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Effects of deafness on acoustic characteristics of American English tense/lax vowels in maternal speech to infants

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Recent studies have demonstrated that mothers exaggerate phonetic properties of infant-directed (ID) speech. However, these studies focused on a single acoustic dimension (frequency), whereas speech sounds are composed of multiple acoustic cues. Moreover, little is known about how mothers adjust phonetic properties of speech to children with hearing loss. This study examined mothers' production of frequency and duration cues to the American English tense/lax vowel contrast in speech to profoundly deaf ($N = 14$) and normal-hearing ($N = 14$) infants, and to an adult experimenter. First and second formant frequencies and vowel duration of tense (/i/, /u/) and lax (/ɪ/, /ʊ/) vowels were measured. Results demonstrated that for both infant groups mothers hyperarticulated the acoustic vowel space and increased vowel duration in ID speech relative to adult-directed speech. Mean $F2$ values were decreased for the /u/ vowel and increased for the /ɪ/ vowel, and vowel duration was longer for the /i/, /u/, and /ɪ/ vowels in ID speech. However, neither acoustic cue differed in speech to hearing-impaired or normal-hearing infants. These results suggest that both formant frequencies and vowel duration that differentiate American English tense/lx vowel contrasts are modified in ID speech regardless of the hearing status of the addressee.
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I. INTRODUCTION

Previous research has demonstrated that early identification of hearing loss and subsequent intervention methods and choices have a significant impact on infants' linguistic and cognitive development (Bergeson *et al.*, 2003, 2005; Houston *et al.*, 2003; Moeller, 2000; Pisoni *et al.*, 2008; Yoshinaga-Itano *et al.*, 1998). Research with normal-hearing infants suggests that both the quality (Kaplan *et al.*, 2002; Kaplan *et al.*, 1999; Liu *et al.*, 2003) and quantity (Hart and Risley, 1995; Hurtado *et al.*, 2008) of infant-directed (ID) speech is directly related to infants' language, cognitive, and socio-emotional development. However, very little evidence is available on the nature of spoken input to prelingually deaf infants and children prior to and after fitting them with assistive devices, such as hearing aids or cochlear implants (Kondaurova and Bergeson, 2011), despite the importance of maternal speech input for the acquisition of language and cognitive skills (Kaplan *et al.*, 2002; Hart and Risley, 1995; Hurtado *et al.*, 2008; Liu *et al.*, 2003). The present study investigates the influence of pediatric hearing loss on the phonetic characteristics of ID speech in a group of mothers interacting spontaneously with their profoundly deaf infants prior to cochlear implantation.

Recent studies have demonstrated that one of the characteristics of ID speech is the modification of its phonetic properties, in addition to changes in prosody, morphology, syntax, and semantics (Bernstein Ratner, 1986; Burnham *et al.*, 2002; Fernald and Kuhl, 1987; Fernald *et al.*, 1989; Kuhl *et al.*, 1997; Papousek *et al.*, 1987; Soderstrom, 2007; Stern *et al.*, 1983). One of the major phonetic modifications in mothers' speech is the hyperarticulation of vowels that results in an expanded vowel space (indexed by first and second formant frequencies, $F1$ and $F2$) for the point vowels /i/, /u/, and /a/ (Burnham *et al.*, 2002; Kuhl *et al.*, 1997; Uther *et al.*, 2007). This vowel expansion is likely to be a linguistically universal feature (Burnham *et al.*, 2002; Kuhl *et al.*, 1997). Kuhl and colleagues (1997) proposed that the exaggeration of vowel space can benefit the infant in several ways. First, an expanded vowel triangle increases the acoustic difference between vowels and makes them more distinct and easier to differentiate from one another. Second, hyperarticulated vowels are judged as better instances of native language vowel categories by adult listeners (Iverson and Kuhl, 1995) and as such may promote infants' greater phonetic categorization ability. In addition, several studies reported an increased variability in tokens representing each vowel category in ID speech (Fernald, 2000; Davis and Lindblom, 2001; Kuhl *et al.*, 1997), which Kuhl and colleagues (1997) suggested could help infants attend to the featural contrasts between vowels, rather than absolute frequencies of adult speech, thereby facilitating the categorization of speech sounds produced by different talkers.

Only a few recent studies have started to investigate the hyperarticulation of vowel space in ID speech to

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hearing-impaired infants fitted with assistive hearing devices (Lam and Kitamura, 2010). In one case study (two participants, twins), the mother decreased the vowel space in speech to her hearing-impaired infant who had hearing aids relative to the normal- hearing twin brother (Lam and Kitamura, 2010). In general, the results of several other studies that examined acoustic characteristics (e.g., prosody) of mothers' speech to hearing-impaired infants fitted with cochlear implants suggest that mothers are sensitive to the hearing abilities of their infants and adjust their speech style depending on the amount of an infant's hearing experience with speech rather than the infant's chronological age (Bergeson *et al.*, 2006; Kondaurova and Bergeson, 2011).

Most of the studies that investigated vowel hyperarticulation in speech to normal-hearing infants relative to adult-directed (AD) speech have focused on vowel contrasts that are differentiated by one primary acoustic dimension (e.g., formant frequencies) in the phonological system of the native language (Burnham *et al.*, 2002; Kuhl *et al.*, 1997; Lam and Kitamura, 2010; Liu *et al.*, 2009; Uther *et al.*, 2007). A recent study by Englund and Behn (2005) also demonstrated that Norwegian mothers exaggerate spectral properties and vowel duration that are both phonologically distinctive features in Norwegian. However, there is little research (Davis and Lindblom, 2001) that has examined the production of vowels differentiated in two acoustic dimensions where one serves a primary (phonological) role while the other bears the secondary (phonetic) role in ID relative to AD speech. For example, American English tense (as in "beat") and lax (as in "bit") vowels are differentiated along two dimensions: spectrum (vowel quality, related mainly to the first three formant frequencies, $F1$, $F2$, and $F3$) and duration (vowel length) (Ladefoged, 2001). Tense vowels are more peripheral in the acoustic vowel space (i.e., lower $F1$, and higher $F2$ and $F3$ values) and longer in duration relative to lax vowels (Ladefoged, 2001). Although native English speakers use predominantly spectral properties both in perception and production of these vowels, they are able to identify tense and lax vowels based on their duration alone when the stimuli are spectrally ambiguous (Gordon *et al.*, 1993). Thus, in order to understand better how maternal input can benefit infants' acquisition of speech contrasts, it is necessary to investigate whether the modification of acoustic characteristics of ID speech occurs simultaneously along all available dimensions that may characterize a speech contrast or only the primary ones that serve distinctive (phonological) roles in the native language.

In general, previous studies have established that vowel duration in ID speech to normal-hearing infants and children is longer as compared to AD speech (Bernstein Ratner, 1986; Englund and Behne, 2005; Kondaurova and Bergeson, 2011; Lam and Kitamura, 2010; Liu *et al.*, 2009; Swanson *et al.*, 1992). Such modification of vowel duration is primarily associated with its prosodic function in the language, modulating infants' attention, and arousal levels assisting in communicating maternal affect to the infant (Fernald, 1989; Fernald *et al.*, 1989; Fernald and Mazzie, 1991), and facilitating language acquisition by providing infants with acoustic information about the syntactic and discourse structure of a language (Cooper and Paccia-Cooper, 1980; Gleitman *et al.*, 1988; Morgan, 1986; Morgan and Demuth, 1996). For example, American English vowels are approximately 30% longer in duration at clause and phrase boundaries than those in the middle of syntactic units (Klatt, 1975, 1976). Moreover, clause-final vowels are much longer in spontaneous ID speech as compared to AD speech (Bernstein Ratner, 1986; Kondaurova and Bergeson, 2011; Morgan, 1986). Because infants as young as 4–6 months are sensitive to prosodic cues (including vowel duration) that coincide with clause and phrase boundaries in ID speech (Nazzi *et al.*, 2000; Seidl, 2007; Seidl and Cristià, 2008; Soderstrom *et al.*, 2003), the exaggeration of vowel duration in ID speech may assist infants in language acquisition (Jusczyk, 1997).

In addition to the role of prosody, vowel duration in ID speech also depends on its phonological/phonetic role in the native language system (Werker *et al.*, 2007). A study by Werker and colleagues (2007) demonstrated that Japanese mothers produced greater differences in vowel duration (a phonologically distinctive feature) to signal the category membership for the Japanese /i/-/iː/ and /ɛ/-/ɛː/ vowel contrast in comparison to Western Canadian English mothers who distinguished similar /ɪ/-/i/ and /ɛ/-/e/ vowels primarily by vowel spectral qualities.

However, as the study by Werker and colleagues (2007) did not include vowel contrasts produced in AD speech, it was not clear to what extent both Japanese and Canadian English mothers modified vowel duration and/or spectral qualities in ID relative to AD speech. In addition, they did not examine vowel duration as a function of word position in the utterance, which could affect the results of the study (Bernstein Ratner, 1986; Kondaurova and Bergeson, 2011). Thus, further research is needed that takes into consideration the influence of both prosodic and phonological factors underlying the modification of acoustic properties of ID speech, which will allow us to better understand its role in infants' language acquisition.

The aims of the current study were (i) to examine acoustic characteristics (spectral properties and vowel duration) of American English tense (/i/ and /u/) and lax (/ɪ/ and /ʊ/) vowels in spontaneous ID speech to hearing-impaired infants with profound hearing loss and to normal-hearing infants and (ii) to investigate whether both spectral properties (primary dimension) and vowel duration (secondary dimension) that characterize the American English tense and lax vowel contrast are modified in ID relative to AD speech.

II. METHOD

A. Participants

Two groups of dyads were recruited for participation: normal-hearing mothers of hearing-impaired infants with profound to severe hearing loss and candidates for cochlear implantation ($N = 14$), and normal-hearing mothers of normal-hearing infants ($N = 14$). Mothers of infants with hearing loss were recruited from the clinical population at the Indiana University School of Medicine, Department of Otolaryngology – Head and Neck Surgery. Mothers of normal-hearing infants were recruited from the local community. All mothers were native American English speakers who grew up in the Midwestern United States and were paid $10 per visit.

Each hearing-impaired infant was diagnosed with profound to severe binaural hearing loss at birth. All infants were fitted with binaural hearing aids and used them at least three months prior to the time of the experiment. Table I presents pure tone average hearing threshold level [decibel hearing level (dBHL)] for the best unaided ear of each participant ($M = 117.02$ dBHL, $SD = 3.2$) and pure tone average hearing threshold level (dBHL) for binaurally aided ears of each of the participants ($M = 84.8$ dBHL, $SD = 8.6$; note that participants 2533 and 4574 were tested for each ear) at the time of the experiment. Six out of 14 infants were enrolled in programs emphasizing oral communication (OC) and one out of 14 infants was using total communication (TC) (see Table I). Parents of the other seven infants did not report their communication mode.

Each hearing-impaired infant was chronologically age-matched with a normal-hearing infant/child. The mean age of infants with hearing loss (female = 5, male = 9) at the time of the experiment was 11.36 months ($SD = 4.31$; range = 6.0–21.8 months) (see Table I). The mean age of normal-hearing infants (female = 10, male = 4) was 11.27 months ($SD = 4.43$; range = 5.8–21.7 months). The mean number of siblings in the families of hearing-impaired infants was 1.6 ($SD = 0.7$) and the mean number of siblings in the families of normal-hearing infants was 1.7 ($SD = 0.7$). The mean age of mothers of hearing-impaired infants was 30.85 years ($SD = 5.30$), and the mean age of mothers of normal-hearing infants was 35.5 years ($SD = 6.0$). This research and the recruitment of human subjects were approved by the Indiana University Institutional Review Board.

B. Procedure

1. Recordings

Mothers of both normal-hearing and hearing-impaired infants were digitally recorded in a single recording session speaking to their infants (ID speech condition) and to an adult experimenter (AD speech condition) in a double-walled, copper-shielded sound booth (Industrial Acoustics Company, New York, NY). In the ID speech condition mothers were asked to sit with their child on a blanket or a chair and to speak to their child as they normally would do at home while playing with quiet toys. In the AD speech condition, an adult experimenter conducted a semi-structured, short interview with each mother. Each ID and AD session lasted approximately 3–5 min. The order of ID and AD speech recordings was counterbalanced across mothers.

Mothers' speech was recorded in one of two ways: (i) a hypercardioid microphone (Audio-Technica ES933/H, Audio-Technica Corp., Tokyo, Japan) powered by a phantom power source and linked to an amplifier (DSC 240, Durham, NC) and digital audio tape recorder (Sony DTC-690, Sony Corp., Tokyo, Japan) or (ii) an SLX Wireless Microphone System (Shure Inc., Niles, IL).[1] The latter system included an SLX1 Bodypack transmitter with a built-in microphone and a wireless receiver SLX4 which was connected to a Canon 3CCD Digital Video Camcorder GL2, National Television System Committee (Canon U.S.A. Inc., Lake Success, NY). The speech samples were recorded directly onto a Mac computer (Apple, Inc. OSX Version 10.4.10, Cupertino, CA) via Hack TV (Version 1.11) software.

2. Analysis

For each ID and AD condition, instances of target high front tense and lax /i/ and /ɪ/ vowels and high back tense

TABLE I. Hearing-impaired and normal hearing infants' demographic information. [Best unaided PTA dBHL = pure tone average (decibel hearing level) of the best unaided ear tested at 500 Hz, 1000 Hz, and 2000 Hz; binaurally aided PTA dBHL = pure tone average (decibel hearing level) of binaurally aided ears tested at 500 Hz, 1000 Hz, and 2000 Hz; CM = communication mode (OC = oral communication, TC = total communication); No. of siblings = number of siblings in the family.]

Hearing-impaired infants							Normal-hearing infants			
Participant	Best unaided PTA dBHL	Binaurally aided PTA dBHL	Age (months)	Sex	CM	No. of siblings	Participant	Age (months)	Sex	No. of siblings
2527	118	83	16.05	F	TC		729	16.10	F	2
2532	107	83	11.64	M	OC		1103	12.30	F	
2534	118	85	7.86	M	OC	1	1309	7.76	F	2
2535	120	108	12.40	F	OC	1	1208	11.71	F	1
3058	117	83	21.80	M	OC		3697	21.70	F	2
3098	117	88	10.30	M	OC		3358	10.50	F	2
2813	118	83	8.30	M	OC	1	2815	8.30	F	1
3259	118	83	12.40	F		1	3585	12.60	M	
2514	118	83	12.76	M		1	1069	12.86	F	2
2528	118	82	15.46	M		2	942	15.69	M	1
2795	118	83	7.70	M		2	3460	7.00	M	3
2533	118	Right ear 105; Left ear 95	5.99	F		2	1169	5.79	F	1
3272	117	70	6.58	F		3	4261	6.50	F	
4574	115	Right ear 110; Left ear 83	9.80	M		1	4558	8.90	M	

and lax /u/ and /ʊ/ 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. We further excluded vowels for which there were overlapping sounds (e.g., infant vocalizations) and extraneous noise. Target words were extracted from recordings using the PRAAT 5.0.21 (Amsterdam, The Netherlands) editor (Boersma and Weenink, 2005). If a mother in any condition produced fewer than three analyzable tokens of a vowel of interest, that vowel would be excluded from the following acoustic analysis. If a mother produced more than 20 tokens of a given vowel, a random sample of 20 vowel tokens was used for the analysis. Prior to acoustic analysis all words were redigitized at 10 kHz and peak amplitude normalized using the PRAAT 5.0.21 editor running on a Dell Optiplex Windows XP (Round Rock, TX) computer with a SoundMAX HD Audio (Norwood, MA) sound card.

a. Formant frequencies. Measurements of vowel onsets and offsets served as input for marking vowel boundaries for a subsequent semi-automatic formant tracking procedure using FormantMeasurer software (Morrison and Nearey, 2010).[2] This software measures formant trajectories using a range of parameters for linear-predictive-coding (LPC), runs eight heuristics to attempt to identify the best track for each of the first three formants ($F1$, $F2$, $F3$), and presents the results for selection by experimenters of the best formant estimates confirmation by experimenters. The number of LPC coefficients for each analysis was nine in order to find four peaks, out of which the three best formant candidates were selected. The sampling frequency was 10 kHz; the lower and upper bounds for the cut-off frequency was roved between 3000–4500 Hz, depending on individual talker characteristics. LPC estimates of $F1$–$F3$ were visually inspected for accuracy by the first author and, when necessary, hand-corrected. Measurements of formant frequencies at the temporal vowel midpoint (i.e., 50% point) are reported in this study.

b. Vowel duration. Vowel duration was measured using the PRAAT 5.0.21 editor following the methods in Peterson and Lehiste (1960) and Hillenbrand *et al.* (1995) studies. We first identified vowel onsets and offsets via a waveform display and confirmed the decision using the spectrogram following previously published methodologies for acoustic measurements (e.g., Ladefoged, 2001; Mullin *et al.*, 2003).

The vowel onset was identified (i) after stops—following the release burst of the stop (including any aspiration), or, if absent, at the starting point which indicated a higher amplitude and higher frequency component; (ii) after fricatives/affricates—from the end of the noise portion of fricatives/affricates; and (iii) after approximants/semivowels—based on the characteristics of their formant structure ($F2$, $F3$, and $F4$) and amplitude reduction across formants. If it was impossible to identify the boundary of the approximant, then two strategies were used. The first strategy was to place the boundary halfway between points at which the segments were clearly vowels and approximant/semivowels. If that strategy was not possible, then one-third of the vocalic portion was assigned to the approximant and two-thirds to the following vowel.

The vowel offset was identified using a combination of the following cues: (i) drop to zero in periodicity in the vowel waveform; (ii) decrease in vowel amplitude; (iii) lack of high frequency components in the voicing produced during the closure of subsequent voiced stops. If it was impossible to identify the end of the vowel followed by an approximant/semivowel, then we applied the same strategies as described for determining a boundary between a vowel onset and preceding approximants/semivowels.

c. Context effects. Due to the spontaneous nature of the speech, it was impossible to control for consonantal and prosodic contexts that can affect vowel duration (Chen, 1970; Crystal and House, 1988a,b; Klatt, 1976). However, we closely examined two variables that have previously been shown to contribute significantly to the variability in the duration of vowels: the utterance position of the word with a target vowel (Bernstein Ratner, 1986; Klatt, 1976; Swanson *et al.*, 1992) and postvocalic consonant voicing (Chen, 1970; Crystal and House, 1988a,b; House and Fairbanks, 1953; Klatt, 1976; Peterson and Lehiste, 1960). Thus, we analyzed vowel duration as a function of three utterance positions: utterance-non-final, utterance-final, and single-word utterance (e.g., "look"). A single-word utterance position was included because words in isolation make up 7%–15% of ID speech in American English (Soderstrom *et al.*, 2008). We also examined the distribution of vowel tokens with respect to postvocalic consonantal contexts (voiced, voiceless, and no postvocalic consonant) in all three utterance positions in order to investigate whether such differences could be a confounding factor.

d. Measurement reliability. To assess reliability, recordings of ten words with target tense and lax vowels (/i/ = 10 words, /ɪ/ = 10 words, /u/ = 10 words, /ʊ/ = 10 words) were randomly selected from productions of each of four [hearing-impaired ID (HI_ID), normal-hearing ID (NH_ID), hearing-impaired AD (HI_AD), and normal-hearing AD (NH_AD)] groups. The primary investigator recalculated the vowel durations and formant frequencies without access to the original measurements. The correlation for each of the sets of vowel measurements was 0.98–0.99.

e. Calculation of vowel space area. Vowel spaces which consist of four vowels have typically been calculated by summing the vowel spaces for two composite three-vowel triangles (Neel, 2008; Fox *et al.*, 2007; Jacewicz *et al.*, 2011). The average $F1$ and $F2$ values (Hz) of the four vowels (/i/, /ɪ/, /u/, and /ʊ/) of each speaker were therefore used to calculate the vowel space areas of the /i-u-ɪ/ and /ɪ-u-ʊ/ composite triangles using Heron's method (Kuhl *et al.*, 1997; Liu *et al.*, 2003). The vowel space area was calculated using the following equations:

$$\text{Vowel space area of Triangle 1 (/i-u-ɪ/)} = \text{ABS}((F1\ \text{/i/} * (F2\ \text{/ɪ/} - F2\ \text{/u/}) + F1\ \text{/ɪ/} * (F2\ \text{/u/} - F2\ \text{/i/}) + F1\ \text{/u/} * (F2\ \text{/i/} - F2\ \text{/ɪ/}))/2), \quad (1)$$

$$\text{Vowel space area of Triangle 2 (/ɪ-u-ʊ/)} = \text{ABS}((F1\ \text{/ɪ/} * (F2\ \text{/ʊ/} - F2\ \text{/u/}) + F1\ \text{/ʊ/} * (F2\ \text{/u/} - F2\ \text{/ɪ/}) + F1\ \text{/u/} * (F2\ \text{/ɪ/} - F2\ \text{/ʊ/}))/2), \quad (2)$$

where ABS is the absolute value, the $F1$ /i/ is the $F1$ value of vowel /i/, $F2$ /ɪ /is the $F2$ value of vowel /ɪ/, and so on. Those mothers who produced all three vowels in Triangle 1 or Triangle 2 were included in the analysis. We decided to analyze the vowel space areas of Triangle 1 (/i-u-ɪ/) and Triangle 2 (/ɪ-u-ʊ/) separately as too few mothers ($N = 11$) produced all four vowels (/i-u-ɪ-ʊ/) in both AD and ID speech.

III. RESULTS

A. Distribution of vowels

In total, we analyzed 883 words with target vowels in ID speech and 888 words in AD speech.[3] Table II presents the distribution of words with target vowels according to utterance position in ID and AD speech for each group. Table III presents the number of participants who produced all four, three, two, or only one vowel in non-final, final, and single-word utterances correspondingly.

As can be seen in Tables II and III, a total of only 13 vowels were produced in AD speech in single-word utterance position across all four vowel categories; five of these were produced by mothers in the hearing-impaired (HI) group participants, while 8 of these were produced by mothers in the normal-hearing (NH) group. Due to the low number of observations, vowels in AD speech in a single-word utterance position were excluded from the analysis. A chi-squared test revealed no significant difference in the distribution of tokens in utterance-final vs non-final position for the HI group compared with the NH group [$\chi^2(1, N = 1599) = 1.28$, $p = 0.26$].

In addition, in ID speech, mothers produced 312 vowels before voiceless consonants, 244 vowels before voiced consonants, and 327 vowels in an open-syllable position. In AD speech mothers produced 177 vowels before voiceless consonants, 292 vowels before voiced consonants, and 406 vowels in an open-syllable position.

B. Formant frequencies

1. Vowel space area of ID and AD registers

Throughout Sec. III, statistics will only be reported for significant results. The first question compared the mean acoustic vowel space for ID and AD conditions in both HI and NH groups for each of two acoustic regions of the parameter space: (i) Triangle 1 (/i-u-ɪ/) and (ii) Triangle 2 (/ɪ-u-ʊ/). Figure 1 shows vowel space areas of Triangle 1 (/i-u-ɪ/) and Triangle 2 (/ɪ-u-ʊ/). Nine mothers in the HI group and ten mothers in the NH group produced all three vowels for Triangle 1 in both ID and/or AD speech. Likewise, five mothers in the HI group and six mothers in the NH group produced all three vowels for Triangle 2 in both ID and AD speech. Table IV presents the values of the calculated vowel space areas for ID and AD speech.

For each triangle, we ran mixed measures analysis of variances (ANOVAs) (SPSS 16.0 for Windows) (IBM Corp., Armonk, NY) with one between-subject variable, Group(HI, NH) and one within-subject variable, Register(ID,

TABLE II. Distribution of words with tense (/i/, /u/) and lax (/ɪ/, /ʊ/) vowels as a function of the word position in an utterance in each group. (HI_ID = hearing-impaired group in infant-directed condition; NH_ID = normal-hearing group in infant-directed condition; HI_AD = hearing-impaired group in adult-directed condition; NH_AD = normal-hearing group in adult-directed condition.)

	Number of vowels				
	/i/	/ɪ/	/u/	/ʊ/	Total
			Non-final		
HI_ID	47	70	42	74	233
NH_ID	42	118	33	101	294
Total_ID	89	188	75	175	527
HI_AD	92	108	48	31	279
NH_AD	87	196	108	28	419
Total_AD	179	304	156	59	698
			Final		
HI_ID	18	33	22	8	81
NH_ID	43	50	13	10	116
Total_ID	61	83	35	18	197
HI_AD	17	26	16	4	63
NH_AD	28	58	27	1	114
Total_AD	45	84	43	5	177
			Single-word utterance		
HI_ID	9	15	12	42	78
NH_ID	18	12	19	32	81
Total_ID	27	27	31	74	159
HI_AD	3	1	2	2	8
NH_AD		3	2		5
Total_AD	3	4	4	2	13
			Total		
HI_ID	74	118	76	124	392
HI_AD	112	135	66	37	350
NH_ID	103	180	65	143	491
NH_AD	115	257	137	29	538

TABLE III. Distribution of participants who produced all four, three, two, or only one vowel in non-final, final, and single-word utterance context. (Abbreviations are the same as in Table II.)

	Number of participants											
	Non-final				Final				Single-word utterance			
	4 vowels	3 vowels	2 vowels	1 vowel	4 vowels	3 vowels	2 vowels	1 vowel	4 vowels	3 vowels	2 vowels	1 vowel
HI_ID	7	5	1		3	3	4	4	3	2	2	5
NH_ID	8	4	1		1	5	5	3	3	2	2	5
HI_AD	6	4	2	1	3	3	4	4		1		4
NH_AD	6	6	1			8	4	1			2	1

AD). The results for Triangle 1 (/i-u-ɪ/) demonstrated a significant effect of Register, $F(1,17) = 5.93$, $p = 0.02$, but no significant effects of Group and no Group × Register interaction.[4] These results suggest that vowel space of Triangle 1 (/i-u-ɪ/) was larger in ID as compared to AD speech registers (see Table IV). These results also suggest that vowel space did not differ between HI and NH groups in both ID and AD speech. The results for Triangle 2 (/ɪ-u-ʊ/) demonstrated no significant main effects of Group or Register, and no Group × Register interaction, suggesting that vowel space did not differ in ID and AD speech.

In summary, the results demonstrated that the expansion of acoustic vowel space in ID relative to AD speech occurred in Triangle 1 (/i-u-ɪ/).

2. Distribution of vowels in ID and AD vowel space

To examine the distribution of ID vowel space relative to AD space, and to determine where the expansion of the acoustic vowel space occurred we compared mean formant frequencies ($F1$ and $F2$) in ID and AD speech for HI and NH groups (see Table V).

Mixed measures ANOVAs with one between-subject variable, Group(HI, NH) and two within-subject variables, Register(ID, AD) and Formant ($F1$, $F2$) were run separately for each vowel. The question of interest was whether there was a difference in $F1$ and/or $F2$ values between HI and NH groups either in ID or AD registers.

For all four vowels the results demonstrated a significant effect of Formant (/i/: $F(1,17) = 2966$, $p < 0.001$; /ɪ/: $F(1,17) = 1398$, $p < 0.001$; /u/: $F(1,17) = 705.4$, $p < 0.001$; /ʊ/: $F(1,9) = 268$, $p < 0.001$) suggesting that, as expected, $F1$ values were lower than $F2$ values (see Table III).

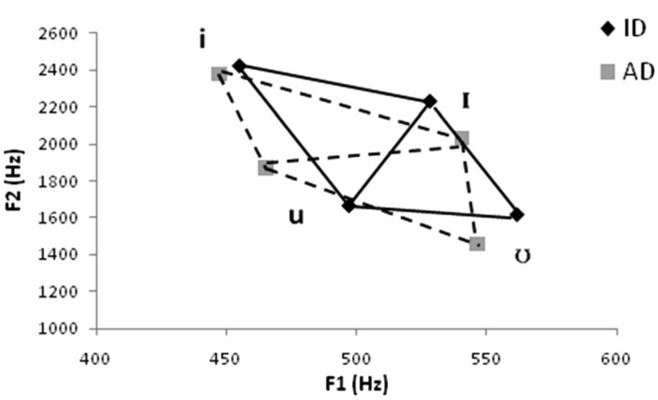

FIG. 1. Mean vowel space area of Triangle 1 (/i-u-ɪ/) and Triangle 2 (/ɪ-u-ʊ/) in infant- directed (ID) and adult-directed (AD) speech.

For two vowels, /u/ and /ɪ/, there was a significant effect of Register (/u/: $F(1,17) = 6.07$, $p = 0.02$; /ɪ/: $F(1,17) = 13.9$, $p = 0.001$) and a significant Formant × Register interaction (/u/: $F(1,17) = 12.9$, $p = 0.002$; /ɪ/: $F(1,17) = 14.6$, $p = 0.001$). For the vowel /u/, *post hoc* [Tukey HSD (honestly significant difference)] tests demonstrated that $F2$ values (Hz) ($M = 1666$, $SD = 309$) in ID speech were lower than $F2$ values ($M = 1868$, $SD = 128$) in AD speech, $p = 0.002$. For the /ɪ/ vowel, *post hoc* (Tukey HSD) tests demonstrated that $F2$ values (Hz) ($M = 2231$, $SD = 215$) in ID speech were higher than $F2$ values ($M = 2030$, $SD = 187$) in AD speech, $p = 0.006$. There were no other significant main effects or interactions.

In summary, the results demonstrated that $F2$ values were lower for the /u/ vowel, and higher for the /ɪ/ vowel in ID as compared to AD speech. In addition, no difference in formant values ($F1$ and $F2$) was found between the groups (HI and NH) for either ID or AD speech.

C. Vowel duration

1. Mean vowel duration

Because duration is perceived and represented logarithmically (Gibbon, 1977; Allan and Gibbon, 1991), we applied a logarithmic transformation to the duration values and all statistical analyses were performed on the log-transformed values (Escudero *et al.*, 2009; Swanson *et al.*, 1992). For readability in Table VI, we present mean vowel duration both in milliseconds and in log values, but in the statistical

TABLE IV. Mean vowel space areas for infant-directed (ID) and adult-directed (AD) speech. (HI = hearing-impaired group; NH = normal-hearing group.)

	Vowel space area (Hz^2) (s.d.)[a]			
	ID	s.d.	AD	s.d
Triangle 1 HI	36094	24752	19054	16409
Triangle 1 NH	32845	26130	22256	8326
Triangle 2 HI	26294	29874	29637	21687
Triangle 2 NH	35782	43399	34169	33188
Total Triangle 1	34384	24828	20740	12531
Total Triangle 2	31829	37091	32281	33188

[a]s.d.=standard deviation.

TABLE V. Mean formant frequencies for ID and AD speech. (Abbreviations are the same as in Table II.)

	Formant values (Hz) (s.d.)							
	/i/		/ɪ/		/u/		/ʊ/	
	F1	F2	F1	F2	F1	F2	F1	F2
HI_ID	476 (36)	2486 (210)	526 (50)	2237 (210)	496 (67)	1657 (248)	535 (52)	1529 (201)
HI_AD	438 (46)	2372 (163)	526 (50)	2008 (191)	457 (30)	1872 (150)	546 (50)	1456 (243)
NH_ID	435 (58)	2365 (279)	529 (42)	2226 (232)	497 (54)	1673 (369)	583 (45)	1691 (264)
NH_AD	455 (27)	2382 (130)	553 (25)	2050 (192)	472 (20)	1866 (114)	588 (36)	1529 (136)
Average ID	455 (52)	2423 (250)	528 (44)	2231 (215)	497 (59)	1666 (309)	561 (52)	1618 (241)
Average AD	447 (37)	2377 (142)	540 (40)	2030 (187)	465 (25)	1868 (128)	569 (46)	1496 (185)

analyses we report mean vowel duration and standard deviation based only on log values.

The initial questions we addressed were whether vowel duration was different across groups (HI, NH) and register (ID, AD). Two-factor, mixed measures ANOVAs were run separately on log-transformed durations for each vowel with the between-subjects variable of Group(HI, NH) and the within-subjects variable of Register(ID, AD).

Results demonstrated a significant main effect of Register for the /i/, /ɪ/, and /u/ vowels only: /i/: $F(1,16) = 27.19$; /ɪ/: $F(1,23) = 15.43$; /u/: $F(1,18) = 31.18$, $p < 0.001$ everywhere, suggesting that mean vowel duration was longer in ID (/i/: M = 5.02, SD = 0.33; /ɪ/: M = 4.43, SD = 0.27; /u/: M = 5.11, SD = 0.37) as compared to AD speech (/i/: M = 4.6, SD = 0.18; /ɪ/: M = 4.20, SD = 0.18; /u/: M = 4.6, SD = 0.19). There were no other significant main effects or interactions.

In summary, the results demonstrated that /i/, /ɪ/, /u/ vowels were longer in ID speech to both prelingually deaf infants and age-matched NH infants as compared to AD speech but did not differ across the hearing status condition. The lack of significant difference in vowel duration for the vowel /ʊ/ could be explained by insufficient power as only 11 participants produced/ʊ/vowels in AD speech.

2. HI and NH groups: Intrinsic vowel duration

We next examined whether mothers maintained intrinsic vowel duration (defined as "an inherent phonological/phonetic duration of a segment," Klatt, 1976) in speech to both HI and NH infants and to an adult experimenter. In order to investigate this question, we conducted two-tailed *t*-tests (independent samples) to compare the duration of tense and lax vowels in each group. The results demonstrated that for all pairs of vowels in each group for both ID and AD speech registers, tense vowels were significantly longer than their lax counterparts (p's from 0.02 to < 0.001).

TABLE VI. Mean duration of tense (/i/, /u/) and lax (/ɪ/, /ʊ/) vowels across hearing status. (Abbreviations are the same as in Table II.)

	Vowel duration			
	[i]	[ɪ]	[u]	[ʊ]
	Milliseconds (s.d.)			
HI_ID	199 (84)	107 (32)	190 (72)	92 (28)
HI_AD	99 (22)	75 (16)	118 (15)	81 (21)
NH_ID	179 (81)	92 (23)	210 (109)	80 (24)
NH_AD	120 (23)	76 (17)	117 (24)	73 (20)
	Log values (s.d.)			
HI_ID	5.07 (0.33)	4.53 (0.27	5. 04 (0.34)	4.31 (0.25)
HI_AD	4.49 (0.18)	4.21 (0.22)	4.66 (0.80)	4.3 (0.21)
NH_ID	4.98 (0.37)	4.36 (0.14)	5.14 (0.37)	4.17 (0.21)
NH_AD	4.65 (0.17)	4.19 (0.15)	4.64 (0.19)	4.22 (0.30)

3. Vowel duration as a function of word position in an utterance

Next, we examined vowel duration as a function of the word position in an utterance. Because our previous analyses demonstrated no group difference in vowel duration between HI and NH groups, we collapsed all data across hearing status. Table VII shows mean duration of vowels in non-final and final utterance positions in both ID and AD speech and in a single utterance position in ID speech.

a. ID vs AD register. In order to examine whether there was a difference in vowel duration across register and word position in an utterance, we ran mixed measures ANOVAs

TABLE VII. Mean duration of tense (/i/, /u/) and lax (/ɪ/, /ʊ/) vowels in ID and AD speech as a function of the word position in an utterance.

	Vowel duration			
	Millisecond (s.d.)			
	Non-final			
	[i]	[ɪ]	[u]	[ʊ]
ID	125 (44)	76 (20)	129 (39)	61 (16)
AD	93 (20)	64 (14)	101 (17)	72 (14)
Final				
ID	216 (124)	135 (62)	188 (81)	217 (135)
AD	171 (65)	118 (41)	137 (52)	165 (26)
Single Utterance				
ID	322 (139)	136 (106)	395 (179)	134 (89)
	Log values (s.d.)			
	Non-final			
ID	4.69 (0.32)	4.25 (0.22)	4.72 (0.37)	4.02 (0.28)
AD	4.45 (0.22)	4.10 (0.21)	4.57 (0.15)	4.22 (0.21)
	Final			
ID	5.23 (50)	4.7 (0.44)	5.37 (0.29)	5.15 (0.49)
AD	5.07 (0.37)	4.63 (0.35)	4.85 (0.36)	5.07 (0.13)
	Single Utterance			
ID	5.63 (0.5)	4.78 (0.7)	5.83 (0.45)	4.42 (1.11)

with one between-subject variable, Position(non-final, final), and one within-subject variable, Register(*ID, AD*) separately for each vowel. Recall that there were too few single-word utterances produced in AD speech that made it impossible to compare the results with ID speech.

The results for all vowels demonstrated a significant effect of Position (/i/: $F(1,25) = 25.39$; /ɪ/: $F(1,42) = 45.9$; /u/: $F(1, 24) = 23.24$; /ʊ/: $F(1,10) = 31.27$, all p's < 0.001) suggesting that vowels in the utterance-final position were longer than those in the non-final position in both ID and AD speech. There was a significant or a marginally significant effect of Register for all vowels except /ʊ/: (/i/: $F(1,25) = 6.27$, $p = 0.01$; /ɪ/: $F(1,42) = 3.33$, $p = 0.07$; /u/: $F(1,24) = 13.61$, $p = 0.001$; /ʊ/: $F(1.10) = 0.30$, $p = 0.59$) suggesting that these vowels were longer in ID than AD speech. The Register × Position interaction was marginally significant for the /u/ vowel only, $F(1,24) = 3.27$, $p = 0.08$. *Post hoc* (Tukey's HSD) tests demonstrated that the vowel /u/ was significantly longer in utterance-final compared to non-final positions only in ID speech, $p < 0.001$, with no significant difference in AD speech, $p = 0.11$. There were no other significant interactions.

In summary, all target vowels were longer in final than non-final utterance positions. Vowels /i/ and /u/ were longer and vowel /ɪ/ was marginally longer in ID as compared to AD speech.

b. ID register. Because ID speech, unlike AD speech, is commonly characterized by some percentage of single word utterances (Brent and Siskind, 2001; Soderstrom *et al.*, 2008), we also compared vowel duration in all three (non-final, final, and single-utterance) positions in ID speech only. We ran one-way ANOVAs for each vowel (/i/, /ɪ/, /u/, and /ʊ/) with one between-subject variable, Position(non-final, final, single utterance) with vowel duration as a dependent variable. Table VII shows mean duration of vowels in log values in non-final, final, and single utterance position in ID speech only.

The results demonstrated a significant effect of Position for each vowel (/i/: $F(2,40) = 19$; /ɪ/: $F(2,56) = 8.5$; /u/: $F(2,43) = 31.51$; /ʊ/: $F(2,49) = 8.75$; all p's < 0.001). *Post hoc* (Tukey's HSD) tests demonstrated that the vowels /i/, /u/, and /ɪ/ were significantly shorter in the non-final position than in both final (/i/: $p = 0.002$; /ɪ/: $p = 0.003$; /u/: $p = 0.001$) and single-word utterance positions (/i/: $p < 0.001$; /ɪ/: $p = 0.003$; /u/: $p < 0.001$). The vowel /ʊ/ was significantly shorter in non-final position than in final position, $p < 0.001$.

The vowels /i/ and /u/ were also significantly shorter in final than single-word utterance positions (/i/: $p = 0.051$; /u/: $p < 0.001$). The vowel /ʊ/ was also significantly longer in the final position than in single-utterance positions, $p = 0.01$.

In summary, the comparison of vowel duration in ID speech as a function of utterance position demonstrated somewhat different patterns for tense and lax vowels. For tense vowels, /i/ and /u/, vowel duration was shorter in the non-final position than in both final and single-utterance positions. Also, vowel duration was shorter in the final position than in the single-utterance position. For lax vowels, /ɪ/ and /ʊ/, duration was shorter in the non-final position than in the final utterance positions.

4. Vowel duration as a function of the contextual distribution of vowels

In order to examine whether vowel duration results were affected by the distribution of tokens across groups as a function of utterance position (non-final, final, and single-utterance position) and postvocalic consonant voicing (before voiced, voiceless consonants, and in an open-syllable position) we ran chi-squared tests. The results demonstrated that there was no significant difference across groups in the distribution of tokens according to utterance position (all p's > 0.05). However, IDs to NH infants contained more tokens with target vowels before voiced, voiceless consonants, and in an open-syllable position (165 vowels before voiceless, 165 before voiced, and 161 in an open-syllable position) as compared to IDs to HI infants (147 vowels before voiceless, 79 before voiced, and 166 in an open-syllable position) infants, $X^2 = 20.58$, df $= 2$, and $p < 0.001$. However, because there was no significant difference in vowel duration between NH and HI infant groups as demonstrated by our results, it is unlikely that this variable could affect the present analysis.

IV. DISCUSSION

The current study examined the modification of two acoustic dimensions, formant frequencies and vowel duration, that signal the American English tense (/i/ and /u/) and lax (/ɪ/ and /ʊ/) vowel contrast in mothers' speech to hearing-impaired infants prior to cochlear implantation and chronologically age-matched normal-hearing infants. The results suggest that mothers hyperarticulate the acoustic vowel space primarily along $F2$ formant frequencies between point /i/ and /u/ vowels, and exaggerate vowel duration for the /i/, /u/, and /ɪ/ vowels in ID relative to AD speech for both infant groups. These results agree with previous research that demonstrated the hyperarticulation of acoustic vowel space (Burnham *et al.*, 2002; Kuhl *et al.*, 1997; Uther *et al.*, 2007) and the exaggeration of vowel duration (Bernstein Ratner, 1986; Englund and Behne, 2005; Kondaurova and Bergeson, 2011; Lam and Kitamura, 2010; Liu *et al.*, 2009; Swanson *et al.*, 1992) in ID speech to normal-hearing infants and extend these findings to maternal speech to prelingually deaf infants prior to cochlear implantation.

The results of the present study also demonstrated that the distribution of vowels in acoustic space was different in speech to both normal-hearing and hearing-impaired infants as compared to adults. That is, $F2$ values in ID speech were decreased for the /u/ vowel and increased for the /ɪ/ vowel as compared to AD speech. The decrease in $F2$ values for the /u/ vowel in ID relative to AD speech agrees with findings from previously reported studies (Bernstein Ratner, 1984; Kuhl *et al.*, 1997) and suggests, from the articulatory perspective, that the constriction is produced further back for ID speech. The upward shift of $F2$ frequencies for the /ɪ/ vowel in ID relative to AD speech, also supported by results from previous studies (Bernstein Ratner, 1984), implies the more fronted constriction in ID as compared to AD speech. Thus, in summary, an increased vowel space in ID relative to AD speech is achieved by changes in the front-back tongue position ($F2$ formant frequencies of /u/ and /ɪ/ vowels) rather than tongue height.

The results of the current study demonstrated no difference between acoustic vowel space area and vowel space distribution across maternal speech to normal-hearing as compared to hearing-impaired infants. Previous research suggested that acoustic vowel space is exaggerated in speech to normal-hearing but not hearing-impaired infants fitted with assistive devices (hearing aids or cochlear implants) (Lam and Kitamura, 2010). The reason for the difference in the results of the current study and the results of previous research could possibly be accounted for by methodological differences. First, the current study investigated the properties of the acoustic vowel space in speech to hearing-impaired infants prior to cochlear implantation. Thus, it is difficult to compare these results to studies that examined maternal speech input to children/infants who had already been fitted with hearing aids (Lam and Kitamura, 2010). Second, Lam and Kitamura (2010) presented a case study where no statistical analysis of the acoustic vowel space was available. Consequently, the results of their study do not take into consideration the between-subject variability that might affect the results, especially in spontaneous speech. Finally, the current study investigated different vowel contrasts in comparison to previous studies (Lam and Kitamura, 2010), suggesting that overall the maternal modification of formant frequencies in spontaneous speech occurs for the point /u/ and non-point /ɪ/, and vowels in ID relative to AD speech, but does not differ in speech to infants with drastically different hearing status.

We also found that mothers consistently exaggerate vowel duration for the /i/, /u/, and /ɪ/ vowels in ID relative to AD speech when addressing both infant groups. This is consistent with previous studies suggesting slower speaking rate in ID relative to AD speech (Bergeson *et al.*, 2006; Liu *et al.*, 2009). Surprisingly, the duration of the vowel /ʊ/ was not different across the registers. The available literature (Bernstein Ratner, 1986), however, demonstrates comparable values for the duration of the /ʊ/ vowel in utterance-final and utterance-medial positions (see Table I in Bernstein Ratner, 1986, p. 306, and Table VII in the present study). Thus, the present results suggest that the production of the lax /ʊ/ vowel was not affected by changes in speech register.

Our findings also demonstrated no difference in vowel duration between hearing-impaired and normal-hearing groups. Similarly, a recent case study (Lam and Kitamura, 2010) demonstrated no difference in duration of point /i/, /a/, and /u/ vowels in speech to a hearing-impaired infant as compared to his normal-hearing twin brother. As prosodic components of ID speech play more attentional and affective roles in early infancy (Burnham *et al.*, 2002; Fernald, 1992; Stern *et al.*, 1983), it is possible that mothers' production of vowel duration does not depend much on the hearing status of an infant, thus resulting in no difference between the two groups.

Overall, our results suggest that mothers modify both primary (formant frequencies) and secondary (vowel duration) acoustic cues that differentiate the American English tense and lax vowel contrast in speech to normal-hearing and to prelingually deaf infants as compared to AD speech. Such results extend the findings of a few previous studies that examined the modification of vowel duration in ID speech from the perspective of its role in the phonological/phonetic system of the native language (Davis and Lindblom, 2001; Englund and Behne, 2005; Werker *et al.*, 2007). However, future cross-language research is needed to investigate the relative modification of the same acoustic dimension (e.g., vowel duration) but with different phonological/phonetic function in the native language system in order to better understand the underlying reasons of such modifications in ID as compared to AD speech.

Previous research suggested that the modification of vowel duration in ID relative to AD speech could be accounted for by the prosodic function of this acoustic dimension primarily facilitating the identification of major syntactic units in conversational speech (Cooper and Paccia-Cooper, 1980; Gleitman *et al.*, 1988; Morgan, 1986; Nazzi *et al.*, 2000; Seidl, 2007; Seidl and Cristià, 2008; Soderstrom, 2007; Soderstrom *et al.*, 2003). The examination of vowel duration in the current study as a function of the word position in an utterance demonstrated that in both ID and AD speech, vowels in the utterance-final position were longer than those in the non-final position. These results are in agreement with previous research demonstrating the lengthening of vowel duration in utterance-final as compared to utterance-initial or medial positions in ID and AD speech (Bernstein Ratner, 1986; Klatt, 1975, 1976; Kondaurova and Bergeson, 2011; Swanson and Leonard, 1994; Swanson *et al.*, 1992). Moreover, we observed the same patterns in speech to profoundly deaf infants prior to cochlear implantation suggesting that mothers modify acoustic cues that signal syntactic (clause) boundaries regardless of the hearing status of the infant. These findings extend the previous research that investigated vowels only in clause preboundary and postboudary positions in speech to hearing-impaired infants prior to and post cochlear implantation (Kondaurova and Bergeson, 2011).

Because ID speech typically contains more single word utterances than AD speech (Brent and Siskind, 2001; Soderstrom *et al.*, 2008), we also included the analysis of vowel duration in a single-word utterance position in ID speech. The results demonstrated a consistent difference in vowel duration for the point /i/ and /u/ vowels: Vowel duration was longer in single-utterance than in final or non-final positions, and was longer in final than in non-final positions. However, non-point /ɪ/ and /ʊ/ vowels were longer only in final as compared to non-final position. These results suggest that the lengthening of vowel duration as a function of utterance position in ID speech depends on the status of vowels: tense (point) vowels that have intrinsically longer duration undergo more consistent (larger) changes in vowel duration as a function of their utterance position in comparison to lax (nonpoint) vowels.

In summary, the results of this study demonstrated that mothers modify both primary (formant frequencies) and secondary (vowel duration) acoustic dimensions that make up the American English tense (/i/ and /u/) and lax (/ɪ/ and /ʊ/) vowel contrast in speech to hearing-impaired infants prior to cochlear implantation and chronologically matched normal-hearing infants in comparison to AD speech. These results suggest that the modification of acoustic properties of ID speech (hyperarticulation of acoustic vowel space and lengthening of vowel duration) is a universal feature even in speech to prelingually deaf infants prior to cochlear implantation. The results of the current study also demonstrated the complexity of the task involving the analysis of vowel contrasts in spontaneous ID speech to hearing-impaired and normal-hearing infants. Future research is needed to investigate different speech contrasts in speech to both hearing-impaired and normal-hearing infants in spontaneous vs controlled speech in order to better understand the relationship between maternal speech input and language acquisition skills in infants with and without hearing loss to develop better clinical interventions used by speech-language therapists and parents of hearing-impaired infants with cochlear implants.

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[1]Different equipment was used because we updated the recording equipment part-way through the ten-year-long project to directly record to the computer and minimize noise from the child. There were no systematic differences across recording sessions or participant groups in terms of recording technology.

[2]A detailed description of the software is available at http://geoff-morrison.net/documents/FormantMeasurer: Software for efficient human-supervised measurement of formant trajectories.

[3]Ideally, the number of words should be a multiple of 3. However, not all mothers produced all tense (/i/, /u/) and lax (/ɪ/, /ʊ/) vowels in both ID and AD speech.

[4]Only significant effects are reported throughout the results section in order to simplify the presentation of the analyses.

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