

Research Article

Vowel Space Characteristics of Speech Directed to Children With and Without Hearing Loss

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Purpose: This study examined vowel characteristics in adult-directed (AD) and infant-directed (ID) speech to children with hearing impairment who received cochlear implants or hearing aids compared with speech to children with normal hearing.

Method: Mothers' AD and ID speech to children with cochlear implants (Study 1, $n = 20$) or hearing aids (Study 2, $n = 11$) was compared with mothers' speech to controls matched on age and hearing experience. The first and second formants of vowels /i/, /a/, and /u/ were measured, and vowel space area and dispersion were calculated.

Results: In both studies, vowel space was modified in ID compared with AD speech to children with and without

hearing loss. Study 1 showed larger vowel space area and dispersion in ID compared with AD speech regardless of infant hearing status. The pattern of effects of ID and AD speech on vowel space characteristics in Study 2 was similar to that in Study 1, but depended partly on children's hearing status.

Conclusion: Given previously demonstrated associations between expanded vowel space in ID compared with AD speech and enhanced speech perception skills, this research supports a focus on vowel pronunciation in developing intervention strategies for improving speech-language skills in children with hearing impairment.

The nature of spoken language input typically experienced by children with normal hearing has a strong influence on the development of linguistic and cognitive abilities (Hart & Risley, 1995; Hurtado, Marchman, & Fernald, 2008; Kaplan, Bachorowski, Smoski, & Hudenko, 2002; Kaplan, Bachorowski, & Zarlengo-Strouse, 1999; Liu, Kuhl, & Tsao, 2003; Soderstrom, 2007). Infant-direct (ID) speech, often referred to as *hyperspeech* (Fernald, 2000), is characterized by a number of prosodic, phonetic, morphological, syntactic, and semantic modifications compared with adult-directed (AD) speech (Bernstein Ratner, 1986; Burnham, Kitamura, & Vollmer-Conna, 2002; Fernald, 1989; Kuhl et al., 1997; Papousek, Papousek, & Haekel, 1987; Soderstrom, 2007; Stern, Spieker, Barnett, & MacKain, 1983). Such modifications are suggested to fulfill three main functions: modulate children's attention

and arousal levels, communicate maternal affect, and facilitate language acquisition (Fernald, 1989; Stern et al., 1983).

Despite evidence regarding the importance of ID speech for development in children with normal hearing, researchers have only recently started to examine the properties of linguistic input to children with hearing loss (Bergeson, Miller, & McCune, 2006; Kondaurava & Bergeson, 2011; Kondaurava, Bergeson, & Dilley, 2012; Kondaurava, Bergeson, & Xu, 2013; C. Lam & Kitamura, 2010). The effect of child hearing status on maternal speech input may serve an important role as a predictor of the enormous variability observed in language acquisition skills in pediatric populations with hearing impairment (Houston, Ying, Pisoni, & Kirk, 2003; McKinley & Warren, 2000; Miyamoto, Svirsky, & Robbins, 1997; Niparko et al., 2010; Pisoni et al., 2008; Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). Depending on the degree of hearing loss and the amount of residual hearing, children with hearing impairment may receive a hearing aid (for little to moderate hearing loss) or a cochlear implant (for severe to profound hearing loss; Joint Committee on Infant Hearing, 2007). The present study examined the phonetic characteristics of ID speech to children with hearing impairment who received an assistive device (i.e., cochlear implant or hearing aid) compared with

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that to matches with normal hearing, focusing specifically on the vowel space to children with hearing impairment.

Substantial evidence demonstrates that one of the major phonetic modifications in ID compared with AD speech concerns the articulation of point vowels /i/, /a/, and /u/, as reflected in an expanded acoustic vowel space, which is indexed by first and second formant frequencies (F1 and F2, respectively; Burnham et al., 2002; Kuhl et al., 1997; Liu et al., 2003; Liu, Tsao, & Kuhl, 2009; Uther, Knoll, & Burnham, 2007). An expanded vowel space in ID relative to AD speech has now been documented in several languages and dialects, including American and Australian English, Swedish, Russian, and Mandarin Chinese (Burnham et al., 2002; Kuhl et al., 1997; Liu et al., 2009). Kuhl et al. (1997) proposed that the increased acoustic distance between vowel categories promotes language acquisition by more effectively separating sounds into contrastive categories and highlighting between-categories differences in ID relative to AD speech. Since this “hyperarticulation hypothesis” was first put forward (Kuhl et al., 1997), several studies have demonstrated evidence in support of the idea that the increased acoustic distance between vowels facilitates language acquisition in children (Liu et al., 2003; Song, Demuth, & Morgan, 2010). Liu et al. (2003) found a positive correlation between the degree of the expansion of mothers’ acoustic vowel space in speech to 6- to 8-month-old and 10- to 12-month-old children and the children’s ability to discriminate native Mandarin Chinese consonant contrasts. In a more recent study, Song et al. (2010) showed that vowel space expansion facilitated 19-month-old children’s word recognition in American English.

Recent studies have presented contradictory results on the degree of vowel space expansion in ID speech to populations both with and without hearing impairment (Cristia & Seidl, 2014; Englund & Behne, 2006; Kondaurova et al., 2012; C. Lam & Kitamura, 2010, 2012). Several studies have demonstrated no enhancement of the distance between vowel categories and/or expansion of the acoustic vowel space area in speech to children with normal hearing compared with AD speech (Cristia & Seidl, 2014; Englund & Behne, 2006). Although evidence of vowel space expansion exists when a talker is aware that an adult listener has a hearing impairment (Ferguson & Kewley-Port, 2002; Picheny, Durlach, & Braida, 1986), partial or no vowel space expansion was observed in speech to children with hearing impairment (Kondaurova et al., 2012; C. Lam & Kitamura, 2010).

A case study by C. Lam and Kitamura (2010) demonstrated that the vowel space area to a 15.5-month-old child with hearing impairment fitted bilaterally with hearing aids was decreased compared with the vowel space area in speech to his twin brother with normal hearing and to an adult experimenter. Research with children who were prelingually deaf prior to cochlear implantation demonstrated an expanded vowel space in ID speech for only a subset of vowels (/u/ and /i/; Kondaurova et al., 2012). In order to investigate the effect of hearing impairment on vowel space in ID speech with more participants, C. Lam and Kitamura

(2012) simulated hearing loss in infants with normal hearing. They placed mothers and infants in separate rooms and used closed-circuit television to allow visual contact between the mother and infant while manipulating the volume of the auditory signal delivered to the child. The authors found that mothers expanded their vowel space when the infants could hear them at full or partial volume but that mothers did not expand their vowel space when the infants could not hear their speech.

Several considerations suggest the need to better understand the phonetic characteristics of speech to children with hearing impairment. First, given the prior links established between vowel space expansion and speech-language development (Kuhl et al., 1997; Liu et al., 2003), it is noteworthy that children with hearing impairment demonstrate lower responsiveness during mother–child interaction compared with children with normal hearing (Koester, 1995; Pressman, Pipp-Siegel, Yoshinaga-Itano, Kubicek, & Emde, 1998; Schlesinger & Meadow, 1972; Wedell-Monning & Lumley, 1980). For this reason, mothers might face greater demand for engaging and maintaining the attention of children with hearing impairment, which could be achieved by sacrificing vowel space expansion in favor of acoustic characteristics of ID speech that function primarily to modulate children’s attention (e.g., pitch, vowel duration, speech rate; C. Lam & Kitamura, 2012). Recent research also suggests that mothers adjust prosodic characteristics of their speech to their child with hearing impairment on the basis of the child’s amount of hearing experience rather than the child’s chronological age (Bergeson et al., 2006; Kondaurova & Bergeson, 2011; Kondaurova et al., 2013). However, mothers also produced more syllables in speech overall to both age-matched and experience-matched children than to the children’s peers with hearing impairment at 3, 6, and 12 months after cochlear implantation. These findings further support the possibility that a child’s hearing status may affect the segmental properties of ID speech (Kondaurova et al., 2013). Overall, further investigation of phonetic characteristics of ID speech to sizeable groups of children with hearing impairment who received assistive devices (both cochlear implants and hearing aids) is needed in order to understand how properties of maternal speech vary as a function of child hearing status and how this input may contribute to language delays (and their prevention) in pediatric populations with hearing impairment.

The present research examines acoustic characteristics of three point vowels—/i/, /a/, and /u/—in speech to children with hearing impairment who received either cochlear implants (Study 1) or hearing aids (Study 2). Investigating speech to both groups of children with hearing impairment allows us to separately examine the characteristics of ID speech specific to each of these groups that differ in age and type of assistive device (which may be related to amount of residual hearing). These acoustic properties of speech to children with hearing impairment were then compared with those produced in speech to children with normal hearing, matched by either chronological age or hearing experience, and to an adult experimenter. This study design permitted

a determination of whether mothers tailor their speech input to the amount of hearing experience of a child with hearing impairment, as has been found in previous studies (Bergeson et al., 2006; Kondaurova & Bergeson, 2011; Kondaurova et al., 2013). We predicted that the acoustic properties of the point vowels /i/, /a/, and /u/ would be more distinctive in ID than in AD speech in the population with normal hearing (Burnham et al., 2002; Kuhl et al., 1997; Liu et al., 2003, 2009; Uther et al., 2007). We also predicted that there would be less vowel space expansion in input directed to children with hearing impairment than in that directed to control groups for ID relative to AD speech (Kondaurova et al., 2012; C. Lam & Kitamura, 2010, 2012).

Study 1

Study 1 investigated how a child's hearing status affected the vowel space characteristics associated with the point vowels /i/, /a/, and /u/ between ID and AD speech. In this study, we focused on vowels in speech directed to children with profound hearing loss who were fitted with cochlear implants (HI-CI), compared with speech directed to children with normal hearing matched on chronological age (NH-CAM) or amount of hearing experience (NH-HEM).

Method

Participants

All mothers were native speakers of American English. Twenty dyads of mothers with normal hearing and their children with hearing impairment fitted with cochlear implants (HI-CI; five girls, 15 boys) were recruited from the clinical population at the Indiana University School of Medicine Department of Otolaryngology—Head and Neck Surgery. The HI-CI group of participants was invited for two visits at approximately 3 and 6 months after cochlear implant stimulation. Table 1 shows the means, standard deviations, and ranges for the ages of the children with hearing impairment. Table 2 provides available information on communication method, deafness etiology, and the type of cochlear implant device for each child in the HI-CI group.

Twenty dyads of mothers with normal hearing and their chronological age-matched children with normal hearing (NH-CAM; 13 girls, seven boys) were recruited from the local community (see Table 1 for details). The NH-CAM children had a chronological age that was matched to that of the HI-CI children at the time of each of the two visits. Twenty dyads of mothers with normal hearing and their hearing experience-matched children with normal hearing (NH-HEM; eight girls, 12 boys) were recruited from the local community (see Table 1 for details).¹ They

¹One mother contributed two speech samples in this study. One sample was from her interaction with her child who had a cochlear implant, and the second was from a separate recorded interaction with her child with normal hearing who was used as an NH-HEM to a different HI-CI participant.

were invited for two sessions that coincided with the HI-CI children's amount of hearing experience (i.e., time poststimulation) at the time of the visit. Thus, NH-HEM children were approximately 3 and 6 months of age at the two visits.

This research and the recruitment of human participants were approved by the Indiana University Institutional Review Board. All mothers were paid \$10 per visit, and most mothers of HI-CI children received reimbursement for mileage and lodging.

Procedure

Recordings

Mothers were digitally recorded speaking to their children and to an adult experimenter in a double-walled, copper-shielded sound booth (Industrial Acoustics Co., New York, NY). In the ID condition the mother was asked to sit with her child on a chair or blanket on the floor and was instructed to speak to her child as she normally would at home. The mother was provided with quiet toys (i.e., green key, pink ball, green turtle, brown dog, blue button, and black cat) but was not explicitly told to say the toy names. In the AD condition each mother gave responses in a semistructured short interview, with an adult experimenter utilizing open-ended questions. Both tasks used spontaneous speech in order to generate a sample that was as naturalistic as possible. ID sessions averaged 5.1 min in length ($SD = 0.9$; range = 2.5–9.6) and AD sessions averaged 4.6 min in length ($SD = 2.7$; range = 1.3–20.5). The order of ID and AD recordings was counterbalanced across mothers.

Mothers' speech was recorded in one of two ways. The initial system used a hypercardioid microphone (ES933/H, Audio-Technica, Tokyo, Japan) powered by a phantom power source and linked to an amplifier (DSC 240) and digital audio tape recorder (DTC-690, Sony, Tokyo, Japan). Partway through this longitudinal project, the equipment was updated to an SLX Wireless Microphone System (Shure, Niles, IL). This system included an SLX1 Bodypack transmitter with a built-in microphone and an SLX4 wireless receiver, which was connected to a 3CCD Digital Video Camcorder GL2 NTSC (Canon, Tokyo, Japan) and recorded the speech samples directly onto a Macintosh computer (OSX Version 10.4.10; Apple Inc., Cupertino, CA) via Hack TV (Version 1.11) software. No systematic differences were found across recording sessions or participant groups in terms of recording technology. Recordings were made at a sampling rate of 22050 Hz with a 16-bit quantization rate.

Mothers were recorded speaking to their children at two sessions and to an adult experimenter at one or both of these sessions. In total, there were 238 recordings (ID condition: HI-CI group = 40 recordings, NH-CAM group = 40 recordings, NH-HEM group = 40 recordings; AD condition: HI-CI group = 38 recordings, NH-CAM group = 40 recordings, NH-HEM group = 40 recordings).²

²Two mothers from the HI-CI group had AD recordings at only one session, whereas the rest of the participants had AD recordings at both sessions. All the participants had ID recordings at both sessions.

Table 1. Age (in months) and hearing experience of participants with hearing impairment fitted with cochlear implants (HI-CI) or hearing aids (HI-HA), their chronological-age matches with normal hearing (NH-CAM), and of their hearing-experience matches with normal hearing (NH-HEM).

Group and age classification	First session		Second session	
	Range	<i>M</i> (<i>SD</i>)	Range	<i>M</i> (<i>SD</i>)
Study 1				
HI-CI group: chronological age	11.2–27.6	18.2 (4.9)	15.8–32.2	21.6 (5.0)
NH-CAM group: chronological age	11.4–27.5	18.2 (4.8)	15.9–32.0	21.6 (4.9)
HI-CI group: hearing experience	2.8–3.6	3.1 (0.3)	5.6–8.0	6.5 (0.6)
NH-HEM group: chronological age	2.8–4.3	3.2 (0.5)	5.0–9.3	6.7 (1.2)
Study 2				
HI-HA group: chronological age	5.6–22.3	11.9 (5.6)	8.7–24.2	14.8 (5.2)
NH-CAM group: chronological age	5.5–21.6	11.5 (5.3)	8.6–23.8	14.7 (5.0)
HI-HA group: hearing experience	2.3–4.5	3.3 (0.5)	4.7–7.9	6.2 (0.8)
NH-HEM group: chronological age	2.3–6.6	3.4 (1.1)	5.0–8.0	6.2 (0.8)

Token Identification

For each ID and AD condition, instances of target /i/, /a/, and /u/ vowels were identified. We included only those vowels that occurred in stressed syllables, defined as monosyllabic content words and primary-stressed syllables of polysyllabic words. Because vowels were extracted from spontaneous speech, they occurred in a variety of segmental

contexts; however, the segmental contexts were comparably varied across ID and AD conditions. Vowels in onomatopoeic speech were included only if the onomatopoeic words were part of a standard vocabulary of imitation sounds (e.g., *beep*, *boo*, *moo*). Due to a vowel merger between /a/ and /ɔ/ in progress in Indiana (Labov, Ash, & Boberg, 2006), it was impossible to reliably determine for a given speaker

Table 2. Hearing assistive device type and processor, communication method, and deafness etiology for participants with hearing impairment fitted with cochlear implants (Study 1) or hearing aids (Study 2)

Code	Device	Processor	Communication method ^a	Etiology
Study 1				
2514	Nucleus 24 K	Sprint	Total	Genetic
2515	Nucleus 24 Contour	Sprint	Cued speech	Auditory neuropathy
2518	Nucleus 24 Contour	Sprint	Oral	Genetic
2519	Med-El C 40+	Tempo +	Oral	Waardenburg syndrome
2523	Nucleus 24 Contour	Sprint	Oral	Unknown
2528	Nucleus 24 Contour	Sprint	Total	Unknown
2529	Med-El C 40+	Tempo +	Oral	Branchio-oto-renal syndrome
2533	Nucleus 24 Contour	Sprint	Oral	Genetic
2534	Nucleus 24 Contour	Sprint	Oral	Auditory neuropathy/LVA
2535	Nucleus Freedom—Contour Adv.	Freedom	Oral	Mondini
2536	Clarion HiRes 90 k	PSP	Total	Unknown
2537	Nucleus Freedom—Straight	Freedom	Total	VATER syndrome
2540	Nucleus Freedom—Contour Adv.	Freedom	Oral	Unknown
2542	Nucleus Freedom—Contour Adv.	Freedom	Oral	Unknown
2543	Nucleus Freedom—Contour Adv.	Freedom	Oral	Unknown
2795	Nucleus Freedom—Contour Adv.	Freedom	Oral	Genetic
2813	Nucleus Freedom—Contour Adv.	Freedom	Oral	Unknown
3029	Advanced Bionics HiRes 90 K	PSP/Harmony	Oral	Unknown
3058	Nucleus Freedom—Contour Adv.	Freedom	Oral	Unknown
3098	Nucleus Freedom—Contour Adv.	Freedom	Oral	Unknown
Study 2				
2114	Oticon Gaia BTEs		Oral	Genetic
2489	Phonak Maxx 211 BTE		Total	Unknown
2491	Phonak Maxx 311 BTEs		Unavailable	Unavailable
2493	Oticon Gaia BTEs		Unavailable	Unavailable
2744	Phonak Power Maxx 411 BTEs		Unavailable	Unavailable
2769	Phonak Maxx 311 BTEs		Oral/Signed Exact English	mitochondrial myopathy/LVA
2884	Phonak Maxx 311 BTEs		Total	Unknown
2891	Oticon Gaia Power BTEs		Oral	Leigh's disease
3029	Oticon Tego Pro BTEs		Oral	Unknown
3031	Oticon Sumo BTE (L), Oticon Tego Pro BTE		Oral/American Sign Language	Unknown
3699	Oticon Tego Pro BTEs		Oral	Unknown

Note. LVA = large vestibular aqueduct; Adv. = advanced; VATER = vertebral, anus, trachea, esophagus, and/or renal abnormalities; BTE = behind-the-ear.

^aCommunication method describes exclusively spoken language (oral) or a combination of spoken language with Signed Exact English (total).

whether a particular token of a low back vowel reflected a single phonemic category or two, given the expectation of substantial within-category variation in the vowel space for the ID register overall. As a result, all instances of low back vowels were treated as a single category. Furthermore, vowel tokens immediately followed by /l/ and /r/ were excluded from the study to prevent any effects of /l/- and /r/-coloring on formant measurements.

The acoustic analysis included measurements of formant frequencies for the three point vowels /i/, /a/, and /u/, which also formed the basis for calculations of vowel space area and vowel space dispersion. The spontaneous nature of the speech led to a low number of analyzable tokens of these vowels in many of the mothers' speech samples. Therefore, speech samples from both recording intervals were combined and treated as a single speech sample in order to ensure that enough data were available for analysis. In addition, the following procedures were applied in the collection of tokens from participants: (a) If a mother in any group (HI-CI, NH-CAM, NH-HEM) produced fewer than three tokens of a point vowel that met inclusion criteria in either speech condition (AD, ID), the mother's data for that vowel would be excluded from the following acoustic analysis; (b) if a mother produced more than 20 tokens of a given vowel in either speech condition (AD, ID), a random sample of 20 vowel tokens was used for the analysis; (c) if a mother was excluded from the analysis of any point vowel on the basis of criterion *a*, this mother's data was also excluded from measurements of vowel space area and dispersion because these measures are dependent on having samples of all three point vowels; and (d) tokens from speech to children with normal hearing were included only in the analyses in which the HI-CI match child had met the previous inclusion criteria and vice versa. On the basis of these standards, 57 participants (19 per group: HI-CI, NH-CAM, and NH-HEM) were included for /a/ formant measures, 45 participants (15 per group) for /i/, and 42 participants (14 per group) for /u/. Thirty-three participants (11 per group) were included in measures of vowel space area and dispersion.

On average, 11 ($SD = 5.2$) tokens of each vowel (/i/, /a/, and /u/) were analyzed in the ID speech condition and 16 ($SD = 5.6$) tokens of each vowel for each speaker were analyzed in the AD speech condition. A total of 929 tokens in the ID speech condition and 1,609 tokens in the AD speech condition were analyzed. The PRAAT 5.0.21 editor (Boersma & Weenink, 2012) and MATLAB (Math Works, 2009) software were used to identify and segment out each vowel in recorded speech on the basis of a combination of waveform and spectral cues.

Acoustic Analysis

Formant frequencies. Phonetic analysts trained in formant analysis first identified the onset and offset of each randomly selected vowel token via visual inspection of spectrogram and waveform information using segmentation criteria established for the Buckeye Corpus (Pitt et al., 2007). Measurements of F1 and F2 were then taken at the vowel midpoint using a combination of spectral slices, visual

inspection of spectrograms, and linear predictive coding estimates; all F1 and F2 measurements were checked by hand for correctness. Analysts identified individual tokens of the target vowels as usable if the first two formants were reasonably clear and measurements fell within an expected range of the mean, plus or minus 3 SD , as determined by mean formant values for female talkers across multiple studies tabulated in Kent and Read (1992). Tokens that fell outside the expected range, that had strongly stratified harmonics, or for which F1 or F2 could not be determined due to high fundamental frequency (F0), coarticulation, poor sound quality, background noise, and so on were checked by one of the authors for usability before being included in or excluded from the analysis. All tokens with an F0 of 350 Hz or higher were excluded due to the quantization of the spectrum (i.e., the trade-off between F0 and formant resolution in time-frequency analysis under source-filter theory; Johnson, 2004; Stevens, 2000); this provided a means of reducing variability and unreliability associated with measurements of high-F0 tokens (Vallabha & Tuller, 2002). If a randomly selected token of a given vowel was excluded for any reason, it was replaced by another token of that vowel randomly selected from among the remaining tokens produced by that mother in the same speech condition. A total of 12% of selected tokens were excluded for various reasons (5% AD condition, 19% ID condition); of these, 65% were excluded for high F0 (33% AD condition, 76% ID condition).

Formant values in Hertz were then converted to mel units. The mel scale is based on psychophysical studies of pitch distance and reflects human perception of frequency more directly than linear Hertz. The relationship between the mel scale and Hertz is a nonlinear, strictly monotonic increasing function, such that above 500 Hz larger and larger intervals are judged by listeners to produce equal pitch increments. The mel scale has been used in many prior studies of vowel space and formant characteristics (e.g., Bradlow, Torretta, & Pisoni, 1996; Englund & Behne, 2005; Kuhl et al., 1997; C. Lam & Kitamura, 2010, 2012). The following equation was used for the conversion of Hertz (Hz) to mels (Fant, 1973, in Bradlow et al., 1996):

$$\text{mels} = \frac{1000}{\log 2} \times \log \left(\frac{\text{Hz}}{1000} + 1 \right).$$

The mels conversion provided the basis for all analyses reported. The means and standard deviations of F1 and F2 were determined for each speaker in both the ID and AD speech conditions.

Vowel space area. Vowel space triangles were constructed in an x - y plane, where the average F1 and F2 values of /i/, /a/, and /u/ vowels were the respective x and y coordinates of the corners. The area of the resultant triangles in both the ID and AD conditions was calculated using the following equation (Liu et al., 2003):

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

Vowel space dispersion. Previous research on AD speech has identified vowel space dispersion as a good index of speech clarity (Bradlow et al., 1996). The vowel space dispersion is calculated by measuring the distance of each token from a central point in the talker's vowel space. This measure provides an indication of the overall expansion or compaction of the set of vowel tokens from each participant and detects fine-grained individual differences in acoustic-phonetic characteristics (Bradlow et al., 1996). By capturing an aspect of vowel production characteristics that is slightly different than that captured using the traditional Heron method (Kuhl et al., 1997; Neel, 2008), this metric helps to provide an assessment of vowel clarity. Vowel space dispersion was calculated using the centroid of each speaker's vowel space triangle and averaging the distances of the individual tokens from the centroid (see Appendix for further detail; Bradlow et al., 1996).

Reliability

The formants of any vowel token whose F1 or F2 was 2 *SD* or more away from a given participant's mean F1 or F2, respectively, were checked by hand to ensure accuracy. In addition, trained analysts remeasured a random selection of 5% of the tokens used in each speech sample for an analysis of interrater reliability. The percentage difference (Δ_i) between the first rater's measurement (r_1) and the second rater's measurement (r_2) was calculated using the equation (Kuhl et al., 1997)

$$\Delta_i = [(|r_1 - r_2|)/r_1] \times 100\%.$$

The average interrater percentage difference was 8.0% ($SD = 8.4$). This is in line with reliability reported in previous studies and indicates high interrater reliability (e.g., Kuhl et al., 1997).

Results and Discussion

Vowel Space Area and Vowel Space Dispersion

We first examined whether an overall difference in vowel space area or vowel space dispersion existed. The means and standard deviations of the vowel space area and dispersion values for ID and AD speech in all three groups are reported in Table 3, and Figure 1 shows vowel space triangles for each group. A 2 (speech style: AD, ID) \times 3 (hearing status: HI-CI, NH-CAM, NH-HEM) mixed-measures analysis of variance (ANOVA) was conducted separately for vowel space area and vowel space dispersion, with speech style as a within-subject factor and hearing status as a between-subjects factor.

The vowel space area results demonstrated a significant effect of speech style, with ID ($M = 80487$ mels, $SD = 36707$ mels) greater than AD ($M = 57094$ mels, $SD = 28769$ mels) speech, $F(1, 30) = 12.299$, $p = .001$, $\eta_p^2 = .291$, but no significant main effect of hearing status or interaction between hearing status and speech style were

Table 3. Average (SD) vowel space area in mels squared and vowel space dispersion in mels for infant-directed (ID) and adult-directed (AD) speech to participants with hearing impairment fitted with cochlear implants (HI-CI, Study1) or hearing aids (HI-HA, Study 2), their chronological-age matches with normal hearing (NH-CAM), and their hearing-experience matches with normal hearing (NH-HEM).

Variable	Hearing status	AD	ID
Study 1			
Area	HI-CI	54878 (32496)	82922 (41161)
	NH-CAM	63672 (31090)	79326 (35213)
	NH-HEM	52730 (23493)	79213 (36981)
	All	57094 (28769)	80487 (36707)
Dispersion	HI-CI	330 (31)	336 (35)
	NH-CAM	322 (33)	333 (34)
	NH-HEM	309 (32)	342 (32)
	All	337 (33)	320 (32)
Study 2			
Area	HI-HA	45159 (19952)	62913 (21529)
	NH-CAM	58609 (14510)	61842 (14207)
	NH-HEM	48914 (13235)	74872 (43906)
	All	50894 (16264)	66542 (28277)
Dispersion	HI-HA	307 (23)	349 (43)
	NH-CAM	329 (19)	315 (18)
	NH-HEM	310 (22)	347 (31)
	All	315 (23)	337 (34)

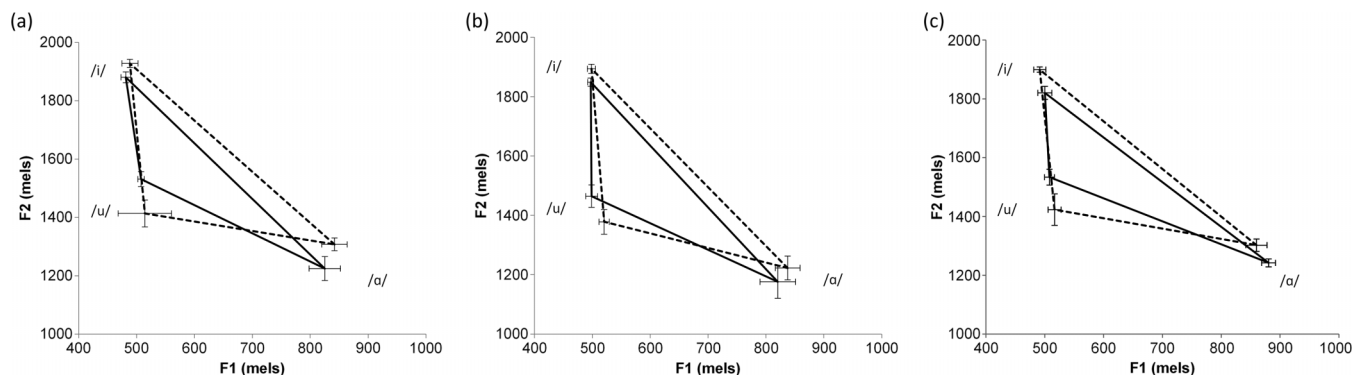
found. The vowel space dispersion results demonstrated a significant effect of speech style, with ID ($M = 337$, $SD = 33$) greater than AD ($M = 320$ mels, $SD = 32$ mels) speech, $F(1, 30) = 5.967$, $p = .021$, $\eta_p^2 = .166$, but no significant main effect of hearing status or interaction between hearing status and speech style were found.

Formant Frequencies

The means and standard deviations for F1 and F2 frequencies of each point vowel in each group are shown in Table 4. A 2 (speech style: AD, ID) \times 3 (hearing status: HI-CI, NH-CAM, NH-HEM) mixed-measures ANOVA was conducted separately for each point vowel (/i/, /a/, and /u/), with speech style as a within-subject factor and hearing status as a between-subjects factor.

The results for /i/ demonstrated a significant effect of speech style, with F2 higher in ID compared with AD speech, $F(1, 42) = 60.087$, $p < .001$, $\eta_p^2 = .589$, indicating a more advanced or fronted tongue position in ID ($M = 1905$ mels, $SD = 46$ mels) relative to AD ($M = 1841$ mels, $SD = 66$ mels) speech. The results also demonstrated a significant effect of hearing status for F2, $F(1, 42) = 3.681$, $p = .034$, $\eta_p^2 = .149$, but no interaction between hearing status and speech style was found. Posthoc Tukey tests revealed that the F2 frequency was higher in the HI-CI group ($M = 1895$ mels, $SD = 597$ mels) compared with the NH-HEM group ($M = 1850$ mels, $SD = 584$ mels), $p = .026$. These results suggest a more advanced or fronted tongue position across speech styles for the HI-CI group compared with the NH-HEM group. Because this difference is present for both ID and AD speech, it is not likely due to an effect of the child's hearing status and may reflect other variables,

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 \pm 1 SEM.



such as interindividual differences. No significant main effects or interaction were found for F1.

The results for /a/ demonstrated a significant effect of speech style, with F2 higher in ID compared with AD speech, $F(1, 54) = 11.165, p = .002, \eta_p^2 = .171$, indicating a more advanced or fronted tongue position in ID ($M = 1267$ mels, $SD = 113$ mels) relative to AD ($M = 1205$ mels, $SD = 141$ mels) speech. The results also demonstrated a significant effect of hearing status for F2, $F(1, 54) = 4.744, p = .013, \eta_p^2 = .149$, but no interaction between hearing status and speech style was found for F2. Posthoc Tukey tests revealed that the F2 frequency was higher in the HI-CI group ($M = 1269$ mels, $SD = 107$ mels) than in the NH-CAM group ($M = 1178$ mels, $SD = 171$ mels), $p = .020$. These results suggest a more advanced or fronted tongue position across speech styles for the HI-CI group than for the NH-CAM group. Because this difference in F2 is present for both ID and AD speech, it is not likely due to an effect

of the child's hearing status and may reflect other variables, such as interindividual differences. No significant main effects or interaction were found for F1.

The results for /u/ demonstrated a significant effect of speech style, with F2 lower in ID compared with AD speech, $F(1, 39) = 16.728, p < .001, \eta_p^2 = .300$, suggesting a more retracted or backed tongue position in ID ($M = 1413$ mels, $SD = 151$ mels) relative to AD ($M = 1506$ mels, $SD = 105$ mels) speech. No main effect of hearing status or interaction between hearing status and speech style were found for F2. No significant main effects or interaction were found for F1.

Summary

Overall, Study 1 demonstrated a more expanded vowel space area and greater vowel space dispersion in ID compared with AD speech, which was reflected in the

Table 4. Average (SD) first formant (F1) and second formant (F2) frequencies in mels for the point vowels /i/, /a/, and /u/ in infant-directed (ID) and adult-directed (AD) speech to participants with hearing impairment fitted with cochlear implants (HI-CI, Study 1) or hearing aids (HI-HA, Study 2), their chronological-age matches with normal hearing (NH-CAM), and their hearing-experience matches with normal hearing (NH-HEM).

Hearing status	Speech style	/i/		/a/		/u/	
		F1	F2	F1	F2	F1	F2
Study 1							
HI-CI	AD	475 (28)	1866 (60)	835 (73)	1238 (126)	526 (40)	1531 (104)
	ID	481 (36)	1924 (51)	842 (60)	1300 (77)	520 (50)	1409 (146)
NH-CAM	AD	495 (21)	1852 (43)	808 (122)	1145 (195)	499 (30)	1475 (116)
	ID	495 (25)	1895 (46)	825 (62)	1211 (141)	525 (30)	1391 (150)
NH-HEM	AD	502 (34)	1805 (76)	869 (53)	1232 (45)	508 (25)	1510 (92)
	ID	490 (33)	1895 (36)	839 (80)	1291 (94)	534 (54)	1440 (163)
Study 2							
HI-HA	AD	515 (33)	1853 (59)	829 (64)	1209 (80)	522 (24)	1523 (94)
	ID	524 (46)	1933 (77)	814 (54)	1272 (97)	527 (45)	1469 (93)
NH-CAM	AD	485 (30)	1842 (35)	869 (28)	1233 (61)	498 (35)	1526 (53)
	ID	500 (32)	1892 (29)	877 (51)	1295 (56)	524 (50)	1456 (106)
NH-HEM	AD	484 (38)	1853 (63)	868 (46)	1227 (36)	505 (23)	1488 (161)
	ID	485 (24)	1914 (52)	863 (81)	1309 (66)	516 (40)	1398 (197)

distribution of the individual vowels /i/, /a/, and /u/ as a systematic shifting in F2 frequency between ID and AD speech across all three groups (HI-CI, NH-CAM, NH-HEM). These findings indicate that the /a/ and /i/ vowels were produced with a more fronted or advanced tongue position and that the /u/ vowel was produced with a more backed or retracted tongue position in ID compared with AD speech. A relatively expanded vowel space area and greater dispersion are consistent with previous findings of greater vowel contrastiveness and clarity in ID than AD speech (e.g., Kuhl et al., 1997).

Study 2

Whereas Study 1 examined vowels in speech to children with profound hearing loss who were fitted with cochlear implants, Study 2 focused on vowels in speech to children with little to moderate hearing loss who had some residual hearing. Due to different amounts of hearing loss and the presence of residual hearing for children with hearing aids, it is possible that the results from Study 1 would not be generalizable to this population. In addition, children are typically fitted with hearing aids at an earlier age than a cochlear implant, which may affect characteristics of speech style to younger children with or without hearing impairment. Study 2 therefore investigated the vowel space characteristics associated with the point vowels /i/, /a/, and /u/ between ID and AD speech directed to children with hearing impairment fitted with hearing aids and children with normal hearing matched on chronological age or amount of hearing experience.

Method

Participants

All mothers were native speakers of American English. Eleven dyads of mothers with normal hearing and children with hearing impairment fitted with hearing aids (HI-HA; five girls, six boys) were recruited from the same population as Study 1 at the DeVault Otologic Research Laboratory at Indiana University School of Medicine. The HI-HA group of participants was invited for two visits at approximately 3 and 6 months after hearing aid fitting. Table 1 shows the means, standard deviations, and ranges for the ages of the children with hearing impairment. Table 2 provides available information on communication method, deafness etiology, and the type of hearing aid device for each child in the HI-HA group.

Eleven dyads of mothers with normal hearing and their chronological age-matched children with normal hearing (NH-CAM; three females, eight males) were recruited from the local community (see Table 1 for details). The NH-CAM children had a chronological age that was matched to that of the HI-HA children at the time of each of the two visits. Eleven dyads of mothers with normal hearing and their hearing experience-matched children with normal hearing (NH-HEM; six females, five males) were

recruited from the local community (see Table 1 for details). They were invited for two sessions that coincided with the HI-HA children's amount of hearing experience at the time of the visit. Thus, NH-HEM children were approximately 3 and 6 months of age at the two visits. Eight NH-HEM participants were also included as NH-HEMs in Study 1. Research approval and participant reimbursement were identical to that in Study 1.

Procedure

Recordings

The recording procedure was identical to that in Study 1. ID sessions averaged 4.9 min in length ($SD = 0.7$; range = 2.8–6.9) and AD sessions averaged 5.1 min in length ($SD = 2.7$; range = 1.3–13.4). In total, there were 130 recordings (ID condition: HI-HA group = 22 recordings, NH-CAM group = 22 recordings, NH-HEM group = 22 recordings; AD condition: HI-HA group = 22 recordings, NH-CAM group = 21 recordings, NH-HEM group = 21 recordings).

Token identification. The token identification procedure and inclusion criteria were identical to those in Study 1. Thirty participants (10 per group, HI-HA, NH-CAM, and NH-HEM) were included for /a/ formant measures, 27 participants (nine per group) for /i/, and 27 participants (nine per group) for /u/. Eighteen participants (six per group) were included in measures of vowel space area and dispersion.

On average, 10 ($SD = 5.8$) tokens of each vowel (/i/, /a/, and /u/) were analyzed in the ID speech condition and 18 ($SD = 3.6$) tokens of each vowel for each speaker were analyzed in the AD speech condition. A total of 1,631 tokens in the ID speech condition and 2,319 tokens in the AD speech condition were analyzed.

Acoustic analysis. Analysis procedures for measuring vowel space area, vowel space dispersion, and F1 and F2 frequencies were identical to those in Study 1. A total of 13% of selected tokens were excluded for various reasons (7% AD condition, 22% ID condition); of these, 59% were excluded for high F0 (26% AD condition, 74% ID condition).

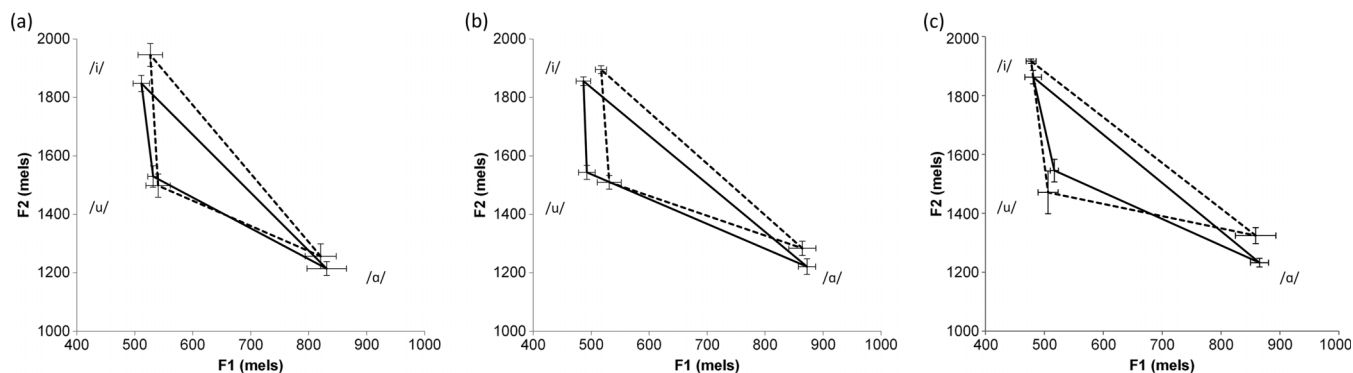
Reliability. Interrater reliability analysis procedures were identical to those in Study 1. The average interrater percentage difference was 6.8% ($SD = 6.2$), indicating high reliability consistent with that of prior studies (e.g., Kuhl et al., 1997).

Results and Discussion

Vowel Space Area and Vowel Space Dispersion

We first examined whether an overall difference in vowel space area or vowel space dispersion existed. The means and standard deviations of the vowel space area and dispersion values for ID and AD speech in all three groups of participants are reported in Table 3, and Figure 2 shows vowel space triangles for each group. A 2 (speech style: AD, ID) \times 3 (hearing status: HI-HA, NH-CAM, NH-HEM) mixed-measures ANOVA was conducted separately for

Figure 2. 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 hearing aids, (b) chronological-age matches with normal hearing, and (c) hearing-experience matches with normal hearing. Error bars show mean \pm 1 SEM.



vowel space area and vowel space dispersion, with speech style as a within-subject factor and hearing status as a between-subjects factor.

The vowel space area results demonstrated narrowly missed significance for the effect of speech style, $F(1, 15) = 4.075, p = .062, \eta_p^2 = .214$; in addition, no significant main effect of hearing status or interaction between hearing status and speech style were found. The vowel space dispersion results demonstrated a significant effect of speech style, $F(1, 15) = 6.911, p = .019, \eta_p^2 = .315$, with ID ($M = 337$ mels, $SD = 34$ mels) greater than AD ($M = 315$ mels, $SD = 23$ mels) speech. Although no main effect of hearing status was found, there was a significant interaction between hearing status and speech style, $F(2, 15) = 4.884, p = .023, \eta_p^2 = .394$. This interaction appears to be driven by the fact that the HI-HA group, but not the other two groups, showed significantly greater ID than AD dispersion in a one-way ANOVA examining the simple effects of speech style; HI-HA: $F(1, 5) = 8.717, p = .032, \eta_p^2 = .635$; NH-CAM: $F(1, 5) = 1.270, p = .203, \eta_p^2 = .635$; NH-HEM: $F(1, 5) = 5.790, p = .061, \eta_p^2 = .537$.

Formant Frequencies

The means and standard deviations for F1 and F2 frequencies of each point vowel in each group are shown in Table 4. A 2 (speech style: AD, ID) \times 3 (hearing status: HI-HA, NH-CAM, NH-HEM) mixed-measures ANOVA was conducted separately for each point vowel (/i/, /a/, and /u/), with speech style as a within-subject factor and hearing status as a between-subjects factor.

The results for /i/ demonstrated a significant effect of speech style, with F2 higher in ID compared with AD speech, $F(1, 24) = 35.216, p < .001, \eta_p^2 = .595$, indicating a more advanced or fronted tongue position in ID ($M = 1913$ mels, $SD = 57$ mels) relative to AD ($M = 1849$ mels, $SD = 52$ mels) speech. No significant main effect of hearing status or interaction between hearing status and speech style were found for F2. For F1, a significant effect of hearing status was

found, $F(1, 24) = 3.934, p = .033, \eta_p^2 = .247$, and a posthoc Tukey test demonstrated that F1 was higher in the HI-HA group ($M = 520$ mels, $SD = 39$ mels) compared with the NH-HEM group ($M = 484$ mels, $SD = 31$ mels), $p = .033$. No significant effect of speech style or interaction between hearing status and speech style were found for F1.

The results for /a/ demonstrated a significant effect of speech style, with F2 higher in ID compared with AD speech, $F(1, 27) = 24.002, p < .001, \eta_p^2 = .471$, indicating a more advanced or fronted tongue position in ID ($M = 1292$ mels, $SD = 74$ mels) relative to AD ($M = 1223$ mels, $SD = 60$ mels) speech. No significant main effect of hearing status or interaction between hearing status and speech style were found for F2. No significant main effects or interaction were found for F1.

The results for /u/ demonstrated a significant effect of speech style, with F2 lower in ID compared with AD speech, $F(1, 24) = 10.898, p = .003, \eta_p^2 = .312$, suggesting a more retracted or backed tongue position in ID ($M = 1441$ mels, $SD = 138$ mels) relative to AD ($M = 1512$ mels, $SD = 109$ mels) speech. No significant main effect of hearing status or interaction between hearing status and speech style were found for F2. No significant main effects or interaction were found for F1.

Summary

Overall, Study 2 demonstrated greater vowel space dispersion in ID compared with AD speech, which was reflected in the distribution of the individual vowels /i/, /a/, and /u/ as a systematic shifting in F2 frequency in all three groups (HI-HA, NH-CAM, NH-HEM). These findings indicate that the /a/ and /i/ vowels were produced with a more fronted or advanced tongue position and that the /u/ vowel was produced with a more backed or retracted tongue position in ID compared with AD speech. These results also suggest that hearing status affected the production of acoustic characteristics of the vowel /i/. The lack of a significant effect of speech style (ID vs. AD, $p = .062$) on vowel space

area may reflect a Type II error associated with relatively small sample size and/or substantial interindividual variability.

General Discussion

Previous studies have demonstrated a relationship between the degree of mothers' speech clarity measured by vowel space area expansion and enhanced speech-language skills in children with normal hearing (Kuhl et al., 1997; Liu et al., 2003). Given that phonetic characteristics of mothers' speech input are affected by a child's hearing status (Bergeson et al., 2006; Kondaurova & Bergeson, 2011; Kondaurova et al., 2013; C. Lam & Kitamura, 2010, 2012), we investigated the effects of hearing status on production of vowel formant frequencies to understand the nature of the spoken language input typically experienced by children with hearing impairment. Here, we examined the modification of acoustic characteristics of three point vowels (/i/, /a/, and /u/) in spontaneous speech directed to children with hearing impairment and to children and adults with normal hearing. Across two studies, mothers of children with hearing impairment fitted with either a cochlear implant (Study 1) or a hearing aid (Study 2) were matched to mothers of children with normal hearing who had the same chronological age or the same amount of hearing experience as the children with hearing impairment.

The present studies demonstrated overall a more expanded vowel space area and dispersion in ID speech to children with and without hearing impairment compared with AD speech. The identified expansion of vowel space area and dispersion in ID speech to children with hearing impairment is a novel finding, as this is the first study to demonstrate that mothers produce more distinctive point vowels in speech to children with hearing impairment compared with AD speech. The present study also demonstrated generally larger vowel space dispersion in ID compared with AD speech. Vowel space dispersion reflects the overall expansion, or compaction, of the tokens from each talker and is positively correlated with both vowel space area and intelligibility (Bradlow et al., 1996). Our results using the vowel dispersion metric in spontaneous speech are consistent with the idea that mothers are producing vowels in a clearer manner when talking to children both with and without hearing impairment. Given prior links established with speech-language skills (Liu et al., 2003), developing an evidence base for how specific characteristics of speech-language input might contribute to—or prevent—language delays in pediatric populations with hearing impairment is the next step. Such investigations are especially needed given that (a) speech-language delays in these populations are common and (b) there are highly variable speech-language outcomes, particularly for children with hearing impairment using cochlear implants (Houston et al., 2003; Miyamoto et al., 1997; Niparko et al., 2010; Pisoni et al., 2008; Svirsky et al., 2000). This variability in outcomes may be explained by differences in the quality of maternal

speech input to children with hearing impairment, a factor that is potentially amenable to intervention by trained speech-language pathologists.

Many researchers have investigated the benefits of speech produced with a clear speaking style. Smiljanic and Sladen (2013) found that children between the ages of 5 and 13 years both with and without hearing impairments who listened to speech in noise showed improved understanding when listening to clear speech (characterized by a slower speech rate, longer target vowels, and expanded vowel space) in comparison with a control speech context. Ferguson (2012) found that the intelligibility-enhancing properties of vowels in clear speech were beneficial for young adults with normal hearing as well as older adults with hearing impairments. J. Lam, Tjaden, and Wilding (2012) asked speakers to read sentences with different instructions for eliciting clear speech; they found that the greatest magnitude of change in vowel spectral measures resulted from the instruction to “overenunciate,” followed by the instruction to “talk to someone with a hearing loss” and then to “speak clearly.” Hazan and Baker (2011) investigated spontaneous speech modification and found that talkers asked to speak as if talking to someone with a hearing loss read sentences with more extreme changes in acoustic-phonetic characteristics compared with intelligibility-challenging conditions (i.e., vocoded speech and speech with babble noise added) but that speakers modulated their speech according to their interlocutors' needs even when not directly experiencing the challenging listening condition.

Recent research by C. Lam and Kitamura (2010, 2012) attempted to investigate how vowels may be modified to a population with hearing impairment. Although informative, neither of these studies can be confidently generalized to a broader population of children with hearing impairment. For example, C. Lam and Kitamura (2012) used a subject population with normal hearing combined with an experimental manipulation designed to simulate deafness and found a difference in the size of the mothers' vowel space area in speech directed to children with normal hearing depending on whether the child could hear his or her mother. Moreover, in a case study involving a single pair of twins, C. Lam and Kitamura (2010) showed that the vowel space area in speech directed to a child with hearing impairment was reduced compared with that in speech directed to his twin with normal hearing. The present research is the first to investigate speech to a relatively large sample of children with actual (rather than simulated) hearing impairment, including children with both hearing aids and cochlear implants, thereby significantly extending the generalizability of research findings in these populations.

The generally greater vowel space area and dispersion in ID compared with AD speech found in the current study can largely be accounted for by the shift in F2 frequencies across point vowels observed for ID compared with AD speech. The increases in F2 for /i/ and /a/ indicate a more fronted tongue position in ID compared with AD speech, whereas the decrease in F2 for /u/ indicates a more backed tongue position in ID speech, consistent with prior research

(Bernstein Ratner, 1984; Kondaurova et al., 2012; Kuhl et al., 1997). The point vowels in each study occurred in varied segmental contexts across ID and AD spontaneous speech; thus, these differences between ID and AD speech are unlikely to be accounted for by coarticulatory influences. Overall, the results provide some support for the hypothesis that the point vowels in ID speech are produced in a more phonologically contrastive manner with more distinctive articulatory positions compared with those in AD speech (Kuhl et al., 1997), which extends the tests of this hyperarticulation hypothesis to speech directed to children with hearing impairment. Because enhanced contrastiveness among vowels has been claimed to bootstrap the learning of sound categories by children (Kuhl et al., 1997; Liu et al., 2003), the findings of the current study suggest that mothers may be facilitating language acquisition for children with hearing impairment by producing an expanded acoustic vowel space area and/or increased vowel space dispersion in ID compared with AD speech.

The next question the current study investigated was whether the child's hearing status, amount of hearing experience, or chronological age affected the degree of expansion of vowel space area or dispersion in ID speech. The pattern of results was similar across both studies in that the vowel space area and dispersion were greater in ID compared with AD speech across groups differing in hearing status. Overall, there were few findings that vowel space characteristics differed as a function of hearing status, amount of hearing experience, or chronological age.

Previous research comparing prosodic characteristics (e.g., pitch and timing) of ID speech to children with hearing impairment using cochlear implants demonstrated that mothers adjusted these characteristics to the hearing experience rather than the chronological age of their children (Bergeson et al., 2006; Kondaurova & Bergeson, 2011; Kondaurova et al., 2013). By contrast, in the current study, overall there were few findings that mothers tailored vowel space characteristics to their child's hearing status or produced input that reflected the degree of hearing experience of a child. The present results extend prior studies examining prosodic characteristics in speech to children with hearing impairment and normal hearing (Bergeson et al., 2006; Kondaurova & Bergeson, 2011; Kondaurova et al., 2013) to the production of segmental characteristics of speech. Vowel space modification has been linked to enhanced speech sound discrimination and word recognition (Liu et al., 2003; Song et al., 2010). These findings, coupled with our results showing few differences in mothers' vowel input to their children as a function of hearing status, suggest potential benefits of therapeutic clinical interventions aimed at shaping the vowel space characteristics of mothers' speech to their children with hearing impairment. However, such a recommendation awaits direct evidence of a causal link between particular vowel space modifications and enhancements to speech and/or language processing or production because prior evidence of relationships between an expanded vowel space and speech discrimination measures has been correlational (e.g., Liu et al., 2003). Moreover, an increasing

body of evidence suggests that the nature of phonetic changes that occur in ID speech is complex, with no preponderance of evidence that the changes would benefit learning of phonetic categories (Cristia & Seidl, 2014; Englund, 2005; McMurray, Kovack-Lesh, Goodwin, & McEchron, 2013; Sundberg & Lacerda, 1999).

The current study demonstrated that the distribution of both F1 and F2 frequencies in the acoustic vowel space of a mother depended on the hearing status of her child. Both groups with hearing impairment showed an increase in either F1 or F2 for /i/ and/or /a/ relative to the groups with normal hearing, suggesting that mothers produced these vowels with a more fronted tongue position in their speech. However, these results did not translate to differences in vowel space area or dispersion. Instead, our study found that in speech to children with cochlear implants there was an increase in F2 frequencies for /i/ and /a/ vowels relative to speech in groups matched on chronological age (/a/) and hearing experience (/i/). In contrast, speech to children with hearing aids was characterized by an increase only in F1 frequency values for the /i/ vowel relative to the group matched on hearing experience. The group formant differences shown in this study may be due in part to interindividual differences of some mothers in the levels of our independent variables or to the use of spontaneous speech. Although spontaneous speech has high ecological validity because it constitutes the natural input mediating language acquisition, it is also uncontrolled in a great many variables, including differences in consonantal environment, position of target words in an utterance, length of utterances, and differences in speech rate, all of which can affect acoustic characteristics of vowels (Bernstein Ratner, 1986; Cristia & Seidl, 2014; Englund & Behne, 2005, 2006; Hillenbrand, Clark, & Nearey, 2001; Kondaurova et al., 2012; Kuhl et al., 1997; Stevens & House, 1963). It has been suggested that prosodic differences (e.g., slowed rate, prosodic position) between ID and AD speech may drive some differences in phonetic attributes, including vowel formants (McMurray et al., 2013), and the present study did not assess the impact of such prosodic differences. Therefore, it remains desirable for future research to tease apart these variables and their potential interaction with vowel characteristics of speech to children who differ in degree of hearing impairment and type of assistive device in order to understand how these factors affect language acquisition in populations with hearing impairment.

In summary, this study demonstrated that, overall, mothers modified their acoustic vowel space for the point vowels /i/, /a/, and /u/ in spontaneous speech to children with hearing impairment who received cochlear implants or hearing aids in comparison with AD speech. Overall there were few findings reflecting differences in the nature of acoustic vowel space modifications in ID speech directed to children with hearing impairment relative to matched controls. Taken together, these results suggest that mothers of children with hearing loss who received cochlear implants or hearing aids produce a more contrastive vowel space for the point vowels /i/, /a/, and /u/ in a manner consistent with

the hyperarticulation hypothesis of ID speech (Burnham et al., 2002; Kuhl et al., 1997; Liu et al., 2009; Uther et al., 2007). Given that vowel space modification has been linked to enhanced speech sound discrimination and word recognition (Liu et al., 2003; Song et al., 2010), the present findings suggest potential benefits of therapeutic clinical interventions aimed at shaping the vowel space characteristics of mothers' speech to their children with hearing impairment.

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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:

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