size, $R = .361$, $F(1, 30) = 4.504$, $p = .042$ (see Figure 2A).

Table 2. Within-subject differences between mothers' ID and AD speech.

Predictors	ID		AD		Mean difference		95% CI of the mean difference		
	M	*SE*	*M*	*SE*	*M*	*SE*	[Min, Max]	*t*(*df*)	*p*
Lexical								*t*(35)	
Lexical quantity	64.3	2.7	104.0	4.9	–39.7	3.9	[–47.7, –31.7]	–10.1	< .001
Lexical diversity	0.33	0.01	0.51	0.01	–0.18	0.02	[–0.21, –0.15]	–12.1	< .001
Suprasegmental								*t*(35)	
Speech rate (syllables/s)	3.8	0.12	4.4	0.09	–0.58	0.12	[–0.79, –0.36]	–5.5	< .001
Median F0 (Hz)	272.5	6.5	187.4	3.9	85.1	5.3	[74.3, 95.8]	16.1	< .001
F0 variability (Hz)	127.5	6.5	35.3	2.0	92.2	6.7	[78.6, 105.8]	13.8	< .001
Segmental								*t*(34)	
Vowel space area (mels)	71,317.5	5,396.7	62,924.7	3,945.5	8,392.8	6,023.7	[–3,848.8, 20,634.4]	1.4	.173
Vowel dispersion (mels)	342.5	5.7	328.8	5.3	13.7	7.3	[–1.0, 28.4]	1.9	.068

Note. ID = infant-directed; AD = adult-directed; CI = confidence interval.

Figure 1. Characteristics of mothers' speech significantly predicted speech-language outcomes in children with cochlear implants at 2 years postimplantation. The abscissa depicts the assessment score value predicted from the linear regression containing the maternal speech characteristics indicated in the text, while the ordinate depicts children's clinical score value 2 years postimplantation. (A) PLS scores of children 2 years postimplantation were significantly predicted by their mothers' lexical quantity (β1) and ID speech rate (β2). (B) PPVT scores of children at 2 years postimplantation were significantly predicted by their mothers' lexical quantity (β1) and vowel dispersion (β2). (C) RDLS-Receptive scores of children 2 years postimplantation were marginally predicted by differences in articulatory vowel space areas in their mothers' ID speech, compared with her AD speech (β1). (D) RDLS-Expressive scores of children at 2 years postimplantation were significantly predicted by their mothers' lexical quantity (β1), mothers' differences in vowel dispersion in ID speech compared with AD speech (β2), and normalized F0 variability (β3). PLS = Preschool Language Scales; PPVT = Peabody Picture Vocabulary Test; RDLS = Reynell Developmental Language Scales; ID = infant-directed; AD = adult-directed.



PPVT

PPVT score change for children with CIs over 2 years postimplantation was not significantly predicted by any speech properties. Although not significant, the best fitting model included normalized F0 variability with a small effect size, R = .214, F(1, 23) = 1.105, p = .304 (see Figure 2B).

RDLS-Receptive

RDLS-Receptive subtest score change over 2 years postimplantation was significantly predicted by the variable of mothers' vowel space areas for ID versus AD speech with a large effect size, R = .963, F(1, 7) = 28.1, p = .001 (see Figure 2C).

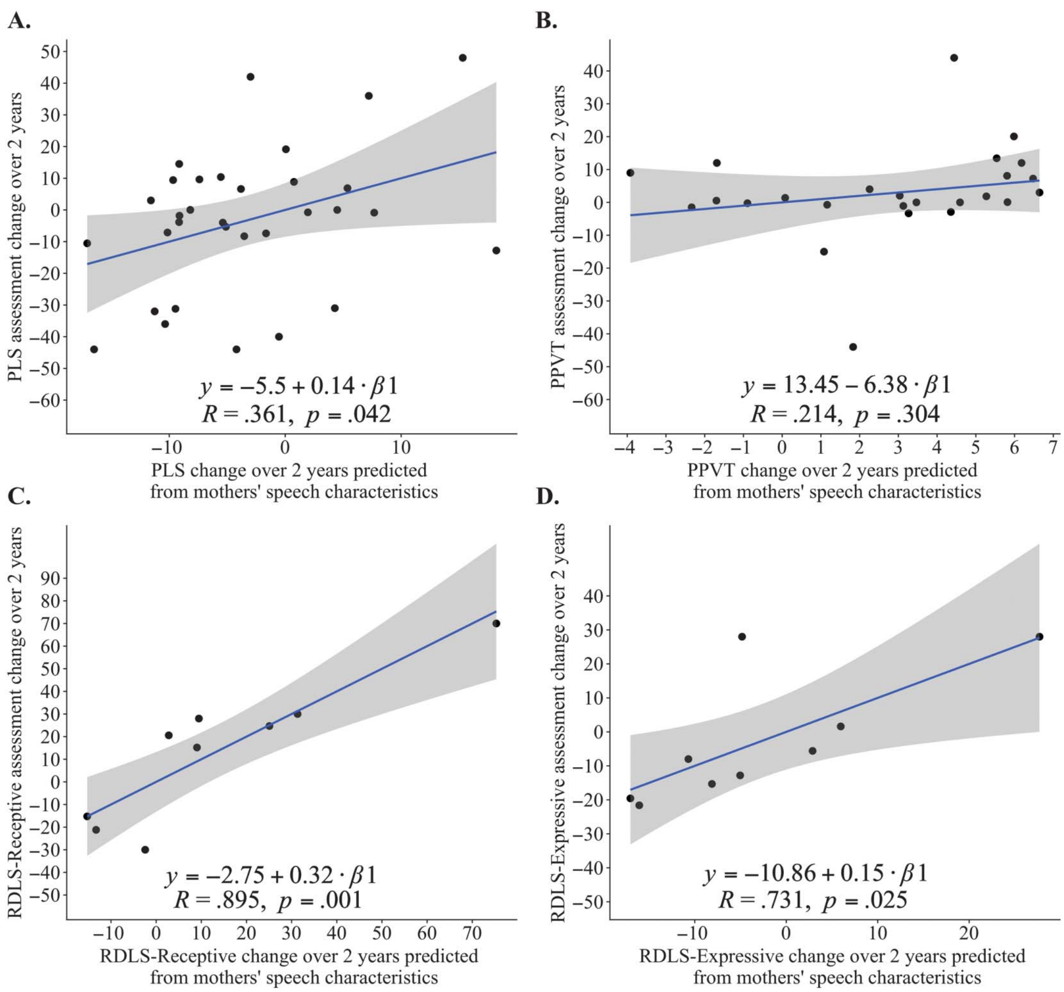
RDLS-Expressive

RDLS-Expressive subtest score change over 2 years postimplantation was significantly predicted by the variable of mothers' vowel space areas for ID versus AD speech with a large effect size, R = .731, F(1, 7) = 8.018, p = .025 (see Figure 2D).

Neither Mothers' Socioeconomic Status nor Child Age of Implantation Accounted for Clinical Outcomes

To determine whether socioeconomic status (SES) might account for variability in outcomes, mother's education (a proxy for SES) was used as an ordinal predictor in

Figure 2. Characteristics of mothers' speech significantly predicted amount of change in over 2 years in multiple measures of clinical speech-language scores for their children with CIs. The abscissa depicts the assessment score change over 2 years predicted from the linear regression containing the maternal speech characteristics indicated in the text, whereas the ordinate depicts children's clinical score change for that interval. (A) Children's PLS score change was significantly predicted by their mothers' vowel space area in ID speech compared with AD speech (β1). (B) Children's PPVT-4 score change was not significantly predicted by any factors but the best fitting model was a prediction based on normalized F0 variability (β1). (C) Children's RDLS-Receptive score change was significantly predicted by their mothers' differences in vowel dispersion in ID speech compared with AD speech (β1) and mothers' ID lexical diversity (β2). (D) Children's RDLS-Expressive score change was significantly predicted by differences in their mothers' vowel dispersion in ID speech compared with AD speech (β1). PLS = Preschool Language Scales; PPVT = Peabody Picture Vocabulary Test; RDLS = Reynell Developmental Language Scales; ID = infant-directed; AD = adult-directed.



a linear regression of children's score attainment at, and growth over, 2 years. The education categories were (a) did not finish high school ($n = 1$), (b) finished high school ($n = 10$), (c) some college ($n = 8$), (d) associate's degree ($n = 4$), (d) bachelor's degree ($n = 9$), (e) master's degree ($n = 5$), and (f) PhD ($n = 1$); education level was unknown for one mother, who was not included in the analysis. SES did not significantly predict any of the clinical speech-language outcome measures, PLS: $R = .452$, $F(5, 26) = 1.336$, $p = .280$; PPVT: $R = .525$, $F(5, 18) = 1.371$, $p = .281$; RDLS-Receptive: $R = .539$, $F(4, 5) = .512$, $p = .732$; RDLS-Expressive: $R = .687$, $F(4, 5) = 1.116$, $p = .442$. SES also did not significantly predict degree of change over 2 years on any speech-language clinical measures (range of p values: .13–.96).

Age of implantation has been identified as a factor that could affect speech-language outcomes given critical windows in neural development that could facilitate language learning. Similar to the approach taken with SES, age of implantation was used as a continuous predictor of 2-year postimplantation estimated outcome scores for each of the four outcomes. Age of implantation did not provide predictive power in most outcomes scores, PLS: $R = .330$, $F(1, 31) = 3.787$, $p = .061$; PPVT: $R = .154$, $F(1, 23) = 0.560$,

p = .462; RDLS-Receptive: R = .210, $F(1, 8)$ = .371, p = .560; RDLS-Expressive: R = .531, $F(1, 8)$ = 3.138, p = .115. The change scores over 2 years did not show any significant effects (range of p values: .57–.93). Given that acoustic measures were collected at approximately 3, 6, and/or 12 months after implantation for all children and that the outcome scores were interpolated to 2 years after implantation for all children, assessing the impact of chronological age is effectively modeled through age of implantation.

Discussion

In this study, spontaneous speech of mothers interacting with their children with CIs or with adults was recorded within the first 12–15 months of the children's CI surgery, whereas child outcome measures of language development were collected at multiple longitudinal intervals starting as early as 6 months postimplantation. Using a small set of well-justified acoustic–phonetic or lexical features considered canonical ID speech indicators for typically hearing children, we tested whether individual differences in mothers' realization of ID speech predicted individual differences in child language outcomes. The main finding was that individual differences in maternal speech indeed significantly predicted enhanced language outcomes and growth in children with CIs 2 years postimplantation.

As predicted, we found evidence of individual variation across the canonical dimensions of mothers' ID speech sampled in this data set. Although two of our measures—normalized F0 median and lexical diversity—were correlated with one or two other factors, five of our sampled variables were statistically uncorrelated with one another across mothers (lexical quantity, vowel space area, vowel dispersion, normalized F0 variability, and speech rate), consistent with individual differences. Subsequent steps involved using statistically uncorrelated speech variables to address our primary question, namely, whether any significant relationships would be found between individual differences in speech in mothers and language attainment measures in their children (i.e., a completely different set of individuals).

Two key findings were that (a) variability in the lexical quantity of maternal ID speech contributed significantly to three (out of three) significant model fits that predicted child language outcomes at $p < .05$ (on PLS, PPVT, and RDLS-Expressive assessments) and (b) variability in vowel space area differences for mothers' ID versus AD speech contributed significantly to three (out of three) significant model fits that predicted child language score changes at $p < .05$ (on PLS, RDLS-Receptive, and RDLS-Expressive assessments). (Two models assessing fits between variability in maternal ID speech properties and language attainment missed overall statistical significance, with p = .064 for RDLS-Receptive 2-year outcomes and p = .304 for PPVT 2-year growth.) Associations between child language attainment and maternal lexical quantity were expected, since studies with typically hearing children have also documented that the quantity of lexical input is a strong predictor of language growth and scholastic achievement (Hart & Risley, 1995; Hurtado et al., 2008; Weisleder & Fernald, 2013). Furthermore, our finding that vowel space area significantly predicted outcomes on multiple assessments is consistent with prior studies with typically hearing children documenting vowel space area differences in maternal ID versus AD speech (Kuhl et al., 1997; Liu et al., 2003), where associations were shown between larger vowel space area differences in ID versus AD speech and later enhanced speech sound discrimination and language scores (Hartman et al., 2017; Liu et al., 2003). Although ID speech was originally proposed to invoke greater clarity or distinctiveness of vowel sounds for language didactic purposes (Kuhl et al., 1997), this hypothesis cannot explain findings from more recent studies. For instance, interior vowels, unlike corner vowels, fail to show greater clarity or distinctiveness in ID speech compared with AD speech (Cristia & Seidl, 2013; McMurray et al., 2013), suggesting a need for a more nuanced explanation for ID speech modification and its potential contribution to language learning.

Vowel space dispersion was a secondary factor contributing to model fits in two models of PPVT and RDLS-Expressive 2-year outcomes. Differences in vowel space dispersion have been tied to overall speech intelligibility (Bradlow et al., 1996). (Note that a single-factor model consisting of lexical quantity in maternal ID alone also significantly predicted both PPVT and RDLS-Expressive 2-year outcomes at $p < .05$.) Overall, these findings support the core hypothesis of this study that individual variability in maternal ID speech realization predicts and, indeed, may influence language acquisition in children with CIs. Later in discussion, we return to consider of why lexical quantity and vowel space area may have significantly predicted 2-year language outcomes versus language growth, respectively.

In contrast to maternal lexical quantity and vowel space factors, we found that suprasegmental (i.e., prosodic) factors, while contributing to descriptions of individual differences in maternal ID speech, played a relatively minor role in statistically predicting language outcomes in children with CIs. Statistical effects of maternal speech prosodic factors were modest or negligible: normalized F0 variability contributed to model fit at $p < .05$ for the model of RDLS-Expressive child language 2-year outcomes, but ID speech rate only marginally contributed to fit for PLS child language 2-year outcomes. In either case, a single-factor model with lexical quantity alone significantly predicted these assessment outcomes as well. Interestingly, Kalashnikova and Burnham (2018) also found that maternal vowel space factors, not pitch or affect, predicted vocabulary size in infants with normal hearing. These findings appear to contrast with research that has framed prosodic factors as central hallmarks of ID speech (cf. Fernald & Kuhl, 1987), while correlational evidence cannot be taken as evidence of causation, these findings are nonetheless consistent with a hypothesis that prosodic attributes of maternal language are relatively less important for differential language development across children with CIs (and normal hearing) than segmental ones (and vowels in particular). For children with CIs, this may be due in part to the fact that pitch cues are generally poorly transmitted by CI devices (Oxenham, 2008), which may reduce the capacity of F0 cues to signal attention to ID speech for children with CIs compared to those with typical hearing (Fernald & Kuhl, 1987). Furthermore, it is not a priori clear that variability in maternal ID speech rate over ranges attested here would influence language acquisition. Although a slower speech rate in natural speech is associated with higher intelligibility (Smiljanić & Bradlow, 2008), this likely reflects effects of a covarying factor, namely, spectrotemporal clarity (Janse et al., 2007). In summary, these results suggest that variability in prosodic factors in maternal ID speech may play a relatively reduced role in language development in children with CIs, compared with typically hearing children.

Before returning to consideration of maternal speech variables that most frequently significantly predicted child language outcomes, we will consider whether other factors might have explained these results. Notably, we found that neither mothers' SES nor child age of implantation accounted for these statistical relationships with clinical outcomes. Although age of implantation has been treated as a major influence on the language development of children with CIs (Geers et al., 2011; Niparko et al., 2010), such effects actually account for a relatively small amount of variability in outcomes in prior literature (Geers et al., 2009, 2007; Tomblin et al., 2005) and the current study.

Returning to our main pattern of results, the above considerations so far leave unaddressed the question of why lexical quantity most often significantly predicted language outcomes at 2 years, whereas vowel space area most often significantly predicted language growth over 2 years. We attribute the finding that lexical quantity of maternal ID speech accounted for child language outcomes at 2 years postimplantation to the critical role of statistical learning from sufficient quantities of language input in order to acquire a basic, working language model of linguistic fundamentals (including vocabulary and syntax), consistent with prior work in typically hearing children (Hart & Risley, 1995; Hoff & Naigles, 2002; Huttenlocher et al., 2010). Children exposed to a greater quantity of lexical input in their first 2 years of hearing experience will more quickly develop a basic working language model, leading to expectations of higher indices of language knowledge (i.e., outcomes) during early language developmental, for example, at 2 years. This explanation is consistent with the fact that lexical quantity was significantly predictive of child language outcomes at 2 years across most assessment instruments (PLS, PPVT, and RDLS-Expressive).

In contrast, our finding that vowel space area differences in maternal ID versus AD speech significantly predicted language growth in children with CIs may reflect specifics of how vowels—as opposed to other acoustic cues—may signal communicative relevance to the child. In particular, we propose that mothers who encode their intent to speak to their child as reliable vowel space area differences between ID and AD speech foster successful (i.e., accurate) perceptual recovery of that maternal intent from (auditory-only) speech signals by their child with a CI. This is consistent with the idea that vowel space spectral differences "survive" acoustic degradation by CIs relatively better than other kinds of cues, such as F0 modification (Oxenham, 2008; Svirsky, 2000). Our explanation draws on the social learning literature, which views ID speech as a type of ostensive cue—that is, a cue which signals a caregiver's intention to convey relevant knowledge about a referent, where other ostensive cues include eye contact, contingent responsivity, and being addressed by one's own name (Eaves et al., 2016; Parise & Csibra, 2013). Ostensive signaling is an important component of the multidimensional construct of "ID speech." We see a tension in the literature between defining this complex, multifaceted ID speech construct in terms of its ostensive value—reflecting a caregiver's intention to convey knowledge to a child—versus defining this construct in terms of how speech is physically realized, compared with the "downstream" effects of the intention to communicate with the child through encoding in actual speech signals. Yet, disentangling ostensive intent of ID speech from how this intention is physically realized in auditory speech signals is essential for our explanation of our findings. Our study design ensured that, in ID speech conditions, caregivers uniformly shared an intention to communicate with their infants. However, mothers encoded this intention differently in their speech signals across canonical features sampled, as revealed by the lack of significant correlation among some variables pairwise. Our proposal that statistical correlations observed between maternal vowel space area differences and child language growth over 2 years reflects differences in acoustic encoding (and recoverability by the child) of maternal ostensive intent on the basis of auditory speech cues alone is consistent with other findings. Notably, vowels as a class have special status in language acquisition (Bouchon et al., 2015; Nazzi & Cutler, 2019), and vowels garner attention and communicate unique information in speech well into the life span (Ladefoged & Broadbent, 1957; Morton et al., 1976). Crucially, ID speech, such as other forms of ostensive cuing, is associated with greater opportunities for joint attentional engagement that facilitate acquisition of lexical, semantic, and pragmatic knowledge from context well beyond 2 years postimplantation. Differences in ability to accurately respond to maternal ostensive speech-based bids for joint attention will differentially foster language development for children that correctly apprehend ostensive intent from maternal ID speech signals. This explanation is consistent with the fact that vowel space area differences were significantly predictive of language growth over 2 years across multiple assessment instruments (PLS, RDLS-Receptive, and RDLS-Expressive).

It is noteworthy that surprisingly little prior research has investigated individual differences in ID speech (Dilley et al., 2014; Ikeda & Masataka, 1999; Kitamura et al., 2002). Crucially, our analysis permitted assessing whether specific patterns of ID modification might benefit children with CIs—a question of focal interest, since CI devices transmit degraded acoustic cues, particularly for F0 (Oxenham, 2008). An assumption central to research with typically developing children has been that the prosodic (i.e., suprasegmental) features of ID speech—including F0 and rate—are definitional to this speech style (Fernald & Simon, 1984); such views have been based in part on evidence of F0 in particular driving normal-hearing infants' attentional preferences for ID speech (Fernald & Kuhl, 1987). However, this emphasis on prosodic variability—together with a tendency of research to focus on group-level differences across ID versus AD speech—potentially misplaces emphasis relative to children with CIs by overlooking possible individual differences in how mothers talk with their infants. As such, prior research has left open how differences in how mothers realize their ID speech might differentially impact language learning in special populations, such as children with CIs.

The above proposals also help explain recent findings that infants with CIs implanted before 24 months with 12 months hearing experience not only reliably discrimination of ID from AD speech, but that they prefer ID speech compared with AD speech (Wang et al., 2017). Attentional preferences for ID speech have previously been demonstrated in typically hearing infants (Cooper & Aslin, 1990; Fernald & Kuhl, 1987; Thiessen et al., 2005). Prototypical sound features of ID speech are thought to promote linguistic skills, including word segmentation and word–object mappings (Ma et al., 2011; Schwab & Lew-Williams, 2016; Singh et al., 2009). Yet, the findings of Wang et al. at first glance appear quite puzzling in light of classic experimental work in typically hearing infants showing that their attentional preferences for ID speech over AD speech are driven primarily by F0 cues (Fernald & Kuhl, 1987). Given that CI devices transmit F0 cues to pitch quite poorly (Oxenham, 2008), it seems unlikely that F0 cues could drive attentional preferences for ID speech in infants with CIs. At the same time, studies of factors facilitating attention to ID speech over AD speech has often sought statistically reliable acoustic indices of ID speech (which involved typically not only a greater vowel space and variable F0 cues), with no consistent acoustic cues emerging that might explain the various findings and effects (Cristia & Seidl, 2013; McMurray et al., 2013). Our explanation for the origins of attentional preferences for ID speech—in children with typical hearing or CIs—proposes that these preferences stem from high-level recognition of others' intentions that derive from social learning about language (cf. Eaves et al., 2016; Parise & Csibra, 2013).

Regarding explanations for our findings, one question which might be raised stems from limitations of our data set concerning variable numbers of longitudinal administrations of language assessments to each child, along with variability in when those assessments were administered. For some children, a given assessment was administered only twice, so that modeling language attainment as anything other than a straight line would have been of questionable validity. We are cognizant of findings that some dimensions of language growth are better described as functions other than straight lines, such as exponential curves, which may in some cases arise from dyadic responsivity of caregivers to children and vice versa (Huttenlocher et al., 2010; Renzi et al., 2017). This raises the possibility that individual differences in children's language growth estimates derived from slopes of regression lines to individual children's data could instead more parsimoniously be described as having arisen from putatively exponential language trajectories that were similar across children. To check this possibility, we conducted an analysis examining whether slopes of regression lines changed systematically as a function of variability in the timing of administration of assessments, on the observation that the instantaneous slope of an exponential function should change monotonically along the abscissa (representing developmental time). This analysis revealed no statistically reliable support for this explanation; see Supplemental Material S1. These findings thus support the view that our linear modeling approach provided reasonable estimates of individual language growth differences—differences that were reliably predicted statistically by individual differences in mothers' speech, but not by exponential patterns of language growth. This could either be because curves are not exponential or because maternal speech entailed a larger effect size than exponential curves.

The current results provide important and provocative preliminary results suggestive of the value of future research that might use a higher constraint design (e.g., manipulation of ID speech exposures to infants). The current study had other limitations not already alluded to, including a relatively small number of children with CIs, and the fact that outcome data were collected at different timepoints for different children, necessitating statistical interpolation of outcomes. Furthermore, we used backward elimination to test which, if any, individual speech factors might predict child language outcomes. Backwards elimination is sometimes criticized in cases where computational studies include hundreds or dozens of exploratory variables and/or when justification for variables is lacking from prior research; however, our study used a small set of predictor variables justified by their status as canonical features of ID speech from prior research. We further eliminated statistically correlated (i.e., multicollinear) factors, thereby guarding against a criticism sometimes leveled at this particular approach. Given these collective limitations, the results should not be taken as the final determination of how maternal speech facilitates language learning for children with CIs but rather as a preliminary point to guide further exploration of this question. Given the difficulty and constraints associated with collecting data of this nature, the current results represent a first step toward answering a very difficult question and we hope they assist future efforts to better understand these relationships. However, the consistently large statistical effect sizes ($r > .50$) observed across multiple models present a compelling picture of potential effects that can be investigated in future studies.

This research advances a relatively small body of extant work on how properties of maternal speech input predict linguistic outcomes for children with CIs. For example, prior work on lexical level maternal speech influences on children with CIs (Szagun & Stumper, 2012) utilized a syntactic measure of maternal speech quality (i.e., mean length of utterance [MLU]). They showed that MLUs of mothers at 12–18 months postimplantation was predictive of MLUs of their children with CIs at 24–30 months postimplantation. Furthermore, research investigating maternal expansions showed mixed evidence for the effect of expansions on linguistic outcomes in children with CIs (Szagun & Schramm, 2016). Therefore, our work builds on prior work by suggesting additional qualities of maternal speech that may benefit language development in children with CIs.

In conclusion, we showed, for the first time, that individual differences in maternal ID spontaneous speech predict later language attainment in children with CIs. The two factors, which most frequently and reliably predicted language attainment scores, were lexical quantity and vowel space area; we advanced a hypothesis that mothers' producing greater lexical quantity supports more rapid statistical learning of a basic, working language model in children with CIs, while producing a distinctive vowel space in ID compared with AD speech supports reliable recovery of mothers' ostensive intention to communicate with their children, thereby fostering more effective learning through joint attentional cues. In spite of some limitations, the present findings thus provide initial support for interventions aimed at boosting quality and quantity of language input to children with CIs; such interventions may have cascading positive effects on educational and social attainment (Geers, 2003; Marschark et al., 2007). Extending this research conducted in the lab by characterizing how variability in natural language environments of children with CIs predicts their linguistic outcomes should be a direction of future work.

Acknowledgments

This research was supported by the National Institute on Deafness and Other Communication Disorders Grant R01DC008581, awarded to D. Houston and L. Dilley. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

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