Child Development, September/October 2000, Volume 71, Number 5, Pages 1258–1270

Prosodic Correlates of Stress in Babbling: An Acoustical Study

Barbara L. Davis, Peter F. MacNeilage, Christine L. Matyear, and Julia K. Powell

Prelinguistic babbling often seems remarkably speech-like, not because it has recognizable words but because it seems to have adult-like prosody. To quantify this impression, we compared disyllabic sequences from five infants and five adults in terms of the use of frequency, intensity, and duration to mark stress. Significantly larger values for the three acoustic variables were observed on stressed than on unstressed syllables independent of syllable position for both groups. Adults showed the correlates of utterance final syllables—lower f_0, lower intensity, and longer duration; infants showed only decrease in intensity. Ratios for stressed to unstressed syllables and participation of the three variables in stress production in individual disyllables were highly similar in both groups. No bias toward the English lexical trochaic stress pattern was observed. We conclude that infants in English environments produce adult-like stress patterns before they produce lexical items, which specify stress. Acoustic and perceptual analyses are used to explore stress marking by prelinguistic infants in an English language environment. Results show that infants employ the three acoustic correlates of stress in individual syllables in a manner largely similar to that of adult speakers, although they do not show second-syllable declination effects or an English language trochaic stress bias.

INTRODUCTION

Prosodic regularity has formed the basis for characterizing prelinguistic babbling as "speech-like" (Kent, Mitchell, & Saucier, 1991; Roug, Landberg, & Lundberg, 1989), although stress has not frequently been explored as an aspect of prelinguistic communication. *Stress* has been defined by changes in fundamental frequency (f_0), intensity, and duration in speech production at the level of the individual syllable in adults (Fry, 1955; Lehiste, 1970; Lieberman, 1960).

Kozhevnikov and Chistovich (1965) have suggested that the syllable is the basic timing unit for language patterning. In acquisition of stress, Kent et al. (1991) propose that coordination of respiratory/laryngeal function with supraglottal closed and open cycles allows the infant to realize necessary frequency, intensity, and duration adjustments in early speech production. The question logically arises of when these coordinative capabilities develop.

Acoustic studies of stress marking in 18- to 24-month-olds (e.g., Kehoe, Stoel-Gammon, & Buder, 1995; Pollock, Brammer, & Hageman, 1993; Schwartz, Petinou, Goffman, Lazowski, & Cartusciello, 1996) have largely shown adultlike use of stress, albeit embedded in a matrix of variability related to comparison targets. In prelinguistic infants (where no target is present), adult perceptions of stress marking may be based on presence of all three variables. Alternatively, a sufficient summed contribution of the three variables may evoke a stress judgment, regardless of whether individual signal attributes are covarying in an adult manner. Of central interest is whether infants establish a link between lexical representation and a *preexisting* motor capacity for adultlike stress production or whether lexical stress may be *learned* as an intrinsic aspect of individual lexical items (e.g., Klein, 1984) or as a rule-based system (e.g., Kehoe et al., 1995). An important preliminary step in resolution of this issue is characterization of the acoustic nature of syllables perceived as stressed in prelinguistic babbling.

Physiological Constraints

The question of physiological constraints on the prelinguistic production of prosodic variables, regardless of language-specific prosodic patterns, arises. Lieberman (1984) has argued that the universal tendency for values of both fundamental frequency and intensity to decline toward the end of an utterance is inherent in human vocalization, related to the rapid decline in subglottal pressure coinciding with the end of the breath group. He suggests that this physiological constraint is present from the onset of infant cry.

Fundamental frequency. Some evidence of a tendency for f_0 to fall in early noncry vocalizations of infants in English-language environments has been presented (e.g., Kent & Murray, 1982; Stark, Rose, & McLaglan, 1975). Reduplicated babbling in English-learning infants has also been reported to show a falling f_0 contour (Levitt, 1993; Whalen, Levitt, & Wang, 1991). In early words, falling f_0 has been shown to occur earlier than rising in English-speaking children's acquisition of stress and intonation (e.g., Cruttenden, 1986; Snow,

1994, 1998). In contrast, rising syllable-level f_0 in early disyllabic words has been reported for French infants (Hallé, Boysson-Bardies, & Vihman, 1991; Vihman, DePaolis, & Davis, 1998). These differences are congruent with differences in target language characteristics. French shows a rising final f_0 contour at both the word and phrase level (Delattre, 1965) far more frequently than English. English shows a falling word level f_0, related to trochaic patterning (i.e., "*hot*dog"), iambic phrase final stressed syllables ("a *ball*") as well as an optional rising contour related to sentence type (Delattre, 1966). Ambient language characteristics may thus present the infant with a target that differs from presumed physiologically natural effects of the production apparatus, thereby complicating full understanding of f_0 effects in early production of stress.

Intensity. Little information is available on intensity variation in infant output. Levitt (1993) analyzed reduplicated strings in five English and five French infants 5–13 months of age. She noted a tendency for English-learning infants to produce highest intensity on the longest nonfinal syllable; French infants tended to produce highest intensity on the long final syllable. Neither effect reached significance. Vihman et al. (1998) studied disyllabic babbling and word productions of nine English- and five French-speaking children in the late single-word period. Their French participants showed higher intensity and f_0 on the second syllable; English participants exhibited slightly higher intensity and f_0 on the first syllable. Both groups showed high levels of variability in the predominant patterns.

Duration. Syllable duration is a third prosodic factor related to stress production. Levitt and Wang (1991) studied syllable durations in five French- and five English-learning infants, 5–13 months of age. No differences were found in the early babbling stage. In later stages of reduplicated babbling, they found that nonfinal syllable durations showed stronger isosyllabicity in the French infants than in the English infants. Their results were significant for the differences between the two groups. Goodell and Studdert-Kennedy (1993) analyzed two-syllable iambic word productions in a group of three 22- and three 32-month-old infants compared with adults. Stressed syllable durations for both infant groups were similar to adult stressed syllable durations. In contrast, unstressed syllables in the 22-month-olds were longer than in the older infants and adults, which suggests that the durational aspect of the stressed–unstressed dimension may emerge during the third year of life and may involve shortening of unstressed syllable durations.

Final-syllable lengthening (FSL) presents an additional aspect of syllable duration that occurs to varying degree in many languages (Delattre, 1966). Lengthening of final syllables has been suggested by Smith (1978, p. 44) as being inherent in the operation of the production apparatus as with preterminal f_0 and intensity decrease: "It seems reasonable to hypothesize that . . . *minimal* final-syllable lengthening may occur universally in languages because of physical level production principles."

Final-syllable lengthening based on physiological characteristics would thus be predicted to be present in prelinguistic output. Evidence on this point is conflicting. Laufer (1980, p. 286) compared the duration of first and second protosyllables (i.e., "relative peak of sonorance characterized by a rise in fundamental frequency, intensity, and duration"). She found evidence of final-syllable lengthening in four infants in the first 24 weeks of life, although she noted difficulty with definition of vocalic spectral components and with distinctions between nuclei and margins of protosyllables. These measurement difficulties suggest caution in interpreting her findings as clear evidence for precursors of final syllable lengthening effects in the first 6 months. Robb and Saxman (1990) reported a consistent tendency for final syllables in babbling to be longer than nonfinal syllables in seven individual participants 8 to 26 months in an English-speaking environment. Durational differences were not statistically significant, however. Oller and Smith (1977) failed to find final-syllable lengthening in reduplicated babbling of six participants, 8 to 12 months of age. However, methodological issues complicate interpretation of their findings because they analyzed small numbers of syllables of differing lengths (2–6 syllables). Snow (1994) found initial duration differences between final and nonfinal syllables in early words of nine infants 16 to 25 months of age, with a shift to isochrony at the same period that the infants began two-word combinations. Final-syllable lengthening slowly reemerged in later stages of development in Snow's data. Both Oller and Smith (1977) and Snow (1994) concluded that final-syllable lengthening appears to be a learned prosodic feature, not an effect of physiological production constraints.

Cross-language studies of final-syllable lengthening in infants illustrate the importance of understanding potential ambient-language effects on production propensities. Levitt and colleagues (Levitt, 1993; Levitt & Uttman, 1992; Levitt & Wang, 1991) found final-syllable lengthening in prelinguistic vocalizations of French and English infants. After 11 months of age, final-syllable lengthening was significantly greater in French than in English infants. In English infants, nonfinal syllables showed considerable variability,

presumably related to word-level trochaic stress patterns in English input. This pattern was compared with relative isochrony for nonfinal syllables in French infants (French shows both word- and phrase-level iambic patterning). Hallé et al. (1991) analyzed vowel duration in disyllabic vocalizations of four French and four Japanese infants 14 to 23 months of age. Final-syllable lengthening was found for the French infants but not the Japanese, congruent with ambient-language patterns for the two target languages. Bacri, DeBoysson-Bardies, and Hallé (1989) studied four English and four French children at 12 months. Final lengthening was found for the English infants di- and trisyllabic productions; for the French infants, final lengthening was found only on utterances of more than two syllables, congruent with English and French stress patterns.

Trochaic-Iambic Bias

The position of stress *placement* in multisyllabic babbled utterances is an additional factor of interest. Cutler (1990) has estimated that there is a three-to-one chance that a "strong" syllable—basically a stressed syllable—will signal onset of a new lexical item in English. A few developmental studies have focused on this issue in production as well. Davis and MacNeilage (1994) analyzed babbling data in a longitudinal study of a 7- to 12-month-old infant. They found no systematic tendency for perceived stress to fall on any syllable position in multisyllabic babbled utterances. Davis and MacNeilage (1990) found that almost 90% of two-syllable words were perceived as trochaic in a longitudinal study of a 14- to 20-month-old infant from the one-word to the multiword stage. These two studies raise the possibility that the trochaic stress pattern might emerge only when infants begin to produce words with lexical stress patterning. Vihman et al. (1998) analyzed trochaic stress patterning in words and babble in nine French- and five English-speaking infants at a single developmental point (25 words). They measured f_0, intensity, and duration and made perceptual judgements of infant syllable stress marking. The French infants showed reliable use of iambic patterning with adultlike duration ratios. In contrast, English participants did not show a consistent trochaic pattern. The authors noted the presence of trochaic word-level and iambic phrase-level models in the input to these infants. They concluded that the presence of both types of model in the ambient input (i.e., "*base*ball" but "a *toy*") could modulate the strong potential presence of a word-level trochaic bias in English-learning infants.

Prosodic stress is a crucial facet of use of the phonological system to express meaning in English. Exploration of prosodic stress during the prelinguistic period allows consideration of the motor capacities the infant brings to the problem of attaching segmental and prosodic characteristics to earliest words. Accordingly, the primary goal of this study was to evaluate the acoustic nature of disyllables perceived as asymmetrically stressed in prelinguistic babbling. Variation of acoustic properties related to syllable position was also investigated to explore potential physiological constraints on syllables related to position in the utterance and to trochaic versus iambic production strategies.

Babbled utterances produced by four normally developing infants between 7 and 12 months were analyzed. Two-syllable utterances in which the syllables were judged perceptually as asymmetrically stressed were participant to acoustic analysis of f_0, intensity, and duration and were compared with asymmetrically stressed, adult, citation-form disyllables. In addition, a sample of infant disyllables perceived as having uniform stress was analyzed to compare with values for the infant asymmetrical disyllables. The possibility of trochaic stress bias was also evaluated by determining whether infants produced first-syllable stress more frequently on the basis of analysis of perceptual data for the total corpus.

METHOD

Participants

Four normally developing infants were studied for 3–4 months beginning at the reported onset of canonical babbling (established through parental report and experimenter observation). These four infants were part of a larger study reported elsewhere (Davis & MacNeilage, 1995b) in which six infants participated. Two infants' data were not available for acoustic analysis; these are the remaining four infants. Parental case history and report of developmental milestones was used to ascertain normal development. In addition, infants were tested formally by using the Battelle Developmental Inventory (Guidubaldi, Newborg, Stock, Svinichi, & Wneck, 1984). Normal hearing acuity was established by using sound field hearing screening techniques. Participants were selected from monolingual English-speaking homes. Table 1 provides participant descriptions and number of sessions for the infants.

The adult database was compiled by using five native speakers of English recruited from the Departments of Speech and Linguistics at the University of Texas at Austin.

Table 1 Description of Participants and Number of Sessions

Subject	Gender	Siblings	Sessions	Age (in months)
C	F	1	12	7–12
R	F	1	13	9–12
N	M	1	16	10–14
P	M	1	14	7–12

Data Collection

Data analyzed for the infants were collected in the course of a larger longitudinal study of babbling and early speech in normal infants. Sessions of 1 hr each were audiotaped in the infant's home in the course of normal daily activity. The examiner was present at each session and interacted with the infant and caretaker. Data were recorded with a TEAC-DA-P20 Digital Audio Tape Deck and an Audiotechnika ATW-1031-831 cordless microphone clipped onto the infant's clothing to maintain a relatively constant mouth-to-microphone distance. Data were selected to analyze the acoustic correlates of infant syllables perceived as stressed rather than to track the development of stress over time.

Adult data were collected in a soundproof booth by using the same audio equipment employed to record the infant database. Each of the 5 adult participants was asked to read five repetitions of a set of 20 disyllabic utterances, half of which carry first-syllable stress and half second-syllable stress. The set included five noun–verb pairs that contrast by stress (i.e., súbject–subjéct, óbject–objéct, dígest–digést, áccess–accéss, ímpact–impáct) and a companion pair of asymmetrically stressed, nonsense disyllables (i.e., pétepete–petepéte). The noun–verb pairs were varied randomly for each speaker to neutralize possible effects of order. Of the total 500 disyllables produced, 479 were judged suitable for acoustic analysis. Twenty-one utterances were excluded because the speaker produced disyllables with equal rather than asymmetrical stress.

Data Analysis

Infant data were analyzed by using both phonetic transcription and acoustic analysis. Tokens initially selected for transcription included all babbled utterances minimally including a consonantlike closing phase and a vowel-like opening phase within a single utterance. Single babbled utterances were bounded by one second of silence, noise, breath, or adult speech (Olswang, Stoel-Gammon, Coggins, & Carpenter, 1987). Items designated as lexical by either the mother or the observer were excluded from the analysis.

Perceptual analysis. Transcribed data were available from another study using the overall corpus (Davis & MacNeilage, 1995a) in which both phones and stress were the emphasis. Data from each infant were transcribed by using broad phonetic transcription by a primary transcriber who was present at the original data-collection sessions. International Phonetic Alphabet (IPA) notation was used, supplemented when necessary by diacritics appropriate for transcription of infant data (Bush et al., 1973; Oller, 1990). The primary transcriber marked stress by using a vertical stress mark placed above and before each stressed syllable when it was perceptually salient. Disyllables were chosen for analysis in this study because they were frequent in the corpus and allowed the opportunity for analysis of stress differences. In total, 601 uniformly stressed and 658 asymmetrically stressed disyllables were transcribed.

Acoustic analysis. Acoustic measurements were used for the infant and the adult data to analyze prosodic and spectral characteristics for two main variables: syllable stress and syllable position. Three measurements were made on the vowel in each syllable analyzed: (1) fundamental frequency (f_0), (2) intensity, and (3) duration.

Acoustic analysis was performed by using Kay Elemetrics (Model 4300) Computerized Speech Laboratory (CSL) software. Data were entered in analog form from the TEAC DA-P20 Digital Audio Tape Deck used for recording and transcription and digitized by the Kay Elemetrics (Model 4300) external module at a rate of 16,000 samples per second for infants and 10,000 for adults.

Infant disyllables were excluded if environmental sounds (i.e., other voices or background noise) interfered with the signal. Tokens were also excluded if a broad-band spectrogram showed a vocalic segment to have highly unstable formant structure. Finally, syllables showing more than an octave range in f_0 were rejected, following Oller's (1986) criteria for canonical syllables. Because data were spontaneous productions collected in a nonlaboratory setting in each child's home, background noise and competing voices were frequently present and greatly reduced the number of tokens accessible for acoustic analysis. Of the transcribed disyllables, 162 disyllables (324 syllables) were analyzed acoustically. Twenty-four disyllables perceived as uniformly stressed (48 syllables) were analyzed as an additional type of reliability check on the asymmetrically stressed tokens that were the major emphasis in this study (i.e., do uniformly stressed tokens show nonsignificant differences between syllables for the three acoustic variables?).

Fundamental frequency was measured by using

both the waveform and a narrow-band spectrogram. Initially, marks were placed at each pitch peak in the vowel waveform. The CSL pitch analysis, including average f_0, was then obtained from the waveform based on the defined pitch peaks. The average f_0 was verified by measuring the 10th harmonic on the narrow-band spectrogram at vowel onset, vowel termination, and three evenly spaced points in between and then averaging the five values.

An intensity contour based upon sound pressure levels was derived for the vowel segment of the waveform. Peak intensity in decibels (dB) was computed automatically by the CSL software.

Vowel duration was measured on the wide-band spectrogram. Initiation was taken to be the onset of the first glottal pulse. Termination for medial vowels was taken at the last glottal pulse before closure of the following consonant and termination of final vowels in open syllables was taken at the point of loss of audible signal, which correlated to marked decrease in the energy of higher formants on the broad-band spectrogram.

To assess the reliability of infant acoustic measurements, 20% of the corpus of disyllables were selected randomly from the set of disyllables analyzed for each of the four participants and measured independently by a second judge. Mean differences between the two judges were f_0, 13.7 Hz; intensity, 5.4 dB; duration, 16 ms.

RESULTS

This study addressed the question of whether duration, fundamental frequency, and intensity varied systematically in disyllabic utterances with respect to perceived stress and location of stress on the first or second syllable. In total, 324 infant and 479 adult disyllables from asymmetrically stressed utterances and 48 infant disyllables from uniformly stressed utterances were measured. Two-way analyses of variance were performed on both infant and adult data sets. Independent variables were stress (stressed or unstressed) and syllable position (first or second). Dependent variables were duration (ms), fundamental frequency (f_0), and intensity (dB). For asymmetrically stressed syllables of infants and adults, possible interaction effects between stress and syllable position were also considered (i.e., do means for each factor in stressed or unstressed syllables vary systematically depending on whether they occur in the first or second syllable in the utterance?). In addition, both infant and adult syllable tokens were examined to assess how many and which of the three acoustic correlates were employed in the production of stressed syllables.

For infant utterances perceived as uniformly stressed, none of the three acoustic correlates showed significant differences as a function of syllable position. Infants' disyllables perceived as asymmetrically stressed did show significant acoustic differences between syllables perceived as stressed and unstressed for all three acoustic correlates of stress. It should be emphasized in understanding these results that no intentionality is implied for these infants; these are babbled disyllables perceived as showing stress differences by adult listeners. There were no interaction effects between stress and syllable position. For adult asymmetric syllables, all three acoustic effects were also significant, as expected. In adults, f_0 and intensity showed a significant interaction effect between stress and syllable position. Table 2 shows the results of the statistical analyses for infant and adult asymmetric disyllable data. Means for all three acoustic correlates are displayed in Tables 3, 4, and 5.

For infants, vowel duration in asymmetric disyllables varied as a function of both position and stress. Although vowels were longer in second syllables than in first syllables, the position effect was not significant, which indicates no consistent final syllable lengthening effect. No significant interaction effects were observed. Vowel f_0 in infant asymmetric disyllables also varied systematically as a function of both position and stress. Vowels were higher in fundamental frequency in initial syllables than in final syllables, and stressed vowels were higher than unstressed vowels as well. Although the stress analysis showed significance, the position effect was not significant: it showed only a weak tendency for f_0 declination in second syllables. Vowel intensity varied systematically as a function of both position and stress, and both effects were significant. In contrast to f_0 and duration, second syllable effects were significant for in-

Table 2 Analysis of Variance for Asymmetrically Stressed Disyllables

Source	*df*	Duration	f_0	Intensity
Adult syllables ($n = 958$)				
Stress (S)	1	89.70*	284.84*	386.37*
Position (P)	1	381.14*	12.76*	67.16*
S × P	1	.31	94.60*	42.34*
Within-group error	954	(.002)	(394.05)	(28.57)
Infant syllables ($n = 324$)				
Stress (S)	1	16.05*	20.19*	49.54*
Position (P)	1	.96	.96	8.02*
S × P	1	2.77	.59	.60
Within-group error	320	(.05)	(7608.44)	(33.79)

Note: mean square errors are enclosed in parentheses.
* $P < .001$.

Table 3 Means and Standard Deviations for Duration (ms) in Asymmetrically Stressed Infant and Adult Disyllables

	Adult Syllables (n = 958)		Infant Syllables (n = 324)	
	M	*SD*	*M*	*SD*
Stress (S)				
Stressed (s)	135	.05	319	.23
Unstressed (u)	108	.06	226	.20
Position (P)				
First (1)	93	.05	267	.20
Second (2)	150	.04	277	.24
S × P				
s1	108	.04	326	.23
s2	163	.05	309	.22
u1	78	.06	190	.11
u2	137	.03	253	.25

Table 5 Means and Standard Deviations for Intensity (dB) in Asymmetrically Stressed Infant and Adult Disyllables

	Adult Syllables (n = 658)		Infant Syllables (n = 324)	
	M	*SD*	*M*	*SD*
Stress (S)				
Stressed (s)	68.14	6.88	69.82	6.11
Unstressed (u)	61.36	4.04	64.98	5.63
Position (P)				
First (1)	66.16	7.69	68.64	5.37
Second (2)	63.34	4.84	66.17	6.99
S × P				
s1	70.69	7.94	70.84	3.89
s2	65.61	4.34	68.49	7.99
u1	61.65	3.83	65.74	5.69
u2	61.07	4.22	64.40	5.55

tensity. Vowels in both initial and stressed syllables were higher intensity. No significant interaction effects were observed in the infant data.

Vowel duration in adult asymmetric disyllables varied systematically as a function of both position and stress. Vowels were longer in second syllables than in first syllables and showed a significant final-syllable lengthening effect, in contrast to the infant data. Fundamental frequency also varied systematically as a function of both position and stress. As in the infant data, adult vowels showed a higher f_0 in initial syllables than in final syllables, and stressed vowels were higher than unstressed vowels. In contrast to the infants, the f_0 declination effect was significant for adults. The difference in f_0 attributable to stress was significantly greater in S1 than in S2. Vowel intensity varied systematically as a function of both position and stress, and for both, effects were significant. In contrast to f_0 and duration, second-syllable intensity effects were significant for both infants and adults.

Magnitude of change for stressed to unstressed syllables was also examined for both groups. Ratios of stressed to unstressed syllable values for each of the variables for both groups are shown in Table 6. Ratios for f_0 and intensity are virtually identical for infants and adults. For duration, the adult ratios are lower than the infant ratios, potentially related to the FSL effect in final syllables in the adult data, which was not present at significant levels in the infant data. In other words, the lower ratio of vowel length in stressed/unstressed syllables in adults compared with infants could be attributed to the fact that a significant number of adult unstressed syllables were longer than stressed syllables when the unstressed syllables occurred in final position.

Although both infants and adults show significant differences between stressed and unstressed syllables for all three acoustic correlates, the question arises of how consistently the three parameters vary in the typical manner in individual disyllables. The patterns for each of the individual parameters for the infant and adult tokens are remarkably similar for the two groups. For both groups, all three parameters are in-

Table 4 Means and Standard Deviations for f_0 (Hz) in Asymmetrically Stressed Infant and Adult Disyllables

	Adult Syllables (n = 958)		Infant Syllables (n = 324)	
	M	*SD*	*M*	*SD*
Stress (S)				
Stressed (s)	143	19.02	359	97.08
Unstressed (u)	121	22.64	314	75.97
Position (P)				
First (1)	135	26.56	344	89.59
Second (2)	130	19.85	328	89.87
S × P				
s1	152	20.00	366	95.20
s2	135	13.38	349	99.34
u1	118	20.71	315	72.47
u2	126	23.85	313	78.91

Table 6 Ratio of Values in Stressed/Unstressed Syllables

	Duration	f_0	Intensity
Adult disyllables	1.25	1.17	1.11
Infant disyllables	1.41	1.14	1.07

creasing as expected for approximately 45% of the tokens. For another 40–45%, two parameters change in the expected direction in stressed syllables. For 10% of the stressed syllables in both groups, only one acoustic correlate changed in the expected direction.

The question that logically arises is which acoustic correlates are present in stressed signals when fewer than the expected three show an increase in value. Figures 1 and 2 display the acoustic correlates present for the infant and adult tokens. When stress is produced with two correlates, intensity and frequency are most frequently higher for both infants and adults. This pattern is far more characteristic of the adult than infant stressed syllables. The pairing of two correlates is more evenly distributed for the infants than for the adult syllables. When one correlate is present, duration is most frequently longer in the infant data, followed by higher intensity and frequency. In the adult data, higher intensity is most frequent, with far fewer instances of duration and frequency increase alone used to signal stress. These minor differences of degree in the use of the three acoustic correlates notwithstanding, the infant data look remarkably similar to the adult data.

In contrast, positional effects on stress marking differ between the two groups. Figure 1 displays results for the infant syllables. Stressed syllables in first- and second-syllable position show a similar pattern of stress marking. Adult positional effects are displayed in Figure 2. Marked differences appear between the first- and second-syllable position for the adult tokens. In first-syllable position, two correlates are far more frequently employed for stress marking and the intensity-frequency increase predominates. In second syllables, use of all three correlates is characteristic. Duration is employed, regardless of the number of acoustic correlates present. For the adult syllables, the patterns for the two syllable positions look quite different from the pattern for all stressed syllables in the left of the figure. The overall finding of significant final-syllable lengthening in adults but not infants could account for the differences related to positional effects seen between the two groups.

The relationship between perceived stress in the infant disyllable corpus and English-language trochaic stress patterns was also analyzed. All disyllables on which two transcribers agreed on the perceptual stress assignment were included in this analysis. Table 7 presents a summary of the stress patterns observed in the disyllabic utterances in the total infant corpus.

Approximately 48% of the infant disyllables were judged to be asymmetrically stressed. Thus, overall totals for uniformly and asymmetrically stressed syllables were approximately equal. For two participants (C and N), use of uniformly and asymmetri-

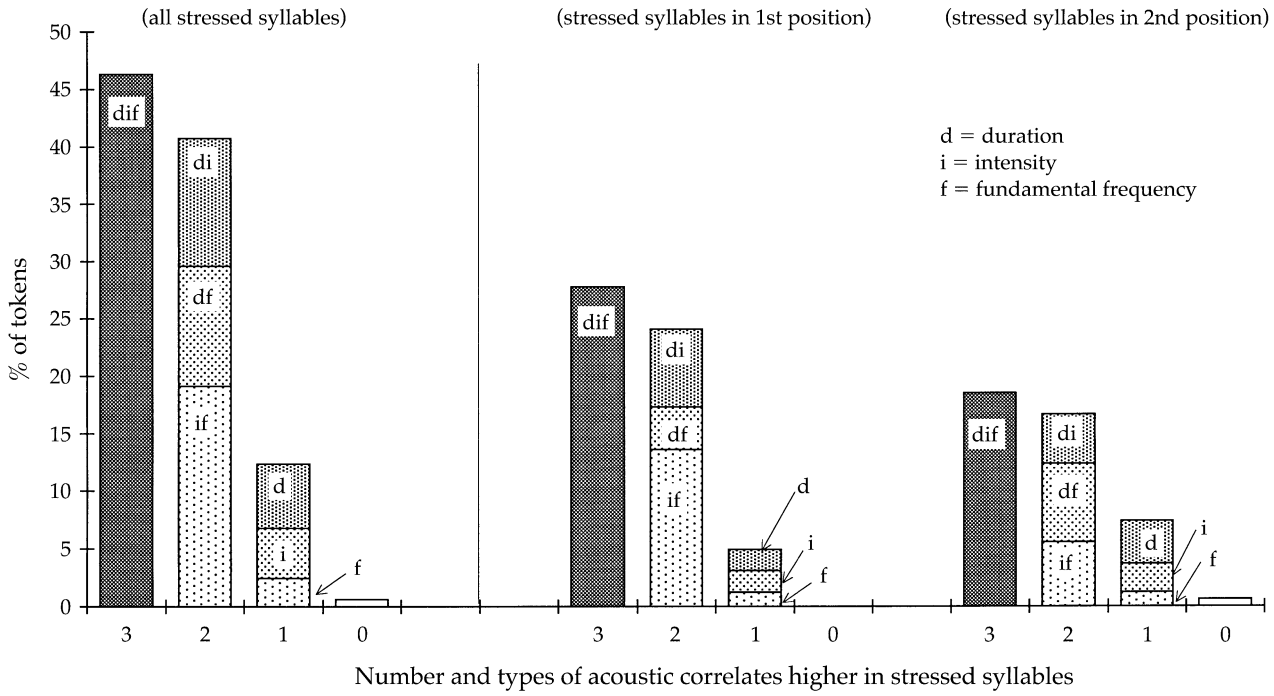

Figure 1 Positional effects on acoustic correlates in infant stressed syllables.

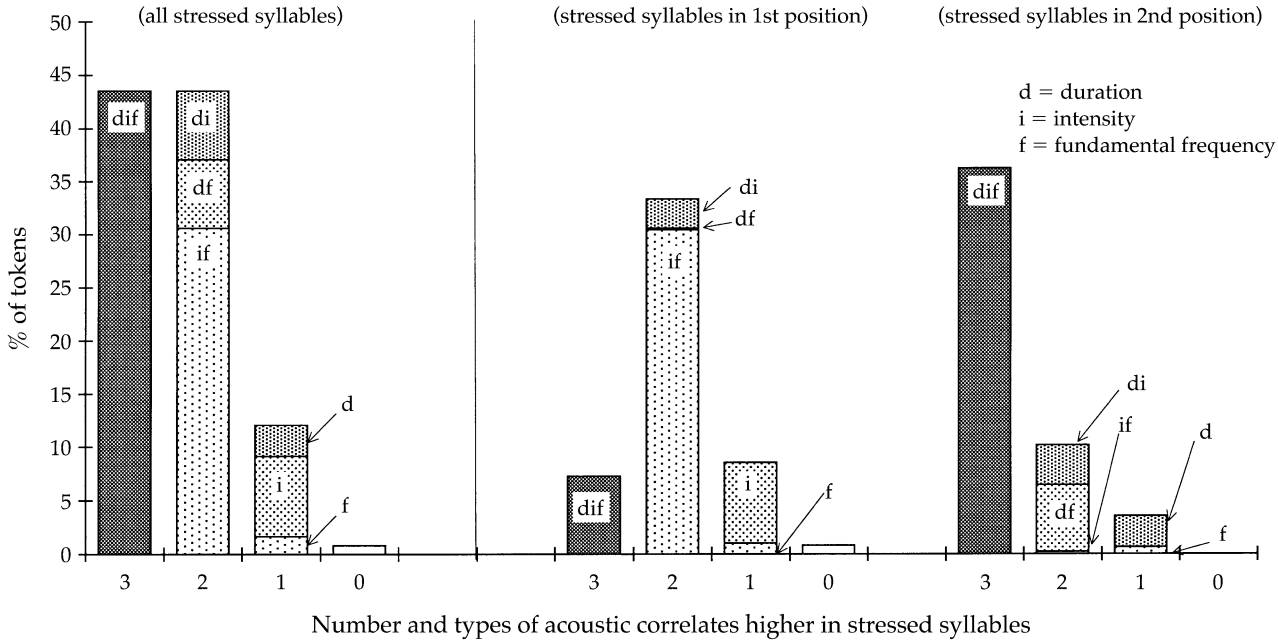

Figure 2 Positional effects on acoustic correlates in adult stressed syllables.

cally stressed syllables was approximately equal. For R, use of uniformly stressed syllables predominated; for P, asymmetrically syllables predominated. Preferred use of asymmetrically stressed disyllables revealed individual differences: Two infants reflected a trochaic stress pattern consistent with stress patterns for English; one participant showed an iambic pattern; and one participant showed an almost equal distribution of first- and second-syllable stress.

DISCUSSION

Babbling infants in this study employed the acoustic correlates of stress for disyllables judged perceptually by adults as uniformly or asymmetrically stressed. Acoustic analysis of infant tokens revealed significant differences between stressed and unstressed syllables, regardless of syllable position, for all three variables, consistent with measurement of acoustic correlates of asymmetric stress in the adult citation form disyllables. In the infants, uniformly stressed disyllables analyzed acoustically did not show significant differences on any of the three acoustic variables. Ratios for infant and adult stressed/unstressed syllables were highly similar as well. These results suggest that asymmetric stress production is perceptually and acoustically apparent in prelinguistic infant output and coexists with production of equal stress disyllables. Most importantly, these acoustic measurements are tightly linked with adults' percept of stress (for both uniform and asymmetric disyllables) in these infants.

Neither infants nor adults always employed the three acoustic parameters in a correlated manner in all disyllabic utterances. For both groups, acoustic analysis revealed that a large percentage of the tokens produced were characterized by changes in only one or two acoustic parameters. No linguistic intent is inferred for these spontaneous vocalizations during the babbling period. However, it should be emphasized that the tokens selected were those for which the percept of stress was agreed on by two listeners. Adult speakers, in contrast, read citation-form disyllables with intentional use of stress contrast. Regardless of speaker differences, the strong impression from these data is one of similarity in acoustic characteristics of stressed syllables between infants and adults. Differ-

Table 7 Relative Frequencies of Disyllables in the Total Corpus with Uniform Stress and Asymmetric Stress on Either the First or the Second Syllable

Subject	Uniform Stress	Asymmetric Stress		
		S1	S2	Total
C	252	126	127	253
R	192	59	70	129
P	32	81	59	140
N	125	94	42	136
Total	601	360	298	658

ences are found in relative distribution of the acoustic correlates and in syllable position effects. FSL was present in adults but not in the infants and likely accounts for differences in syllable position effects between the two groups.

These results lend support to the conclusion that these infants are coordinating the three acoustic correlates of English syllable-level prosody in a relatively adultlike manner before they produce the lexical items that specify where stress is placed in an utterance. Respiration and phonation are coordinated with supralaryngeal events to produce a *percept* of syllable-level stress differences in adult listeners. These prelinguistic vocalizations do not indicate control of the acoustic parameters required for words incorporating placement of stress in a particular location. However, these results do imply that the development of stress placement in first words of more than one syllable should primarily involve establishing a linkage between lexical representation and an *existing* physiological capacity to produce perceptible stress. These data do not specifically answer the question of when such physiological capacities develop. As with sound and sequential properties, these infants can be said to be globally representing the prosodic properties of speech production in an English-speaking environment.

Sound types and sequences are noted to be "speechlike" at the onset of canonical babbling, around 7 months. Prosodic capacities appear to be available concurrently with these sound and sequential properties to support the "speechlike" percept of these prelinguistic productions. Continuity has been a hallmark of recent work on segmental development in early word acquisition, where infants are seen as employing production capabilities apparent in babbling during early speech (Vihman, Ferguson, & Elbert, 1986; Vihman, Macken, Miller, Simmons, & Miller, 1985). Production of first words is seen as linking lexical representations with already-existing segmental and sequential output capacities. These data lend support to continuity in prosodic development as well because differential stress production is present in prelinguistic babbling for use in first words.

The finding that babbling infants can modulate the three prosodic variables in syllables perceived as stressed does not necessarily mean that control is finally established. An additional issue related to development of intentional control for acoustic correlates of stress difference is variability. Acoustic studies of the early word period showed acoustic correlates of stress to be present in 18- to 24-month-olds (Goodell & Studdert-Kennedy, 1993; Kehoe et al., 1995; Pollock et al., 1993; Schwartz et al., 1996). Participants in these studies, however, showed variability and were not completely adultlike in various aspects of stress marking. Previous transcription-based studies of 2-year-olds also indicate high variability in correct stress assignment for intended word targets (e.g., Hochberg, 1988; Klein, 1984; Leopold, 1947; Menn, 1976). In the prelinguistic infants in this study, uniformly and asymmetrically stressed sequences coexist at the perceptual level, which indicates that variable syllable-level stress marking is also characteristic in this period.

Ambient-language effects seem apparent in aspects of stress marking in languages with a consistent target, as indicated by final-syllable lengthening results in prelinguistic French infants where the presence of languagelike use of FSL was noted (Bacri et al., 1989; Hallé et al., 1991; Levitt, 1993; Levitt & Uttman, 1992; Levitt & Wang, 1991). Hallé et al. (1991) found FSL and f_0 declination to be absent in Japanese infants, as they are in the target language. In contrast, for English, where the ambient-language target is more complex with trochaic word-level and iambic syllable-level stress patterning, infants showed more variability across available studies in both FSL and f_0 (e.g., Levitt & Wang, 1991; Vihman et al., 1998). Variability in duration may thus be characterized as a complex combination of production effects (e.g., Smith, 1978; Tingley & Allen, 1975) and perceptual effects related to ambient language characteristics (e.g., Hochberg, 1988; Klein, 1984; Levitt & Wang, 1991; Pollock et al., 1993; Vihman et al., 1998).

The adult participants in this study showed position effects for all three acoustic correlates of stress: Second syllables were significantly longer and lower in f_0 and amplitude as predicted by a model of vocal function that proposes loss of energy at the end of an utterance. A physiological basis has been posited for final-syllable lengthening and for f_0 and intensity declinations (Lieberman, 1976; Smith, 1978), which are reliably present in adult speakers. The infants in the present study did not show the same effects at significant levels except for intensity, although the trends were in the same direction as in adult participants.

The notion of when and where FSL may be apparent in early development has not been clearly established. There was no overall tendency in these English learning infants for lengthening of the final syllable. The effect should be present if there is either an inherent tendency toward it or an ability to simulate its presence in the ambient language. Laufer (1980) found evidence of final lengthening in protosyllables in infants 0–24 weeks, although examination of protosyllables introduces methodological difficulties in comparing with early canonical syllables

(Oller, 1980), which are more comparable with mature speech output. In contrast, in babbling infants in an English language environment, studies by Oller and Smith (1977) and Levitt and Wang (1991) suggested that FSL was not clearly present. In Robb and Saxman's (1990) study of infants 8 to 26 months old, final lengthening was present, but results did not reach significance for the group data. As noted earlier, the broad age span of these participants might introduce complexities related to developmental level (e.g., Snow, 1994). In babbling French infants, FSL was observed by Levitt and Wang (1991). However, Konopczynski (1986) failed to find evidence of FSL in French infants 8–10 months of age. It was not present in the Japanese infants studied by Hallé et al. (1991) consistent with adult Japanese, also lending credibility to the impact of ambient language effects as early as the 25-word point. A potential conclusion from the results of this study taken in the context of other findings is that FSL may be an inherent effect of the production system, possibly manifest early in development (Laufer, 1980), which may be modulated by ambient language effects by the prelinguistic babbling stage. The ambient-language effects may be particularly strong in languages that present a target congruent with inherent production effects (e.g., French). In languages where ambient-language effects are counter to inherent tendencies of the production system, infants may show more variability in FSL. This interpretation is consistent with that of Vihman et al. (1998) in their study of early words in French and English infants. By 18 to 24 months (Snow, 1994), FSL may or may not be apparent, related to the stage of language development of the individual infant. A complex of effects related to production, perception, and language development level may be responsible for FSL characteristics at any one point in time.

Although second syllables were lower than first syllables in f_0, these infants did not show significant syllable-level effects of f_0 declination as did the adults. Once again, studies of earliest periods of development (Kent & Murray, 1982; Stark et al., 1975) indicate some evidence for f_0 declination in acoustic studies of early noncry vocalizations. Falling intonation contours are reported as developing earlier than rising in English language environments (e.g., DeLack & Fowlow, 1978). In studies of babbling and early words, presence of a falling or rising terminal f_0 at the word level appears to be related to target language characteristics. The situation for f_0 declination appears thus to mirror that for FSL, where early characteristics of infant vocalization appear to be mediated by the potential effects of ambient language in the period of babbling and first words.

Only for intensity variations do the infant and adult data show similar results for terminal syllables. For both, significantly less intensity is found for second syllables of asymmetric disyllables. Intensity variation is thought to arise from respiratory function in normal adults and is proposed as being lower in terminal syllables as a result of termination effects in the production system (Lieberman, 1984). Potentially, this aspect of stress production might show perceptual effects of language environment as well. Available data on babbling and first words (Levitt, 1993; Vihman et al., 1998) indicate some small potential effects with considerable variability. In the present study, however, infants and adults showed consistent patterns. It should be noted that single-word trochaic patterns might enhance a tendency toward this pattern in these English-learning infants. Recent studies of the relationship between vocal intensity and respiration (Finnegan, Luschel, & Hoffman, 1998) indicate that respiratory forces in normal adults control both temporary and sustained increases in intensity. The congruent results for infants and adults found in these data indicate that respiratory support for temporary (stress-related) increases in intensity are available to prelinguistic infants. In addition, for this aspect of stress marking, no ambient language effects have been reported comparable to those explored for f_0 and duration.

In comparison with the word-level trochaic pattern for adult English speakers, these infants showed individual differences in stress placement. Only one infant showed predominant use of asymmetric stress; two others showed approximately equal use of symmetric and asymmetric stress and one used uniform stress predominantly. In asymmetric disyllables, two infants produced trochaic patterns, one iambic, and one showed no preference. The small size of this database limits generalization of findings. A conclusion based on these results, however, is that no consistent use of asymmetric stress patterns or trochaic bias is apparent in this corpus of transcribed disyllables. At a prelexical stage these infants are producing acoustic correlates of adult stress to some degree independent of the linguistic details of the adult lexicon. They may focus only later on matching stress patterns to lexical models. The relatively well-established pragmatic use of f_0 (D'Odorico & Franco, 1991; Flax, Lahey, Harris, & Boothroyd, 1991; Galligan, 1987) provides a further example of the freedom of the output system from specifically lexical constraints at this age. These results mirror the inconsistent trochaic patterning found in English-learning infants in the first-word period by Vihman et al. (1998). The strong–weak alternation is proposed as being present in early stages

of syntactic organization in English-learning infants (e.g., Gerken, 1994). It does not clearly appear to develop during babbling as a preferred frame for the subsequent trochaic words in the way that the open–closed alternation of babbling may serve as a frame for subsequent development of segmental and syllabic diversity (Davis & MacNeilage, 1995b; MacNeilage & Davis, 1990).

Absence of a trochaic bias on stress placement in production contrasts with findings on perceptual bias by Jusczyk, Cutler, and Redanz (1993) suggesting that 9-month-old English-learning infants, as a group, evince greater sensitivity to trochaic than iambic input patterns. It should be noted, however, that the individual participant patterns in the Jusczyk et al. study showed some variability as well. In their first experiment, 21 out of 24 participants showed trochaic bias. In the second, 15 out of 24 showed trochaic bias.

CONCLUSION

The four infants in this study showed evidence of coordination of the respiratory, laryngeal, and supralaryngeal systems for production of uniformly and asymmetrically stressed disyllables in a largely adult-like manner. No intentionality is suggested for canonical babbling vocalizations. Instead, our findings suggest that these infants are able to bring physically available coordinative abilities to the later task of learning language-specific and rule-based stress differences in words. Syllable-ordering differences between infants and adults were found to be related to FSL and f_0, which have been proposed as strong effects predicted by the operation of the production system. No trochaic bias was present in these data, which suggests that it may emerge later as a learned aspect of the prosodic system. This type of study of prelinguistic infants can help to disentangle potential physiologically available capacities from effects of the ambient language environment on acquisition.

The production of differential stress in disyllables, observed in this study in the prelinguistic canonical babbling period, should be investigated longitudinally through onset of first words and later stages to understand the impact of developmental stage on manifestation of prosodic patterns. Additional studies of ambient-language effects in varied languages would allow a fuller understanding of the interactive role of perception and production across developmental stages. These results, interpreted in the context of other research in this area, suggest that prosodic aspects of speech production may be best viewed as a complex tapestry. It is a tapestry woven from contrasting but complementary threads of physiological effects and perceptual influences from the environment interacting in varied ways during the course of language development from prelinguistic vocalization to multiword sequences.

ACKNOWLEDGMENTS

This paper was prepared with support from research grant #HD-27733-07 from the National Institute of Health. The authors would like to extend special thanks to Marilyn Vihman and Rory DePaolis for helpful comments on earlier versions of this manuscript.

ADDRESSES AND AFFILIATIONS

Corresponding author: Barbara L. Davis, Dept. of Communication Sciences and Disorders, University of Texas at Austin, Austin, TX 78712; e-mail: babs@mail. utexas.edu. Peter F. MacNeilage, Christine L. Matyear, and Julia K. Powell are also at the University of Texas at Austin.

REFERENCES

Bacri, N., DeBoysson-Bardies, B., & Hallé, P. (1989). Prosodic processing in French and American infants' babbling. In *Proceedings of Speech Research '89* (pp. 5–8). Budapest: Linguistic Institute of the Hungarian Academy of Sciences.

Bush, C. N., Edwards, M. L., Edwards, J. M., Luckau, C. M., Macken, M. A., & Peterson, J. D. (1973). On specifying a system for transcribing consonants in child language. In *Stanford child language project.* Stanford, CA: Department of Linguistics, Stanford University.

Cruttenden, A. (1986). Intonation. Cambridge: Cambridge University Press.

Cutler, A. (1990). Exploiting prosodic probabilities in speech segmentation. In G. T. M. Altmann (Ed.), *Cognitive models of speech and processing: Psycholinguistic and computational perspectives.* Cambridge, MA: MIT Press.

Davis, B., & MacNeilage, P. F. (1990). Acquisition of correct vowel production: A quantitative case study. *Journal of Speech and Hearing Research, 33*, 16–27.

Davis, B. L., & MacNeilage, P. F. (1994). Organization of babbling: A case study. *Language and Speech, 37*(4), 341–355.

Davis, B. L., & MacNeilage, P. F. (1995a, August). Articulatory preferences in first words: The frame content hypothesis. In *Conference Proceedings of the XII International Congress of Phonetic Sciences*, Stockholm, Sweden.

Davis, B. L., & MacNeilage, P. F. (1995b). The articulatory basis of babbling. *Journal of Speech and Hearing Research, 38*(4), 1199–1211.

DeLack, J. B., & Fowlow, P. J. (1978). The Ontogenesis of differential vocalization: Development of prosodic contrastivity during the first year of life.

Delattre, P. C. (1965). *Comparing the phonetic features of En-*

glish, French, German, and Spanish. Heidelberg, Germany: Julius Groos Verlag.
Delattre, P. C. (1966). A comparison of syllable length conditioning among languages. *International Journal of Applied Linguistics, 4*, 182–198.
D'Odorico, L., & Franco, F. (1991). Selective production of vocalization types in communication contexts. *Journal of Child Language, 18*, 475–499.
Finnegan, E., Luschel, E., & Hoffman, H. (1998). Modulations in respiratory and laryngeal activity associated with changes in vocal intensity during speech. *NCVS Status and Progress Report*, 11–21.
Flax, J., Lahey, M., Harris, K., & Boothroyd, A. (1991). Relations between prosodic variables and communicative functions. *Journal of Child Language, 18*, 3–19.
Fry, D. (1955). Duration and intensity as linguistic correlates of stress. *Journal of the Acoustical Society of America, 27*, 765–768.
Galligan, R. (1987). Intonation with single words: Purposive and grammatical use. *Journal of Child Language, 14*, 1–21.
Gerken, L. (1994). Sentential processes in early child language: Evidence from the perception and production of function morphemes. In H. C. Nusbaum & J. C. Goodman (Eds.), T*he Transition from Speech Sounds to Spoken Words.* Cambridge, MA: MIT Press.
Goodell, E., & Studdert-Kennedy, M. (1993). Acoustic evidence for the development of gestural communication in the speech of 2-year olds: A longitudinal study. *Journal of Speech, Language, and Hearing Research, 36*, 707–726.
Guidubaldi, J., Newborg, J., Stock, J. R., Svinicki, J., & Wneck, L. (1984). *Battelle Developmental Inventory.* Allen, Texas: DLM Teaching Resources.
Hallé, P. A., Boysson-Bardies, B., & Vihman, M. M. (1991). Beginnings of prosodic organization: Intonation and duration patterns of disyllables produced by Japanese and French infants. *Language and Speech, 33*, 99–110.
Hochberg, J. G. (1988). Learning Spanish stress: Developmental and theoretical perspectives. *Language, 64*, 683–706.
Jusczyk, P. W., Cutler, A., & Redanz, N. J. (1993). Infant's preference for the predominant stress patterns of English words. *Child Development, 64*, 675–687.
Kehoe, M., Stoel-Gammon, C., & Buder, E. H. (1995). Acoustic correlates of stress in young children's speech. *Journal of Speech, Language, and Hearing Research, 38*, 338–350.
Kent, R. D., Mitchell, P. R., & Saucier, M. (1991). Evidence and role of rhythmic organization in early vocal development in human infants. In J. Fagard & P. H. Wolff (Eds.), *The development of timing control and temporal organization in coordinated action.* Oxford, U.K.: Elsevier.
Kent, R. D., & Murray, A. D. (1982). Acoustic features of infant vocalic utterances at 3, 6, and 9 months. *Journal of the Acoustical Society of America, 72*, 353–365.
Klein, H. (1984). Learning to stress: A case study. *Journal of Child Language, 11*, 375–390.
Konopczynski, G. (1986). Vers un modèle développemental du rythme français: problèmes d'isochronie reconsidérés à la lumière des données de l'acquisition du langage. *Bulletin de L'Institut de Phonétique de Grenoble, 15*, 157–190.
Kozhevnikov, V. A., & Chistovich, L. A. (1965). *Speech: Articulation and perception.* Washington, DC: Joint Publications Research Service, U.S. Department of Commerce.
Laufer, M. Z. (1980). Temporal regularity in prespeech. In T. Murray & A. Murray (Eds.), *Infant communication: Cry and early speech.* Houston, TX: College Hill Press.
Leopold, W. F. (1947). Speech development of a bilingual child: A linguist's record. Chicago: Northwestern University Press. *Journal of Phonetics, 4*, 91–112.
Levitt, A. G. (1993). The acquisition of prosody: Evidence from French- and English-learning infants. In B. Boysson Bardies, S. de Schoen, P. Jusczyk, P. MacNeilage, & J. Morton (Eds.), *Developmental neurocognition: Speech and face processing in the first year of life* (pp. 385–398. Dordrecht, the Netherlands: Kluwer.
Levitt, A., & Utman, J. (1992). From babbling toward the sound systems of English and French: A longitudinal two case study. *Journal of Child Language*, 19–49.
Levitt, A. G., & Wang, Q. (1991). Evidence for language specific rhythmic influences in the reduplicative babbling of French and English learning infants. *Language and Speech, 34*(3), 235–249.
Lehiste, I. (1970). *Suprasegmentals.* Cambridge, MA: MIT Press.
Lieberman, P. (1960). Some acoustic correlates of word stress in American English. *Journal of the Acoustic Society of America, 32*, 451–454.
Lieberman, P. (1976). Phonetic features and physiology: A reappraisal. *Journal of Phonetics, 4*, 91–112.
Lieberman, P. (1984). *The Biology and Evolution of Language.* Cambridge, MA: Harvard University Press.
Locke, J. (1983). *Phonological Acquisition and Change.* New York: Academic Press.
MacNeilage, P. F., & Davis, B. L. (1990). Acquisition of speech production: Frames, then content. In M. Jeannerod (Ed.), *Attention and performance XIII: Motor representation and control* (pp. 453–475). Hillsdale, NJ: Erlbaum.
MacNeilage, P. F., Davis, B. L., & Matyear, C. L. (1997). Babbling and first words: Phonetic similarities and differences. *Speech Communication, 22*, 269–277.
Menn, L. (1976). *Pattern, control and contrast in beginning speech.* Unpublished doctoral thesis, University of Illinois at Urbana-Champaign.
Oller, D. K. (1980). The emergence of the sounds of speech in infancy. In G. Yeni-Komshian, J. F. Kavanagh, & C. A. Ferguson (Eds.), *Child phonology: Vol. 1. Production* (pp. 93–112). New York: Academic Press.
Oller, D. K. (1986). Metaphonology and infant vocalizations. In B. Lindblom & R. Zetterstrom (Eds.) *Precursors of early speech* (pp. 21–35). Hampshire, U.K.: MacMillan.
Oller, D. K. (1990). *Logical international phonetic programs.* Miami, FL: Intelligent Hearing Systems.
Oller, D. K., & Smith, B. L. (1977). Effect of final syllable position on vowel duration in infant babbling. *Journal of the Acoustical Society of America, 62*, 994–997.
Olswang, L., Stoel-Gammon, C., Coggins, T., & Carpenter, R. (1987). *Assessing linguistic behavior.* Seattle, WA: University of Washington Press.
Pollock, K., Brammer, D. M., & Hageman, C. F. (1993). An acoustic analysis of young children's productions of word stress. *Journal of Phonetics, 21*, 183–203.

Robb, M., & Saxman, J. (1990). Syllable durations of preword and early word vocalizations. *Journal of Speech and Hearing Research, 33*, 583–593.

Roug, L., Landburg, I., & Lundburg, L. J. (1989). Phonetic development in early infancy: A study of four Swedish children during the first eighteen months of life. *Journal of Child Language, 16*, 19–40.

Schwartz, R. G., Petinou, K., Goffman, L., Lazowski, G., & Cartsciello, C. (1996). Young children's production of syllable stress: An acoustic analysis. *Journal of the Acoustic Society of America, 99*, 3192–3200.

Smith, B. (1978). Temporal aspects of English speech production: A developmental perspective. *Journal of Phonetics, 6*, 37–67.

Snow, D. (1994). Phrase-final syllable lengthening and intonation in early child speech. *Journal of Speech and Hearing Research, 37*, 831–840.

Snow, D. (1998). A prominence account of syllable reduction in early speech development: The child's prosodic phonology of tiger and giraffe. *Journal of Speech, Language, and Hearing Research, 41*, 1171–1184.

Stark, R. E., Rose, S. N., & McLaglan, M. (1975). Features of infant sounds: The first eight weeks of life. *Journal of Child Language, 2*, 205–221.

Tingley, B. M., & Allen, G. D. (1975). Development of speech timing control in children. *Child Development, 46*, 186–194.

Vihman, M. M., DePaolis, R., & Davis, B. L. (1998). Is there a trochaic bias in early word learning? Evidence from infant production in English and French. *Child Development, 69*, 935–949.

Vihman, M. M., Ferguson, C. E., & Elbert, M. (1986). Phonological development from babbling to speech: Common tendencies and individual differences. *Applied Psycholinguistics, 7*, 3–40.

Vihman, M., Macken, M., Miller, R., Simmons, H., & Miller, J. (1985). From babbling to speech: A reassessment of the continuity issue. *Language, 60*, 397–445.

Whalen, D., Levitt, A., & Wang, Q. (1991). Intonation differences between the reduplicative babbling of French- and English-learning infants. *Journal of Child Language, 18*, 501–516.