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Acquisition of Serial Complexity in Speech Production: A Comparison of Phonetic and Phonological Approaches to First Word Production

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Abstract

Comparison was made between performance-based and competence-based approaches to the understanding of first word production. The performance-related frame/content approach is representative of the biological/functional perspective of phonetics in seeking explanations based on motor, perceptual and cognitive aspects of speech actions. From this perspective, intrasyllabic consonant-vowel (CV) co-occurrence patterns and intersyllabic sequence patterns are viewed as reflective of biomechanical constraints emerging from mandibular oscillation cycles. A labial-coronal sequence effect involved, in addition, the problem of interfacing the lexicon with the motor system, as well as the additional problem of initiation of movement complexes. Competence-based approaches to acquisition are within the generative phonological tradition; involving an initial assumption of innate, speech-specific mental structures. While various current phonological approaches to acquisition involve consideration of sequence effects and intrasyllabic patterns, they do not adequately establish the proposed mental entities in infants of this age, and are nonexplanatory in the sense of not considering the causes of the structures and constraints that they posit.

Introduction

Two theoretical approaches have characterized investigation of the acquisition of speech production [Vihman, 1996]. They are encompassed within the competence/performance dichotomy initially formulated by Chomsky [e.g. 1984]. The competence-related approach is the approach of modern generative phonology. It is primarily devoted to the characterization of innate phonological knowledge specific to humans that is considered to be a component of Universal Grammar. The performance-related approach is centered in phonetics and can be characterized as a predominantly biological or functional approach. It is an attempt to understand speech production in terms of

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the motor, perceptual, and cognitive properties derived from studies of speech-related actions and from the evolutionary heritage of the vocal-auditory system. A goal of this paper is to compare these two approaches to the understanding of acquisition of speech production by considering how they apply to a corpus of first-word productions from 10 infants in an English language environment. We will focus on several aspects of serial organization: intrasyllabic and intersyllabic regularities in first-word structure, patterned regularities related to word-level patterns, and initiation and termination patterns in serial organization.

Phonetic Approaches

Phonetic approaches characterize the nature of acquisition as being motivated by development of speech motor control and perceptual influences [e.g. Kent, 1984; Lindblom et al., 1993; Locke, 1983; Studdert-Kennedy, 1986]. These treatments focus on relationships among articulatory, respiratory and phonatory components of the speech production system as well as the potential impact of perceptual development in babbling [Werker and Tees, 1984] and early words [Stager and Werker, 1997]. Emphasizing the time domain, the infant's development of speech production patterns is characterized as operating within an overall rhythmic envelope consisting of close-open movements with resultant alternations between non-resonant and resonant acoustic output [e.g. Bickley et al., 1986; Koopmans-van Bienum and van de Steldt, 1986].

Differentiation of movement patterning from the substrate of available production and perceptual capacities is emphasized [e.g. Thelen and Smith, 1994]. These functional perspectives propose that the actions of the body rather than the status of underlying mental representations or rules are basic to explanation and understanding of observed patterns [e.g. Clark, 1997]. Explanation is based on understanding of the physically based motivation for patterns observed. As noted by Lindblom [1992], functional perspectives require that the units be 'earned' rather that being granted a priori status based on frequency of occurrence. Lindblom [1992, p. 134] suggests the notion of 'independently motivated explanatory principles' in which the search for precursors and independent motivation is emphasized, in contrast to explanation based on description of relative frequency. For example, the principle of 'markedness' in phonological theory [e.g. Archangeli, 1997] suggests that frequently occurring properties are 'unmarked,' as in Archangeli's [1997, p. 2] statement that 'The term markedness is used to refer to this continuum (from language universal to language specific) with completely unmarked properties being those found in virtually all languages and extremely marked properties being found quite rarely.' She then proposes that the markedness concept is 'explanatory.' The functionalist perspective requires a criterion other than frequency, or early emergence [e.g. MacNeilage and Davis, in press], as is presently required for designating unmarked sounds in acquisition [Paradis and Prunet, 1991].

Frames then Content

Within this functionalist phonetic tradition, a general theoretical account of early motor control of speech production has been developed [e.g. Davis and MacNeilage, 1990, 1994, 1995; MacNeilage and Davis, 1990a, b, 1993; MacNeilage et al., 2000].

This approach is embedded in a neo-Darwinian theory of the evolution of speech, the frame/content theory [see MacNeilage, 1998, for a comprehensive presentation of the frame/content theory]. Initial formulation of the theory was heavily dependent on evidence of segmental serial ordering errors in adult speech, particularly the tendency for misplaced segments to obey syllable structure constraints. This focus on the question of serial organization was originally motivated by Lashley [1951], who made extensive use of evidence from speech errors in raising the fundamental question of how we are to understand the serial organization of any action sequence.

According to the frame/content theory, serial organization of speech resulted from the evolution of a capacity to place segmental ‘content’ elements (consonants and vowels) into syllable structure ‘frames.’ The syllable frames are considered to have evolved from ingestion-related mandibular cycles used in chewing, sucking and licking, with the open phases consisting of vowels and the closed phases consisting of consonants [MacNeilage, 1998]. The initial interest in speech acquisition was in the question of how the segmental independence indicated by adult serial ordering errors develops [MacNeilage and Davis, 1990a]. In the context of acquisition, the ‘frames then content’ perspective provides a testable framework for exploring acquisition of speech production abilities beginning at the onset of babbling [around 7 months; Oller, 1980; Stark, 1980]. In this view, the task facing the infant is to gain independent control of coordinated articulators in the time domain, thus addressing for speech the general problem of serial order in action systems. As Lashley [1951] posed the question: ‘How is any action sequence organized?’ For speech acquisition, the solution to Lashley’s [1951] question requires mastery of serial organization as well as initiation and termination of action sequences.

Rhythmic mandibular oscillation (i.e. the frame) accompanied by phonation is the aspect of the infant movement system available for the initial approximation of the serial organization of adult speech at the onset of canonical babbling [MacNeilage and Davis, 1990a, b, 1993]. The ‘unit’ in babbling is considered to be the rhythmic mandibular cycle which yields simulations of ‘consonants’ in the closure phase, ‘vowels’ in the open phase, and ‘syllables’ as the consequence of these alternations between consonants and vowels. No subcycle independence of component articulators such as tongue, lips, or soft palate is required for the infant to produce speech-like sequences.

With development, segmental content elements (consonants or vowels) are gradually differentiated from the frame to become separate entities as the infant acquires increasing control over the coordination of articulators in action sequences. For example, as the tongue becomes relatively more independent of the jaw, the infant is predicted to produce place variegation in consonant sequences and reduce syllable reduplication. Control over soft palate closure predicts growth in alternation of nasals and orals rather than pervasive nasal or oral quality throughout sequences. Most importantly, action in the time domain is a basic tenet in contrast to descriptions of the status of underlying rules or phonological representations.

The possibility of an initial frame dominance was first suggested by a study of a single infant, 14–20 months of age [Davis and MacNeilage, 1990]. Three consonant-vowel (CV) co-occurrence preferences were found: coronal consonants with front vowels, dorsal consonants with back vowels, and labial consonants with central vowels. The two lingual patterns (coronal-front and dorsal-back) seemed to result from an extremely basic property of matter of all kinds, namely inertia – in this case inertia of the tongue. The labial-central pattern may result from mandibular oscillation alone, and, as a ‘pure frame’ [MacNeilage and Davis, 1990b], may be a manifestation of prototypical syllable structure. The coronal-front and dorsal-back patterns are considered as superimposed on the basic frame, resulting in ‘fronted frames’ and ‘backed frames’ [MacNeilage and Davis, 1990b]; hence the term frame dominance. They are viewed as results of a relative absence of active intersegmental changes from one tongue position to another during close-open sequences. We predicted that these patterns would also be observable in babbling as they seemed to represent basic aspects of the vocal production system, and did not seem to be a result of perceptual experience [Davis and MacNeilage, 2000]. No lip rounding is predicted in the labial context for either the consonant or the vowel, as this would add an active lip movement to the mandibular cycle, suggesting that the lips are actively able to operate in the cycle along with the mandible. This prediction is in contrast to the prediction of phonological approaches for co-occurrence of labials and rounded vowels [Clements and Hume, 1995; Levelt, 1994].

A number of subsequent studies have largely confirmed the existence of these three CV co-occurrence patterns in both babbling and early words, though the studies of early words have for the most part been based on small databases per infant. A study of 1 infant during canonical babbling [Davis and MacNeilage, 1994] revealed the presence of the labial-central and coronal-front associations, although not dorsal-back associations, because too few dorsals were produced to analyze. Davis and MacNeilage [1995] subsequently studied 6 normally developing infants during babbling. The three predicted intracyclic CV associations, involving stops, nasals, and glides, were confirmed at significant levels in all infants (18 total predictions for 6 infants). Only 9 above-chance associations were found in instances in which CV associations were not predicted. Gildersleeve-Neumann et al. [in press] considered consonants with lower frequency of occurrence (fricatives, liquids, and affricates) in 4 of the infants previously studied in babbing. CV co-occurrence patterns similar to the patterns for stops, nasals, and glides were found (coronal consonants with front vowels and labial consonants with central vowels).

Other studies have confirmed some aspects of these intracyclic CV associations in both English-speaking infants and in cross-language investigations during babbling and first words. Vihman [1992] studied 23 infants learning French, English, Swedish and Japanese in the first word period. Labial-central and dorsal-back associations were confirmed; coronal-front associations were not. In Vihman’s [1992] analysis, [æ] was considered a central vowel, complicating evaluation of the coronal-front association. Boysson-Bardies [1993] studied first and second syllables separately in French, English, Swedish and Yoruba infants during first words. Her results showed predominance of labial-central associations in first syllables except in the English infants. Coronal-front associations were found for French, Swedish and English, but not Yoruba. Dorsal-back associations were not confirmed. Oller and Steffans [1993] studied 4 infants at 10–12 months and 16–24 months. In the early period, the coronal-front and dorsal-back associations were confirmed. By 16–24 months, CV associations had weakened. These weakened associations were interpreted as consistent with development toward more segmental function.

Davis et al. [1999a] summarized evaluations of CV associations in French, Swedish and Japanese (Stanford database, courtesy of M. Vihman), Brazilian Portuguese [Teixeira and Davis, in press] and Equadorean-Quichua [Gildersleeve-

Neumann, unpubl. diss.] during the first word period. In 24 infants across five languages, CV associations were broadly confirmed except for 1 of the 2 infants studied in Brazilian-Portuguese [Teixeira and Davis, submitted]. Zlatic et al. [1997] found significant CV associations for labials and coronals in the babbling period for 1 of 2 bilingual infants learning English and Serbian, and only the coronal effect for the other. Dorsals were not tested, as they occurred with very low frequency in both infants. Zmarich and Lanni [1999] studied 1 Italian infant during the first-word period. They found predicted labial-central and coronal-front associations, but not dorsal-back vowel associations. Confirmation of the predicted associations in the majority of infants studied supports the predictions of mandibular frame dominance [Davis and MacNeilage, 1995] as a general characterization of intracyclic properties of early vocalizations. Nonconfirmations suggest the need for more attention to patterns produced by individual infants including their tendencies to focus on particular lexical items.

In addition to the prediction that the three CV co-occurrences would be present in both babbling and speech, a second manifestation of frame dominance emerged, namely that when successive syllables of a babbled utterance differed, the difference was predicted to be primarily attributable to variability in the amplitude of mandibular oscillation [MacNeilage and Davis, 1990b]. The expectation was that consonants would vary primarily in the aspect of consonantal manner attributable to degree of mouth aperture, rather than in place of articulation, and that vowels would vary in height, or openness, rather than in the front-back dimension. This prediction was confirmed for all 6 infants in our study of babbling [Davis and MacNeilage, 1995].

Our predictions that there would be common findings in the babbling period (7–12 months) and the first word period (12–18 months) with regard to intrasyllabic and intersyllabic organization were encouraged by a number of findings suggesting that these two stages have a number of other properties in common [e.g. Oller et al., 1976; Stoel-Gammon and Cooper, 1984; Vihman et al., 1985, 1986]. Investigations of babbling and early speech have demonstrated a common preference for labial and coronal stop, nasal, and glide consonant types [Locke, 1983; Roug et al., 1989; Stoel-Gammon, 1985]. Mid and low front and central or 'lower left quadrant' vowels [Bickley, 1983; Buhr, 1983; Kent and Bauer, 1985; Lieberman, 1980] predominate. Simple CV and CVCV syllable shapes [Stoel-Gammon, 1985; Vihman, 1992] and consonant initiations with vowel terminations are highly typical [Kent and Bauer, 1985]. While consistency of production patterns has been described in some perspectives [Locke, 1983; Stoel-Gammon, 1988], individualized strategies for realizing early output [Ferguson and Farwell, 1983], termed cognitive or problem solving strategies, have been emphasized by others [Menn, 1983].

Along with the various similarities between babbling and first words, three differences have been observed in a number of studies. First, while coronal consonants tend to predominate in babbling, Boysson-Bardies et al. [1992] found that labial consonants are more frequent in the first words of English, French, Japanese, and Swedish infants [see also Stoel-Gammon and Cooper, 1984; Vihman et al., 1986]. In addition targets for first words phonetically transcribed from the *MacArthur Communicative Development Inventory* [Fenson et al., 1992] also show high proportions of labials [Davis et al., 1999a, b; Teixeira and Davis, submitted; Stoel-Gammon, 1998]. Second, a number of investigators have observed a pattern originally termed 'fronting' by Ingram [1974] whereby the first consonant in a word tends to have a more anterior place of articulation than the second. Third, in our original study [Davis and MacNeilage, 1990] and in a preliminary report involving 4 subjects producing first words [MacNeilage et al., 1997], we have observed a tendency for more high vowels to appear in final position. Use of a high vowel in final position has also been noted in infant-directed speech by Ferguson [1978].

Phonological Approaches

Modern phonological approaches have centered on description of speech in terms of patterns of distinctive features [see Goldsmith, 1990, for a review]. Jakobson's [1998] early perceptual theory considered distinctive feature contrasts as unfolding in a universal, innately guided order. Linear generative phonology [Chomsky and Halle, 1968] was based on the presence of innately available features. Representation was conceptualized as a series of sequenced phonemes, each analyzable into an unstructured bundle of features.

A variety of current phonological approaches to acquisition have replaced these early perspectives. Nonlinear or autosegmental theories [e.g. Goldsmith, 1979, 1990] propose a hierarchical underlying representation whereby features can extend over domains either greater than or less than a single segment. Within this autosegmental framework, feature geometry [e.g. Clements, 1985; Paradis and Prunet, 1991] attempts to account for sequential regularities by proposing hierarchical tiers where elements on one tier of a hierarchy may be organized sequentially, but elements on different tiers are unordered relative to one another in a sequence. Importantly, within feature geometry, a feature is specified first as an attribute of an entire word or syllable and gradually is specified as an attribute of a segment as the child develops [Iverson and Wheeler, 1987; Levelt, 1994]. Grounded phonology [e.g. Archangeli and Pulleyblank, 1994] stresses the phonetic basis of phonological representation, suggesting that feature representations are restricted by phonetic properties of the articulatory system. Optimality theory [e.g. McCarthy and Prince, 1993] uses ranked violable constraints to determine the output form for a given input. In optimality theory, each production of a word is motivated by a detailed set of output constraints which may be ordered differently (resulting in 'constraint violation') in different languages and in different children during successive developmental periods [see Bernhardt and Stemberger, 1998, for a review of acquisition from this perspective].

In each of these diverse phonological perspectives, emphasis is on how the nature of underlying representation and output rules (i.e. the child's competence) functions to drive performance during acquisition of the adult sound system. Whether explicitly stated or not, all these models have in common the assumption that a genetically specified a priori form underlies the nature and patterning of output in early phonological acquisition. In this paper we will focus primarily on the implications of these approaches for serial organization in the first word period: the intrasyllabic (in our terms, intracyclic) CV co-occurrence patterns, and the intersyllabic (in our terms intercyclic) patterns and word level patterns. Phonological treatments of these two phenomena in infant speech will be introduced here and discussed in more detail once the findings of our study have been reported.

CV co-occurrence patterns in early speech have not been widely analyzed. There has only been one phonological treatment: Levelt [1994] analyzed the words of 12 Dutch infants aged from 1;4 to 2;11. She found three CV co-occurrence patterns – the two lingual patterns (coronal-front and dorsal-back) and a co-occurrence of labial consonants with rounded vowels. No relation between labial consonants and central vowels was reported. She proposed to account for these findings by pointing to their fit to a distinctive feature system formulated by Lahiri and Evers [1991] in which each of the CV pairs was designated as a single distinctive feature. The same feature designation is suggested by Clements and Hume [1995] within the subarea of feature geometry.

A number of phonologists have analyzed the fronting phenomenon. Levelt [1994] found a sequence of events whereby infants strongly favor consonant harmony in their first words, then begin to develop the fronting pattern. The finding of early consonant harmony together with the finding of the three CV co-occurrence patterns led her to conclude that in the initial stage of word production, distinctive features are specified for the whole word. For example, when [puf] is produced for Dutch *poes* (cat) the joint feature of labial consonant-rounded vowel is considered to apply to the entire word. When the infant subsequently produces the correct fronting pattern in the form of [pus] for *poes* Levelt [1994] concludes that the 'left edge' of the word 'becomes available' for place of articulation specification. The final consonant is then considered as being produced as a result of underspecification [Archangeli and Pulleyblank, 1994].

Others have suggested alternative phonological interpretations of the fronting phenomenon. Macken [1995] has suggested that it results from a 'melody' template in which the consonant sequence is specified in advance. Velleman [1996] has characterized metatheses resulting in fronting patterns, and exceptions to the patterns in individual infants, within the framework of optimality theory. All these individual approaches will be considered in more detail later.

In this study, three classes of serial organization patterns will be evaluated in these infants producing single words to evaluate the nature of serial organizational patterning: (1) *Intercyclic (intersyllabic) patterns* will be analyzed to determine whether the CV co-occurrence patterns reported in babbling [Davis and MacNeilage, 1995; Levelt, 1994] are also present in this first word corpus for English. (2) *Intracyclic (intrasyllabic) patterns* will be considered to evaluate the nature and distribution of reduplication and variegation. An additional question concerns the relative frequencies of the various variegated patterns as they relate to the 'fronting' tendency. (3) *Word-level patterns* will be analyzed for consonant and vowel dimensions in initiation, continuation, and termination phases of word shapes produced. Word-level patterns are also a consistent focus of current nonlinear and optimality approaches, where sequence level constraints are expressly addressed with hierarchical representations and ranked violable output constraints.

Method

Data from 10 infants were analyzed for this study. Words occurring during the first-word stage (roughly 12–25 months) were analyzed in 4 (C, R, N, P) of 6 infants studied during babbling [Davis and MacNeilage, 1995], 1 infant (H) studied during babbling and early speech [Davis and MacNeilage, 1994], and 1 additional infant (M) studied during babbling and early speech, who has not been reported previously. In addition, 4 infants (J, K, A, B) were studied during the first word period only [Jasuta, 1987, unpubl. diss.]. The 'Appendix' reports subject characteristics for all 10 infants. All infants were located through informal referrals from the community. Seven infants had one sibling, and 3 were only children. Six infants were male, and 4 were female. All infants were from monolingual English-speaking homes. Parent case history reports were used to establish normal development. In addition, the *Battelle Developmental Screening Inventory* [Guibaldi et al., 1984] was administered to establish normal development. Hearing screening was completed using sound field techniques. All infants scored within normal limits on both hearing and developmental screening testing.

Data Collection

Data collected for infants studied by Davis and MacNeilage [1994, 1995] (i.e. C, R, N, P, M, H) were part of a longitudinal study of babbling and early speech. Data were collected between approximately 7 months and 3 years of age for the larger study. For the present study, words analyzed occurred between 9 and 25 months of age (Appendix) beginning from the onset of first identifiable words within a session until approximately the onset of two-word combinations. The Jasuta [1987] study (i.e. J, K, A, B) included the first-word period from the onset of between 5 and 10 words until the beginning of two-word combinations. Sessions were audiotaped either once weekly [Davis and MacNeilage, 1994, 1995] or biweekly [Jasuta, 1987]. Taping occurred in the normal home environment [Davis and MacNeilage, 1994, 1995] or in the University of Texas Speech and Hearing Center [Jasuta, 1987]. In the Davis and MacNeilage [1994, 1995] studies, infants wore an Audio-Technika ATW1031 remote microphone clipped at the shoulder. Jasuta [1987] used a Wollensak recorder and external microphone placed as near as possible to the infant. The 'Appendix' includes chronological ages of the infants, number of sessions, and number of word types and tokens for each infant.

Data Analysis

Data selected for analysis consisted of all word tokens occurring in the sessions. In the Davis and MacNeilage [1994, 1995] studies, parent report and observer notes were used to establish the point of onset of first meaningful words within a session. Word onset was established when both the parent and the observer noted and agreed on use of a phonetic form in a clearly established communicative context (e.g. 'ba' while holding a ball). In most instances of early word use, the parent reported that the same form was being used in other contexts during the period before the session in which it was used for a word. In some instances, the parent was the first to recognize a word form, as it had occurred since the last data session. Each token analyzed was recognized as a communicatively directed phonetic form by both the parent and the observer. In the earliest word sessions explicit agreement between parent and observer that the infant was producing a word form in a communication context was obtained. As word use increased, it became easier to determine which vocalizations were words for the parent and the observer.

In the Jasuta [1987] study (i.e. J, K, A, B), monitoring contacts were made with the parents until word use of between 5 and 10 words was reported in the normal home environment. A word was counted as established when it was heard in spontaneous use on two different occasions. For both studies, onomatopoeic forms without CV structure (e.g. 'brrrm' while playing with a car) were excluded from analysis.

A primary transcriber for the Davis and MacNeilage [1994, 1995] studies (a different transcriber for each subject) phonetically transcribed all word tokens. Jasuta was the primary transcriber for the 4 infants in her study. Broad phonetic transcription supplemented by diacritics available for infant speech [Bush et al., 1973; Oller, 1980] was used for all transcription.

All transcribed data were entered for computer analysis using software designed for analysis of infant data [Oller and Delgado, 1990]. For purposes of analysis, consonants were grouped into labial, coronal, and dorsal places. Palatal [j] was classified as a coronal, and the glide [w] was classified as a labial. Fricatives and liquids were not included in the analysis as they occurred with very low frequency in the corpus [see Gildersleeve-Neumann et al., in press, for a study of these sounds in 4 subjects]. Vowels were transcribed using individual symbols and grouped in the following categories: high front [i, ɪ], mid front [e, ɛ], mid-central [ʌ, ə], low front [æ], low central [a], high back [u, ʊ] and mid back [o, ɔ]. High central vowels and low back vowels were not analyzed as they occurred very infrequently in the corpus.

Reliability was computed for consonants and vowels separately to assess the level of transcriber agreement underlying the analysis results reported. A set of 50 words was randomly selected across the entire period from the lexical corpus of each infant in the Davis and MacNeilage [1994, 1995] group. Selected words were transcribed by 5 persons familiar with transcription of infant vocalizations. A point-to-point method was used to calculate the percentage of times that the 5 transcribers agreed with the original transcriber on the consonant or vowel types in each lexical item. Labial, coronal and dorsal stops, nasals and glides were analyzed as individual consonant types. Vowels were grouped into the same seven categories that were used for computer analysis.

Reliability for consonants was computed for individual consonant types in the corpus. Reliability averaged 75.95% for the 5 transcribers. Agreement for labials overall was 79%; for coronals, 79.2%, and for dorsals, 69.6%. Reliability for vowels was 66.3% overall. For front vowels, reliability was 66.3%, for central vowels, 55%, and for back vowels, 77.5%. These reliability figures are well-matched with figures for other studies of this period of first word acquisition. Jasuta's [1987] reliability for consonants only was reported as being 98%.

Results

General Characteristics

Words were mainly monosyllables (58.7%) or disyllables (34.1%). These two types accounted for 92.8% of word types recorded in the corpus, compared to 45% for English [Kent, 1994]. Consonant place characteristics showed overall predominance of labials (41.3%) followed by coronals (36.1%) and dorsals (9.94%). The 'other' place category (mostly glottal stops) accounted for the remaining consonantal sounds. For consonant manner, the order of frequency of use was oral stops (55.3%), nasals (21.6%) and glides (8.5%). 'Other' manners of articulation, which included liquids, fricatives, affricates and glottal stops as well as [h] accounted for 14.4%. Glottal stops and [h] accounted for 6.1% of this category, reducing the percentage of fricatives, affricates and liquids to 8.3%, compared with 7.6% reported for babbling [Gildersleeve-Neumann et al., in press]. Vowel height results showed similar frequencies of occurrence in the high, mid, and low dimensions with little variability across infants. In the front-back vowel dimension, central (37.6%) and front (36.3%) vowels were higher in frequency than back vowels (23.5%), consistent with frequencies for English [Kent and Reed, 1992].

Intracyclic Patterns

Patterns of intracyclic co-occurrence between consonants and vowels are shown in table 1 for individual infants. Based on χ^2 analysis, results are expressed as a ratio of observed to expected frequencies for each cell (expected value is 1.0). Expected frequencies were derived from the overall frequency of the particular consonant and vowel types in the corpus. Thus, if 70% of all consonants were coronal consonants, and 50% of the vowels were front vowels, then the expected frequency of coronal consonants with front vowels would be $0.7 \times 0.5 = 0.35$ or 35% of all CV pairings. For the 10 infants, 30 cells were predicted to show values above 1.0 (i.e. the labial-central, coronal-front and dorsal-back associations for each subject). Results of the predictions are noted in boldface on the diagonal for each infant.

Table 1. Ratio of observed to expected occurrence of labial, coronal, and dorsal consonants with front, central, and back vowels

Child	Consonant	Vowel		
		front	central	back
C	Coronal	**1.26**	0.77	0.92
	Labial	0.93	**1.11**	0.91
	Dorsal	0.68	1.00	**1.54**
R	Coronal	**1.02**	0.81	1.35
	Labial	0.95	**1.14**	0.76
	Dorsal	1.17	0.55	**1.59**
N	Coronal	**1.96**	0.41	0.58
	Labial	0.51	**1.36**	0.87
	Dorsal	1.29	0.48	**2.30**
P	Coronal	**1.13**	0.84	1.07
	Labial	0.59	**1.47**	0.76
	Dorsal	–	2.58	–
M	Coronal	**1.55**	0.17	1.22
	Labial	0.50	**1.69**	0.86
	Dorsal	1.45	0.75	**0.61**
H	Coronal	**1.51**	0.52	0.25
	Labial	0.50	**1.47**	1.70
	Dorsal	1.88	–	–
K	Coronal	**1.14**	0.87	1.00
	Labial	0.82	**1.18**	0.94
	Dorsal	1.34	0.61	**1.18**
J	Coronal	**1.79**	0.56	1.09
	Labial	0.41	**1.34**	0.86
	Dorsal	1.18	0.85	**1.13**
A	Coronal	**1.65**	0.50	1.87
	Labial	0.81	**1.21**	0.50
	Dorsal	0.50	0.98	**1.63**
B	Coronal	**1.38**	0.59	1.13
	Labial	0.91	**1.09**	0.96
	Dorsal	0.80	1.17	**1.06**

For 2 infants, too few dorsals were available to analyze. Of the 28 remaining predicted associations, 27 were confirmed. The exception involved the dorsal-back association. Of the 60 nonpredicted associations, 58 were available for analysis. There were 15 (25%) above-chance co-occurrences. The difference between predicted (27/28) and nonpredicted (15/58) results was significant [χ^2 (1) = 38.5, $p < 0.0001$, n = 86]. Of the 15 nonpredicted outcomes above 1.0, six were coronal-back associations and six were dorsal-front associations.

A more detailed analysis of CV interactions was performed to determine whether the observed CV co-occurrences were present uniformly in all types of utterances in the corpus and whether there were VC co-occurrences as well. Group values are presented as there was little variation overall in individual infant values. Co-occurrences were examined for CV and VC portions of CVC and CVCV syllables to assess the strength of CV versus VC associations. Tables 2 and 3 show results of these analyses for the group. In table 2a, bilabial-central and coronal-front associations were found for both CV and VC in CVC syllables; dorsal-back did not show above chance association. In addition, 3 of 6 nonpredicted associations were found for the CV portion and

Table 2. CV interactions in CV (**a**) and VC (**b**) portions of CVC sequences (n = 519)

a CV

Consonant	Vowel		
	front	central	back
Coronal	1.50	0.42	1.25
Labial	0.51	1.33	0.98
Dorsal	1.09	1.56	0.23

b (C)VC

Vowel			Consonant
front	central	back	
1.50	0.38	1.27	coronal
0.44	1.53	0.79	labial
0.58	1.5	0.71	dorsal

Table 3. Consonant vowel interactions in CV CV (**a**) and CVCV (**b**) portions of CVCV sequences (n = 1,023)

a CV CV

C1	V1			C2	V2		
	front	central	back		front	central	back
Coronal	**1.17**	0.60	1.11	coronal	**1.23**	0.56	1.11
Labial	0.93	**1.21**	0.82	labial	0.82	**1.35**	0.98
Dorsal	0.87	0.84	**1.8**	dorsal	1.13	0.56	**1.32**

b CVCV sequences

V2			C2
front	central	back	
1.36	0.65	1.07	coronal
0.76	**1.27**	0.74	labial
1.01	0.74	**1.85**	dorsal

2 of 6 for the VC portion of CVC syllables. Coronal-back and dorsal-central associations were present in both; dorsal-front was found in the CV portion.

Table 3a, b displays results for CVCV utterances. For all three environments analyzed, the three predicted associations were found in both the first and second syllables. In the ClVl syllable, only one nonpredicted association was noted (coronal-back). For the C2V2 syllable and the medial VC sequence, coronal-back and dorsal-front associations were noted. In summary, while the predicted coronal-front and labial-central co-occurrences are present in all environments in either CV or VC sequences and were always the strongest patterns for these sequences, the predicted dorsal-back co-occurrence pattern only occurs in multisyllabic utterances (i.e. the CVCV forms analyzed here).

Table 4. Frequencies of reduplication for consonant place (**a**) and consonant manner of articulation (**b**) in CVC and CVCV environments

a Place frequencies

	LL	CC	DD	OO	Total
n	717	386	98	27	1,228
%	58.4	31.4	8.0	2.2	100

b Manner frequencies

	SS	NN	GG	OO	Total
n	897	313	15	3	1,228
%	73	25.5	1.2	0.2	100

L = Labial; C = coronal; D = dorsal; O = other; S = stop; N = nasal; G = glide.

Table 5. Frequencies of variegation for labial, coronal, and dorsal place of articulation in CVC and CVCV environments

	Consonant 2						
	labial		coronal		dorsal		total
	n	%	n	%	n	%	n
Consonant 1							
Labial			182	44.4	92	22.4	
Coronal	74	18.0			29	7.1	
Dorsal	6	1.5	27	6.6			
							410

As indicated earlier, these data represent two groups of infants from two different studies, transcribed by different persons. C, R, N, P, M, and H were transcribed by our research group [Davis and MacNeilage, 1995]. K, J, A, and B were transcribed by Jasuta [1987]. Jasuta [1987] was not aware of the hypotheses in this study when her data was gathered and transcribed for analysis. Comparing the two subgroups revealed median ratios of 1.41 (coronal-front), 1.37 (labial-central), and 1.51 (dorsal-back) for the Davis and MacNeilage [1995] study, and 1.49 (coronal-front), 1.21 (labial-central), and 1.25 (dorsal-back) for the Jasuta [1987] study. This consistency in results for two different data sets suggests that transcription bias based on knowledge of the predicted co-occurrences is not a major factor in results.

Intercyclic Patterns

Reduplication and Variegation

Table 4 summarizes the frequencies of reduplication for consonants. Reduplication referred to maintaining both consonant place and manner characteristics across a sequence. Reduplication, also termed 'consonant harmony' in phonological treat-

Table 6. Reduplicated and variegated height (**a**) and front-back frequencies (**b**) for vowels in CVCV environments

a Height frequencies

	Reduplicated			Variegated					
				lowering			raising		
	HH	MM	LL	HM	HL	ML	MH	LM	LH
n	159	171	212	32	17	54	226	228	115
%	13.1	14.1	17.5	2.64	1.4	4.45	18.6	18.8	0.09
	Height reduplication		44.6	Height variegation					55.4

b Front-back frequencies

	Reduplicated			Variegated					
				backing			fronting		
	FF	CC	BB	FC	FB	CB	CF	BF	BC
n	281	350	57	39	25	80	290	55	15
%	23.6	29.4	4.78	3.27	2.1	6.71	24.3	4.61	1.26
	F-B reduplication		57.7	F-B variegation					42.2

ments, accounted for a large percentage of consonant sequencing in the two main types of consonant sequences (i.e. CVC and CVCV). Overall the frequency of reduplication was 57.6%. This percentage was larger than the percentage of reduplication during babbling [Davis and MacNeilage, 1995], which showed an overall mean of 39.8% and a median of 50%. In this first word data, labials were the most frequently reduplicated place (58.4%) followed by coronals (31.4%). Stops (73%) and nasals (25.5%) were the dominant manner categories in reduplicated sequences. In adult languages, in contrast, consonant repetition is highly disfavored [MacNeilage et al., 1999].

Nature of Variegation: Consonants

The percentage of C(V)C sequences that were reduplicative was 70.3%, and thus 29.7% of sequences were variegated. Table 5 displays results for CVC and CVCV sequences variegated in place of articulation. The highest frequency variegated sequence was labial-coronal (44.4%) constituting almost a half of all variegated instances. Overall, labials constituted about two thirds of onsets in variegated disyllables. Thus, the typical disyllabic structure added tongue movement to initial labial closure, rather than initiating labial closure after tongue movement. Lingual onsets totaled about 20%. Moving the tongue from one to another lingual place within a sequence (7.1% for coronal-dorsal and 6.6% for dorsal-coronals) was far less prominent in consonant sequencing. The excess of final over initial dorsals noted in variegated sequences is consistent with a variety of studies of first word productions showing a preference for dorsals in final position [e.g. Vihman and Hochberg, 1986]. However, dorsals are only favored in final position relative to labials. When they co-occur with coronals, the other lingual place of articulation, dorsals occur in final position at approximately the same ratios as coronals.

Comparison of labial-to-coronal frequencies for 6 of the 10 infants (C, R, N, P, M, N) for whom both babbling and word data are available showed a dramatic asymmetry between use of labials in babbling and in first words. In babbling the 6 infants showed a 0.46 ratio of labials to coronals; the ratio was reversed in words with a 1.76 ratio of labials to coronals. In babbling, coronals were more frequent than labials in all 6 infants; in words, labials were more frequent than coronals in all but 1 infant (P).

For vowels (table 6), overall levels of reduplication (termed vowel harmony in phonological accounts) were lower than for consonants. Variegated disyllables showed a 3.2:1 ratio of tongue raising over tongue lowering in the height dimension. For the front-back dimension, there was a 3:1 ratio of tongue fronting to tongue backing in sequences. Taken together, these results show a preponderance of a rising forward movement with the tongue when vowels are variegated in sequences. As described later, these results were partly a consequence of a high frequency of front vowels in final position.

This study made two predictions regarding variegation in cases where only one parameter varied. First, the observed-to-expected ratios for manner variegation alone would exceed the ratios for place variegation alone for consonants. Second, the observed-to-expected ratios for vowel height variegation alone would exceed the ratios for variegation in the front-back dimension. It was not possible to test the consonantal hypothesis statistically on individual infants, as several infants had very few instances of consonant variegation. Pooling across infants, there were 140 instances of place variegation without manner variegation and 75 instances of manner variegation without place variegation. The expected frequencies were 178 and 37, respectively. A χ^2 test of the relation between observed and expected frequencies was significant [χ^2 (1) = 47.1, $p < 0.0001$, n = 215]. There were about twice as many manner changes as expected, but only about 80% of the expected number of place changes.

There were 446 instances of vowel height variegation and 49 instances of front-back variegation. Except for 1 infant, it was possible to perform χ^2 tests of the hypothesis of an excess of height over front-back variegation for individual infants. In 8 infants there was a significant excess of height variegation over front-back variegation. In the 9th infant there was a trend towards more front-back variegation, but it was not significant. Overall, the proportion of height changes to front-back changes was 7 times that expected by chance. These results are consistent with findings for babbling [Davis and MacNeilage, 1994, 1995].

Word Level Patterns

Word Complexity. Production patterns within individual word types were examined to understand the overall use of the major dimensions of consonant and vowel production (except for voicing) in various word shapes. For all 10 infants, consonant place and manner, and vowel height and front-back dimensions were described for CV, CVC, and CVCV words. These three types accounted for 92.8% of the words in the corpus (‘Appendix’). Figures 1–4 display results of this analysis. In figures 1 and 2, consonant place and manner results are displayed for CV, CVC-C1, CVC-C2, CVCV-C1 and CVCV-C2. C1 refers to the initial consonant. C2 refers to the next consonant in a sequence, which may be either the medial (i.e. CVCV) or the final consonant (i.e. CVC). For both consonant place and manner, CVC-C2 position showed the most diversity. CVC-C2 is the only consonant position analyzed here that is absolutely final; all the other consonants were either word-initial or intervocalic. In the CVC-C2 word-

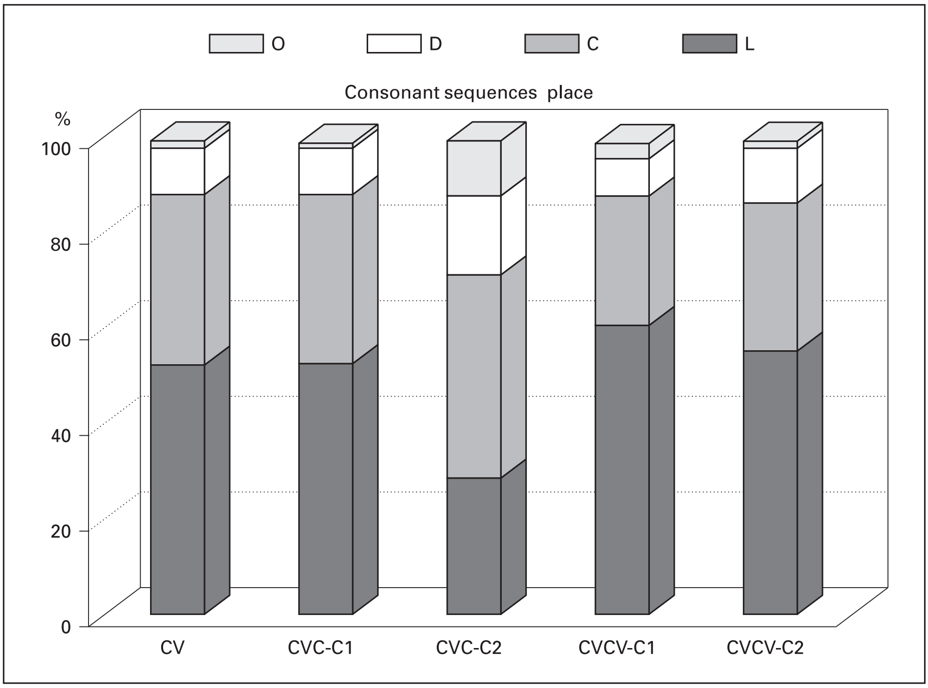


Fig. 1. Consonant place of articulation in CV, CVC, and CVCV words. L = Labial; C = coronal; D = dorsal; O = other.

final position, more dorsal and 'other' (i.e. glottal) place categories were represented as well as more fricative, affricate and 'other' manner categories. Overall, the predominant place and manner categories for all C2's were labial and coronal stops and nasals. It should be noted that there are more coronals and fewer labials in C2 when it is absolutely final, in contrast to the overall predominance of labials that has been noted overall. Vowel height results in figure 3 show predominance of low and mid vowels in CV, CVC-V1 and CVCV-1 positions. CVCV-V2, the final position for CVCV, showed a greater frequency of high vowels. This pattern was not apparent in CV words, in which low and mid vowels predominate, even though the V was also word-final. Vowel front-back results in figure 4 showed the same general pattern of greater diversity in CVCV-V2 position, where there is a higher frequency of front vowels than in the other three word positions. This high front vowel convergence in CVCV-V2 was noted earlier, in the form of more vowel diversity in word-final position. The use of back vowels, noted as being lower in frequency overall, was higher in CV and CVC positions, both in monosyllables, indicating some emerging diversity for vowels.

Position in the Word. As expected from other studies, consonants were highest in frequency in initial position and vowels highest in final position. C:V ratios were 2.7:1 for initial ando 0.28:1 for final position ('Appendix'). Distribution of vowel types in initial, medial, and final word positions is shown in figures 5–7. In initial position (fig. 5), two vowel types predominated: the neutral vowels (46.4%) and the low-central vowel [a] (17.9%). Together these two vowel qualities accounted for 64.3% of initial-onset vowels

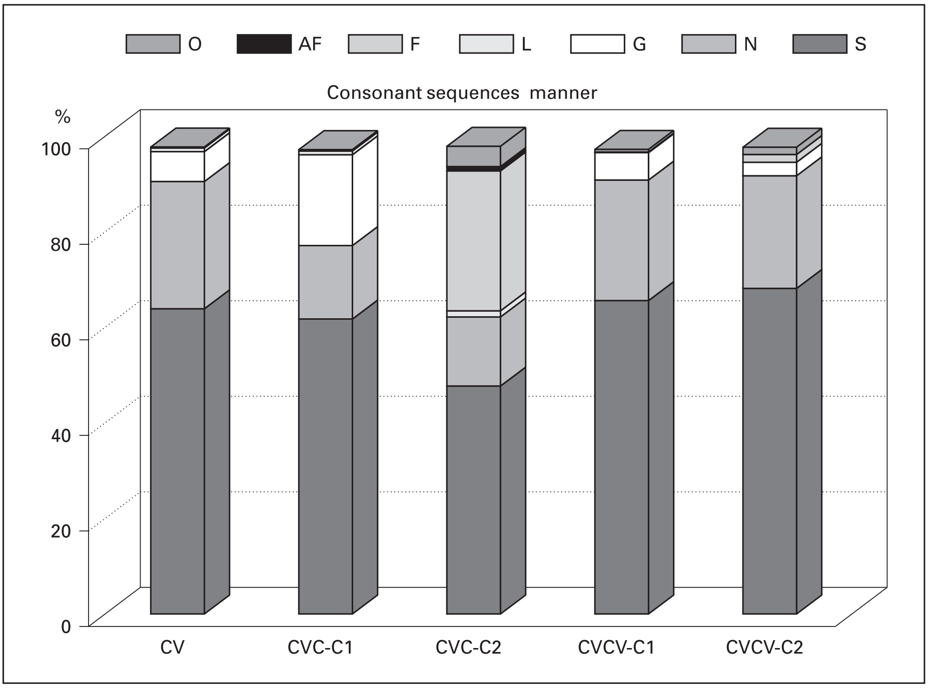
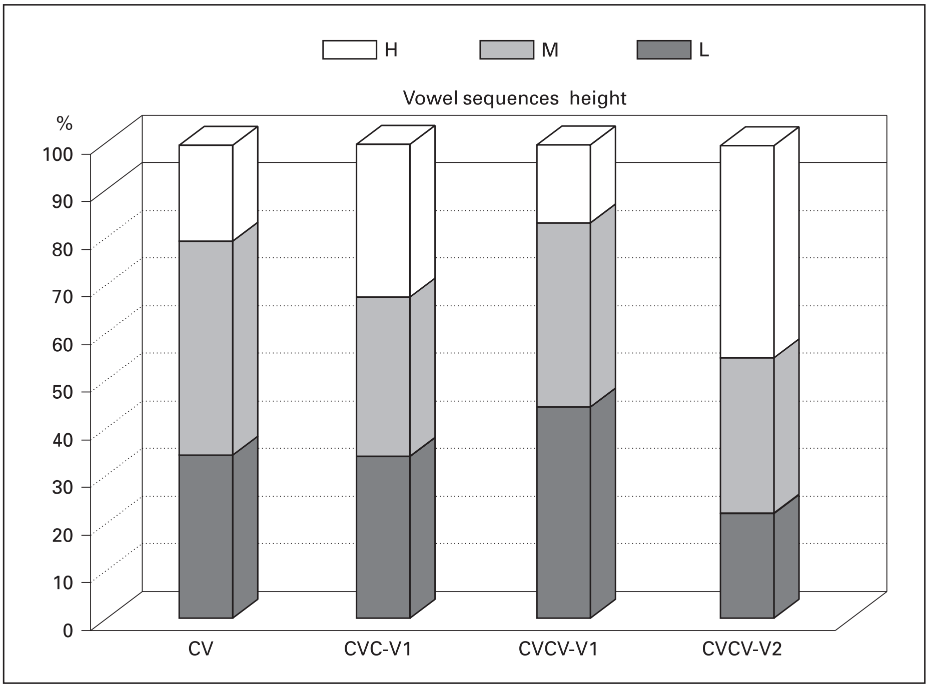


Fig. 2. Consonant manner of articulation in CV, CVC, and CVCV words. S = Stop; N = nasal; G = glide; L = liquid; F = fricative; AF = affricate; O = other.

as compared with 44% of vowels within words. In medial position (fig. 6), vowel qualities were more diverse. All except [o, ɔ] occurred more than 10% of the time. As in initial position, [a] and [ʌ, ə] were highest in frequency. Final position (fig. 7) shows the most diversity, especially in the higher use of high front vowels [i/ɪ]. Except for final [i/ɪ], [a] and [ʌ, ə] are highest in frequency in all word positions.

Summary

Frequencies of sounds and sound patterns were, in general, similar to those of babbling. Labial and coronal stops and nasals and low or mid-front vowels were the most frequent sounds in CV, CVCV and CVC word shapes. Open syllables with consonant onsets were most frequent. However, labials were the most frequent consonants in words in all but 1 subject, while coronals were most frequent in babbling. Words showed virtually no increase from babbling in the use of liquid, fricative, and affricate manners of articulation. Predicted intracyclic CV co-occurrences of labial-central, coronal-front, and dorsal-back were found in both CV and VC sequences. The most frequent instances of other co-occurrence patterns were coronal-back and dorsal-central. Reduplication, as in babbling, occurred at well above-chance levels. Variegated sequences showed manner exceeding place for consonants and height exceeding front-back for vowels as predicted. Variegated sequences in which consonant place change occurred showed a strong tendency toward initial labial closure, followed by lingual closure, primarily labial-coronal. Diversification of both consonant and vowel qualities occurred in absolute word-final position, only somewhat influenced by overall word complexity. Vowel initiations, though infrequent, favored neutral or low central vowels more than in other word positions.



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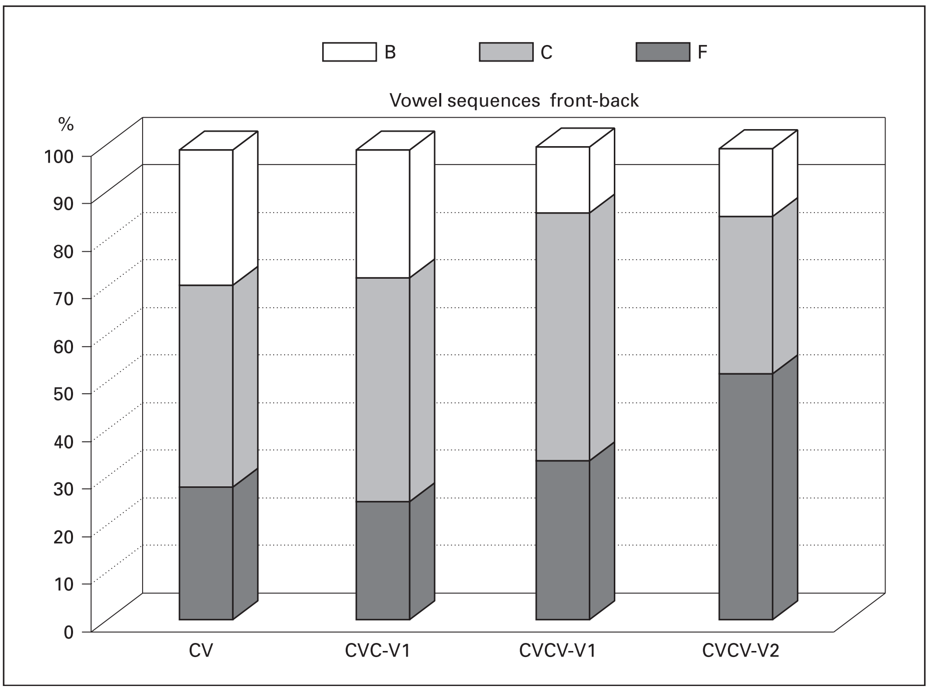

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Fig. 3. Vowel height characteristics in CV, CVC, and CVCV words. L = Low; M = mid; H = high.
Fig. 4. Vowel front-back characteristics in CV, CVC, and CVCV words. F = Front; C = central; B = back.

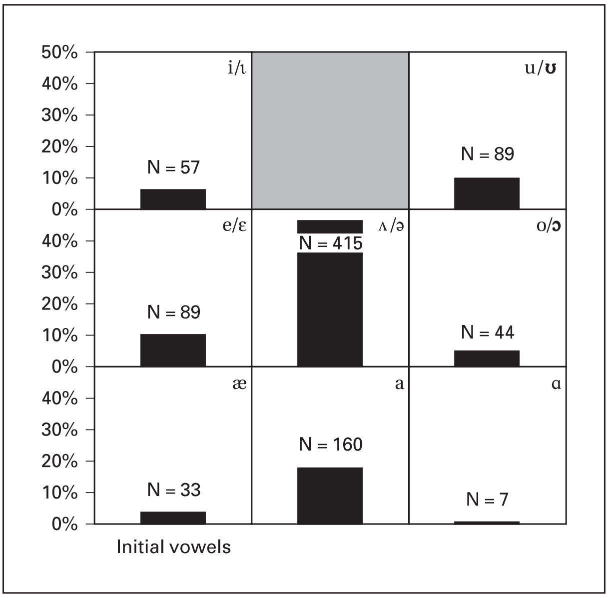

Fig. 5. Vowel qualities in word-initial position.

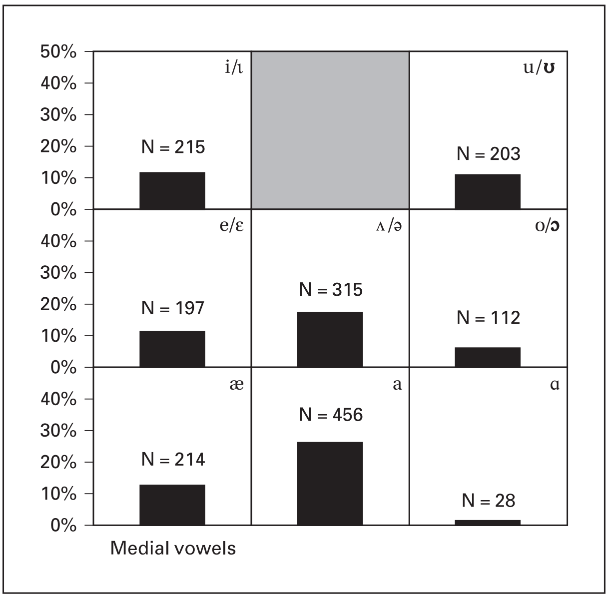

Fig. 6. Vowel qualities in word-medial position.

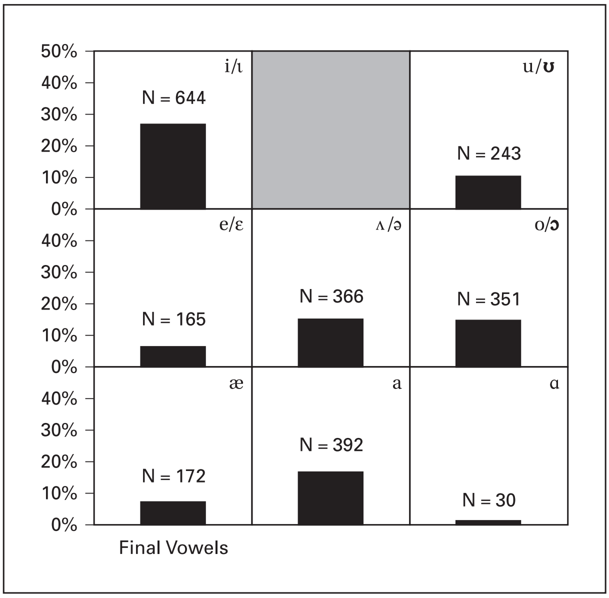

Fig. 7. Vowel qualities in word-final position.

Discussion

Findings in this study relate to the three main levels of serial organization of speech described earlier – intracyclic and intercyclic patterns and word-level patterns, including initiations and terminations. According to the 'frames then content' perspective, words are like babbling because they share the frame dominance pattern first observed at the onset of babbling [Davis and MacNeilage, 1995]. The frame produced by mandibular oscillation is responsible for most of the variance in production patterns observed during the early single word period and gives a coherent principle for explanation of each of these three levels of serial organization. Evidence for the emergence of content is based on relative freedom of articulator movement from the jaw-related dominance of the frame. Overall, there is only a limited escape from the frame-related dominance characteristic of babbling in the single-word period studied here. The first signs of emergence of relative freedom of other articulators from the mandibular cycle are found in the form of the labial-coronal effect and in diversification of consonant and vowel qualities at utterance termination.

Intracyclic Patterns

All three of the predicted CV co-occurrence patterns were found in these infants in an English language environment, virtually without exception. In contrast to Levelt [1994], labial consonants did not co-occur with rounded vowels in these infants. This pattern has not been reported in studies of other investigators, although the issue was not specifically considered. However, only 1 of our 10 subjects showed an above-chance co-occurrence of labials with back vowels.

It is important for the interpretation of these patterns to ask whether they are also present in languages. They have been found in a number of languages. MacNeilage and Davis [1993] analyzed intracyclic CV relationships using data from two different studies of five languages each by Janson [1986] and by Maddieson and Precoda [1991]. The coronal-front and dorsal-back associations were found, not the labial-central association, in both data bases. Predicted intracyclic CV associations were also tested for stops and nasals in English and nine other languages [MacNeilage et al., 1999]. Mean ratios of observed to expected frequencies across languages were 1.18 for coronal-front, 1.10 for labial-central, and 1.27 for dorsal-back associations. A further study including all English consonants [Davis et al., 1999b] based on analysis of 33,654 lexical types in the *Shorter Oxford English Dictionary* [SOED; Quinlan, 1992] found the coronal-front and dorsal-back, but not the labial-central associations present at significant levels.

Not only are these three patterns frequently present in languages, but they have also been observed to be the only patterns to be present above chance level in a suggested proto-word corpus (hypothetical words of earlier languages) of 27 words presented by Bengston and Ruhlen [1994], MacNeilage and Davis [2000]. Bengston and Ruhlen [1994] have proposed global etymologies, similar words in different languages presumed to derive from a common source, indicating a monogenesis of origin for world languages. The common occurrence of these results in infants, languages and the proto-word corpus suggests a fundamental status for these CV co-occurrence constraints in languages.

In contrast to the babbling and first word periods, where both CV and VC sequences showed predicted CV co-occurrences, none of the three VC co-occurrence patterns was found in the group of ten languages analyzed [MacNeilage et al., 1999]. This difference between infants and languages suggests a potential site of increase in diversity in languages. The presence of VC co-occurrences in infants, but not languages, suggests that adults have overcome intracyclic mandibular co-occurrence constraints at the level of VC transitions. This development may be related to the well-known tendency in languages to place the syllable boundary after the vowel [e.g. Bell and Hooper, 1978]. The labial-central and dorsal-back co-occurrences were present in VC sequences in the Bengston and Ruhlen [1994] proto-word corpus (O/E: 1.85 and 3.40, respectively) but not the coronal-front co-occurrence [MacNeilage and Davis, 2000].

The CV co-occurrence results from our biological/functional perspective can be compared with an interpretation from Levelt's [1994] phonological perspective. Our interpretation of the three co-occurrence effects asserts that they have in common the frame produced by mandibular oscillation. We have suggested an explanation of this frame in terms of an evolutionary exaptation from earlier ingestive cyclicities. Evolution via communicative cyclicities such as lipsmacks forms the foundation of syllabic organization [MacNeilage, 1998]. Fronted and back frames are considered as variants involving a relatively static (inert) nonresting tongue position. We will not suggest a possible explanation for a co-occurrence of labial consonants with back vowels, as the generality of this effect is presently in doubt.

Consider Levelt's [1994] interpetation of the CV co-occurrence patterns. The findings common in Levelt's [1994] data and ours were the two lingual co-occurrence effects. Dutch has three front rounded and three back rounded vowels. In English, rounding is restricted to back vowels. Levelt [1994] considers the fit of these two patterns to the coronal and dorsal features in the Lahiri and Evers [1995] feature system to 'account for' her results. The features are considered to exist at an abstract underlying level, although this is not explicitly stated. Levelt [1994] offers no reason other than description of the infant patterns *why* these particular CV relations are observed rather than any other potential CV co-occurrences. In contrast, our imputation of an inertial basis for these co-occurrences refers explicitly to the observed behaviors in our infants and finds a rationale in the mandibular oscillation cycle without independent control of the tongue within syllables.

We propose that a basic time-dependent close-open alternation of the mandible underlies CV sequences. Levelt's [1994, p. 84] equivalent to our postulation of the frame is to assert that 'universal sonority templates take care of the sequencing of segments in the word.' Sonority is a perceptually based abstract concept [Blevins, 1995]. As such, there is no obvious way that it could underlie the close-open alternation observable at the performance level of production. No attempt is made to explain the reason for existence of proposed sonority patterns in Levelt's [1994] proposal.

There now appears to be sufficient evidence of a tendency for labial consonants to co-occur with central vowels. This co-occurrence does not fit any of the distinctive features in the Lahiri and Evers [1991] consonant system. Only rounded vowels are associated with labial consonants in Levelt's [1994] framework, though she does not make it clear why this pairing is favored in the Lahiri and Evers [1991] system. Levelt [1994] would designate the consonant in a labial-consonant central vowel sequence with the distinctive feature 'labial.' What would this mean? We have argued that labial stops may not involve any active movement of the lips. Instead the lips come together as a passive result of the oscillation of the mandible. Munhall and Jones [1998] have verified this effect in 1 babbling infant with physiologic measurement. If this result proves to be generally true in infants, then Levelt [1994] and others who postulate the labial feature in early words are apparently postulating the existence of an abstract labial entity with no consequences at the performance level in terms of active movement of the lips [according to the Munhall and Jones, 1998, finding]. The labial pairing with round vowels predicted by Levelt [1994] would be based in our perspective, on later learning-based phases of acquisition where the rounding for the vowel can be produced within a syllable by independent control over lip rounding in addition to the lip closure afforded by mandibular oscillation alone.

Clements and Hume [1995] also designate labials and rounded vowels with a single distinctive feature – labial – in their explication of current feature geometry. They also designate low central vowels as 'phonologically placeless,' and therefore, by definition, unassociated with any consonant, emphasizing the fact that their feature system relates to an *underlying* level of representation. In the light of the strong labial-central co-occurrences we have noted in babbling infants, first words, languages, and the proto-language corpus, Clements and Hume's [1995] treatment of low central vowels as unassociated with any consonant is not easily justified.

Two previously unobserved CV co-occurrence patterns were found in the present study: dorsal-central and coronal-back. Frame/content predicts dorsal-back associations. The nonpredicted dorsal-central association may be a sign of development of the allophonic variation in place of articulation of dorsals well known in English words, where front allophones are produced in words such as *key* and back allophones are produced with words such as *c*<u>*oo*</u> [Ladefoged, 1975]. The coronal-back sequence may be a reflection of lexical influences (such as the word *no,* which was very frequent in the case study reported in Davis and MacNeilage [1990]. Potential lexical influences in the early word period should be explored carefully for full understanding of the interface between phonetically based movement patterns and lexical salience during this period. Lexical influences are also a site for exploration of individual differences across infants related to the overall patterns described in this analysis.

Intercyclic Patterns

Consideration of Lashley’s [1951] perspective on organization of action sequences emphasizes the importance of intercyclic regularities in understanding babbling and early speech output. Frequency of repetition vs. change in sequences (i.e. reduplication vs. variegation) and the nature of variegation are two integral aspects of systematic description of serial output. In this study of first words, most cycles were reduplicated, as in babbling, indicating frame reiteration as a continuing tendency. Davis and MacNeilage [1995] studying pairs of syllables in the babbling of 6 infants found a median level of consonant reduplication of 67%; overall median syllable reduplication was 50%. Both of these levels are well above chance expectations based on the overall frequencies of consonants and vowels in the total corpus. Repetitions of movement cycles by infants indicate an absence of the serial differentiation characteristic of adult speech patterns. Reduplication of the same movement pattern rather than change during a sequence reduces the complexity for the production system for the child in the initial stages of attaching production patterns to meaning. Thus, the reduplication tendency is not overcome during the first word period, because in order to produce words infants must interface the motor system with the lexicon to code intentional meaning, introducing the problem of ‘functional load’ in managing the lexical and the production systems concurrently.

Relative frequency counts for patterns of repetition and change within words of languages indicate that languages disfavor consonant repetition [Vihman, 1978]. The terms ‘reduplication’ and ‘variegation’ have usually been applied to babbling and first words only. MacNeilage et al. [2000] analyzed stop and nasal sequences in ten languages. The average tendency for consonant repetition across the ten languages was 67% of chance values, much lower than repetition levels found in babbling and first words. This type of finding may reflect avoidance in languages of the confusability resulting from sequences containing repeated instances of the same item in input [Conrad and Hull, 1964] and in output [MacKay, 1987]. In addition, while repetition is present in languages to some degree, reduplication may be typically the realization of a particular morpheme rather than a purely phonological phenomenon [McCarthy, 1988].

In regard to patterns of variegation, one prediction to be tested in this study was that these infants will show more manner changes than place changes and more height changes than front-back changes, as was true of all 6 infants in the earlier study of babbling [Davis and MacNeilage, 1995]. In this study, intercyclic variegation also was dominated by the mandibular oscillatory cycle for both consonants and vowels; manner changes predominated over place changes and height over front-back changes. The result indicates a continuation of this aspect of frame dominance into the first word period in serial sequences.

This study also confirmed findings of other studies that have shown a tendency for consonants earlier in a word to have a more anterior place of articulation. However the results cast doubt on the usefulness of the term ‘fronting’ to describe these patterns, as we found that coronal-dorsal and dorsal-coronal sequences occurred about equally often. Thus, the fronting principle did not hold across the board. As the present study is the first to present statistical data on the relative frequencies of the various possible sequences in a number of subjects, further study of this question would be useful.

The strongest specific interconsonantal variegation tendency was for a labial-coronal sequence. Data from other languages emphasizes the generality of this effect. Locke [1983] found labial consonants to be most frequent word-initially with coronals most frequent word-medially in the first words of Czech-learning infants. Teixeira and Davis [submitted] found labial-coronal sequences to account for 25% of variegated sequences in first words of 2 Portuguese-Spanish learning infants during the first word period.

This sequence is also present in modern languages. MacNeilage et al. [1999] studied ten languages representing several major language families. They found the labial-coronal effect at statistically significant levels ($p > 0.001$) in all languages except Swahili and Japanese. In addition, in the proto-word corpus of Bengston and Ruhlen [1994] there were 8 labial-coronal sequences but only 1 coronal-labial sequence [MacNeilage and Davis, 2000].

We have suggested that the preference for the labial-coronal sequence is a self-organizational consequence of three factors: the relatively greater ease of production of labials than coronals, the new demands of interfacing the mental lexicon with the motor system, and the special problem of initiating action complexes [MacNeilage et al., 1999, 2000]. While coronals are more frequent in babbling, labials are more frequent in first words, as reported by a number of studies. The widely reported tendency for labial consonants to be more frequent than coronal consonants when an infant begins to produce first words was also strongly evident in these infants. Labials are proposed as easier to produce than coronals in infants because they may involve only mandibular movement while coronals also require a tongue fronting movement. The possibility that labials are easier than coronals is also suggested by the fact that infants who have been temporarily prevented from babbling and early word production by tracheotomies uniformly show a very strong preference for labials in their subsequent first word attempts [Bleile et al., 1993; Locke and Pearson, 1990; Vaivre-Douret et al., 1995]. Thus, the specific problem of interfacing the lexicon with the motor system may also be reflected in the retum to use of labials in first words when coronals, which match language preferences, are most frequent in babbling, when there is no lexical target.

It is well known in motor system neurophysiology that relatively separate circuitry is involved in initiated movements vs. continuing movement complexes once they are initiated [e.g. Kornhuber, 1987]. Problems specific to initiation of movement are well known, for example, in Parkinson’s disease. If labials are indeed easier, and there is any specific demand on initiation of an action involving interfacing the lexicon with the motor system, then these factors combined may produce a tendency to initiate variegated sequences with a labial. The labial-coronal sequence in infants is considered to be a self-organizational consequence of the operation of these biomechanical, cognitive and motor constraints [MacNeilage et al., 2000]. We would consequently predict that it would be present in the first words of infants even when it is not present in the ambient adult language, as for example in Japanese, where infants produce labial-coronal sequences that are not favored in the ambient language.

Our interpretation of the labial-coronal effect also leads to a prediction regarding first word structure in hearing-impaired infants. It has often been noted that these infants produce many more labial than coronal consonants, presumably because of the availability of visual information from the production of labials but not coronals [e.g. Osberger and McGarr, 1982]. We have predicted that these infants might have an even greater excess of labial-coronal over coronal-labial sequences than hearing infants, even though, in either sequence labial and coronal consonants occur with equal frequency [MacNeilage and Davis, 2000].

Another explanation of the increase in labials in first words is that labials are facilitated by the visual information available from production of labials [e.g. Stoel-Gammon, 1988; Vihman et al., 1985]. Like the labial ease hypothesis, this explanation requires the supposition that functional load increases when an infant first has to interface a lexical representation with the movement control system. Without this supposition, neither hypothesis is consistent with the fact that coronals are favored in the earlier babbling stage, while labials are favored in first words. However, the visual information hypothesis cannot account for the preference of tracheotomized infants for labials, or the tendency to favor a variegated consonantal sequence that begins with a labial.

Consonant variegation in first words has been a focus within phonological treatments of acquisition. Levelt [1994] focused on the strong labial-coronal sequence trend in her data. She interpreted this finding in the context of an earlier tendency for interconsonantal reduplication. On the basis of the CV co-occurrences she found, Levelt [1994] concluded that the features labial, coronal and dorsal were initially specified for the entire word. In considering the sequence of events whereby the word for Dutch *poes* (cat) was originally produced as [puf], and later (correctly) as [pus], Levelt [1994] suggested that the 'left edge' of the word 'becomes available' for a word-internal place of articulation specification (labial). The final coronal consonant is considered to result from coronal 'underspecification'. The concept of underspecification of coronals is based on various aspects of the role of coronals in languages [e.g. Paradis and Prunet, 1991], and applies to relationships between different levels of derivation of output from input in a phonological system. Its relevance to infant organization or to the actual control of output in adults has not been established. In contrast with our interpretation, no rationale is suggested for the preference for labial-coronal rather than coronal-labial sequences.

Levelt [1994] regards her characterization of the labial-coronal effect as preferable to that arising from the 'fronting' conception, namely that it results from a co-occurrence restriction on consonants in that the first consonant of a word must have a more front place of articulation than the second. This assumption is the basis for Macken's [1995] supposition that the sequence is a consequence of a labial-coronal 'template'. One difference between these two phonologically based characterizations is that Macken [1995] makes no mention of vowels in this context while Levelt [1994] incorporates CV associations.

One of the characteristics of the labial-coronal pattern in infants is that it often results from a metathesis whereby a labial-coronal sequence is produced when the correct adult version of the word contains a coronal-labial sequence [e.g. [pwaeta] for *sopa,* Macken, 1979]. Velleman [1996] has analyzed these early metatheses in terms of optimality theory [McCarthy and Prince, 1993]. In optimality theory, sound patterns are characterized in terms of a family of violable 'constraints' ranked in different ways to account for different patterns. Using this approach, Velleman [1996, p. 183] was able to characterize not only typical patterns such as the labial-coronal pattern but also other nontypical patterns of individual infants reported in the literature. Velleman [1994] concludes that 'Absolute claims about metathesis, such as fronting [Ingram, 1974], strict positional restrictions [Levelt, 1994; Macken, 1993] are too inflexible for the full range of child patterns which occur. Varying patterns of metathesis… can all be accounted using a constraint-based approach, within which specific manner and place features are aligned with edges of words.'

Velleman [1996] raises the important question of how to incorporate individual differences between infants into theories of speech acquisition. The question is central to biological approaches because, without inter-individual variation within a species there could be no natural selection. In the present study, and in others, we have found relatively few exceptions to developmental trends in serial organization either in English or in cross-language studies [e.g. Locke, 1983]. In child phonology, variability has been ascribed to cognitive 'problem solving' [e.g. Ferguson and Farwell, 1975; Menn, 1983], without establishing the basis for why infants would chose varied strategies. It would be a mistake to conclude that application of optimality theory or cognitive problem solving to either typical patterns or exceptions explains why these patterns occur. No characterization using optimality theory is explanatory in the sense that it deals with the causes of observed patterns.

The status of vowels intervening between the two different consonants in a labial-vowel-coronal sequence is a problematical aspect of phonological approaches to this aspect of serial complexity. Levelt [1994] only allows rounded vowels in this context. Macken [1992] and Velleman [1996] do not consider vowels. However, from our phonetic approach, vowels are integral to understanding serial patterns. Their omission involves the tacit assumption that the consonants surrounding them are discrete entities, whether described using optimality theory, grounded phonology, or underspecification. We characterize the LVC pattern as a sequence beginning with a pure frame (labial consonant plus *central vowel*) followed by a fronting movement involving *front vowels* if the mouth is open and coronal consonants if the mouth is closed. Consequently either central or front vowels might be expected to occur but not back vowels. Earlier onsets of the fronting movement would be facilitative of front vowels. Elsewhere we have reported vowel frequencies in LVC sequences produced by the infant in the Davis and MacNeilage [1990] study [MacNeilage and Davis, 1999a, b]. The observed-to-expected ratios of the three vowel categories were: front, 0.96; central, 1.28; back 0.31. As predicted, front and central vowels predominated strongly over back vowels. Back vowels that include rounded vowels would be the category predicted from Levelt's [1994] analysis.

Word Level Patterns

Word level patterns in this study showed continuity with babbling as well as increase in diversity. Open syllables with consonant onsets predominated, as has also been noted in languages [Bell and Hooper, 1978]. In infants, frequency counts of consonant and vowel occurrences by word position have documented the pervasiveness of consonant onset and vowel offset in syllables [e.g. Kent and Bauer, 1983; Locke, 1983; Oller and Eilers, 1982; Stoel-Gammon, 1985]. In addition, multiple studies have noted first emergence in word-final position for dorsals [Vihman and Hochberg, 1986] and fricatives [Kent and Bauer, 1985; Locke, 1983; Oller and Eilers, 1982].

For the infrequent vowel initiations in this study, neutral or low-central vowels were characteristic, as in babbling. The initial neutral vowel pattern would appear to be associated with onset of phonation from a resting position rather than active lingual initiation reflected by use of front or back vowels. These analyses are of the single word period where use of function words such as articles (e.g. *a*) occur infrequently and thus would not contribute substantially to the pattern of neutral vowel initiations. Medial position showed highest frequency of mid and low, front and central vowels, as predicted by the labial and coronal CV co-occurrence patterns found in babbling and words. The final high vowel pattern appears to be a new development from the babbling period, evidence of diversification in first words over babbling. Expansion of vowels from the lower left quadrant, as in babbling, was thus found to be highly context-dependent, occurring in absolute final position, rather than interconsonantally. This word-final high vowel pattern appears to be characteristic of English. Davis and MacNeilage [1990] also found greater frequencies of high vowels in final syllables of disyllables in analysis of the Thorndike and Lorge [1994] dictionary.

Absolute final position for the varied utterance types characteristic of this period (i.e. CV, CVC, CVCV) showed the most versatility for both vowels and consonants, though there was some interaction with word length. This increase in versatility at the end of words perhaps reflects freedom to vary output at the termination of an action sequence because of the absence of demand for subsequent movement control and should motivate a search for similar patterns in infants in other language environments. Redford et al. [1997] studied positional constraints on consonants in CVC syllables in 6 infants during babbling. They found a tendency for final consonants to repeat the place of articulation of nonfinal consonants. In addition, final position showed relatively higher frequencies of fricatives, voiceless consonants, and nasals. Consonant repetition was interpreted as consistent with frame dominance, or the tendency of a relatively constant mandibular cycle to characterize utterances in a CVC sequence. Increases in fricatives and voiceless consonants in final position were attributed to an utterance-terminal energy decrease in the production system [MacNeilage and Davis, in press]. These utterance termination patterns indicate a strong positional bias for escape from the dominance of the mandibular cycle in first words as well as in babbling.

Greater variety in syllable-final than in syllable-initial words in these infants distinguishes acquisition patterns sharply from those proposed in adult phonologies, where onsets show more variety than codas [Beckman, 1998; Maddieson, 1984]. This disparity between acquisition and mature language patterns lends credence to a self-organization account of infant output at this stage as infants are not clearly patterning on the environment or 'learning,' since adult speakers show relatively more diversity in onsets rather than terminations of words.

General Discussion

The results of this study were generally consistent with others in showing a basic continuity of output patterns from babbling to first words, but also a few changes. Similarities are not simply confined to the transition phase, but apply to the single word period in general. From the present perspective frame dominance is an appropriate explanatory characterization of the single word as well as the babbling period. In one respect, frame dominance might be considered to increase in this period as the increase in labials might indicate a regression to increased use of an easier form. However the increasing diversification of structure in final position and the new use of the labial-coronal sequence are two steps toward increasing serial complexity.

A phonetic interpretation of first word patterns is that their predominant causality is motor, consistent with the predictions of the frame content hypothesis [MacNeilage and Davis, 1990a]. Elsewhere we have referred to a 'motor core' of early speech which includes the basic syllabic oscillation, the tendencies towards consonantal beginnings and vocalic ends, the CV co-occurrence patterns, all present in babbling, and the labial-coronal pattern in first words [MacNeilage et al., 2000]. The only exception to this assertion of motor causality is the suggestion that there is a functional load increase – a cognitive effect – when a premotor conceptual level is added to the motor routines of babbling for the production of lexical items.

Perceptual factors do not appear to play a very important role in determining the overall form of the output patterns, even though speech problems of hearing-impaired infants show they are far from irrelevant [e.g. Osberger and McGarr, 1982]. There has been little evidence for a progression of first word acquisition based on perceptual distinctiveness, as suggested by Jakobson [1941–1968]. Moreover, there seems to be no obvious basis in perceptual facilitation for any of the preferences for sounds and sound patterns observed in the babbling and first word stages – labial and coronal stops and nasals, vowels in the lower left quadrant, consonant initiations and vocalic terminations, the CV co-occurrence patterns, the labial-coronal effect and the tendency toward reduplication [see Davis and MacNeilage, 2000, for a discussion of this question.

Phonetic approaches emphasize a motor and performance focus whereby the infant's actions in development lead to eventual instantiation of adult level speech production characteristics. The embodiment perspective [e.g. Clark, 1997; Lakoff and Johnson, 1999] provides a larger intellectual context for interpretation of this data. This perspective suggests that mental representation cannot be fully understood without consideration of activities available to the body for building such representations. These data suggest that understanding dynamic characteristics of the production mechanism in serial action [i.e. Lashley, 1951] is integral to explaining acquisition of a mature speech production system. Similar output characteristics in infants and adults emerge from common properties of the production system [i.e. a 'motor core', MacNeilage et al., 2000]; different characteristics are based on the degree of independent control over articulators in the time domain. The surprising similarities between adult and infant speakers suggest that earliest emergence of serial complexity in speech production is in some important respects an aspect of self-organization in a complex system, rather than a learned behavior. A basic requirement for 'learning' is that learners perceive and reproduce behaviors present in the environment with increasing accuracy and consistency. Motor skill literature suggests that motor learning is a progressive rather than an instantaneous process [e.g. Schmidt, 1991]. A fundamental tenet of speech acquisition has been the incomplete nature of infant competence in producing adult-like behaviors and on the time course of development of speech production skill. The presence of similar serial characteristics in infants from the *onset* of babbling at levels similar to adults suggests the presence of basic tendencies inherent in producing serial output common to infant and adult speakers rather than efficient early learning of complex patterns.

Phonological approaches to the study of acquisition, with the exception of Macken's [1995] consonantal templates, have involved fitting conceptions worked out in the study of languages to the first word stage of speech. Current phonological approaches (i.e. underspecification theory, grounded phonology, optimality theory, nonlinear systems) differ broadly regarding the status of underlying representations as well as the way(s) in which such representations relate to output. However, all involve attributions of cognitive capabilities, and are based on the preformed status of the competence level.

Few would dispute that a satisfactory conception of modern adult speech production must include a hierarchy of organizational components including both a motor level, and premotor levels that would be more readily characterized as conceptual. In contrast, our conception of the earliest stages of speech acquisition is, with one exception, basically confined to the motor level. From our standpoint the evidence regarding what actually occurs during babbling and first word production does not necessitate positing a dominant level of organization at these stages that is basically conceptual.

Few would deny the likelihood that natural selection for speech has had implications for both performance and competence levels and their interface with one other. The capability of using a single coherent system with both these components is what has evolved. We accept this view in general terms. However, we posit that characteristics of the articulatory apparatus operating in real time to produce output do not require a previously specified underlying conceptual structure for explaining the origin of patterns in early word production. In contrast, phonological views emphasize the proposition that an innate prespecified conceptual structure underlies first word productions. While grounded phonology [Archangeli and Pulleybank, 1994] relies on articulatory descriptors, emphasis is on descriptors of competence as determined by prespecified structures, not on performance. In our view, early stages of speech production are founded on the infant's performance capabilities, shared largely with adult speakers, as evidenced by their presence in languages as well as in infants. Later stages of mastery of ambient language-specific complexity are based on increase in motor skill across development. This development allows the child to learn to produce the specific characteristics of the ambient environment to support development of phonological competence. Competence is, in this view, based on performance.

Phonologists assert that their conceptual structures 'account for' the patterns under consideration in acquisition. The phrase 'account for' has an explanatory connotation, having to do with causes of the phenomenon being considered. However no explanations are presented for why first word phenomena are the way they are. Miller [1990, p. 321] has noted this as a characteristic perspective of modern linguistics. In his words: 'Linguists tend to accept simplifications as explanations.' Consider, Levelt's [1994] use of the three single features of feature geometry that group certain consonant-vowel combinations. As Ohala and Ohala [1991, p. 273] have pointed out, this conception makes it possible within feature geometry to 'notate,' i.e. describe states that involve consonant-vowel relationships, such as assimilations 'but it cannot really explain them.'

One specific problem seems to arise with optimality theory in consideration of acquisition. Phonologists [e.g. Bernhardt and Stemberger, 1998; Velleman, 1996] claim as a virtue of optimality theory the number of different patterns that it can account for. In reality optimality theory appears to be so flexible that there is no pattern that it could not 'account for.' It is unclear what is gained for explanation in accounting for all of a number of successive different unsuccessful attempts of an infant to produce a word applying the constraint hierarchy of optimality theory.

It should be noted that variability in productions of lexical items in first words has been widely attested in the literature on early phonological acquisition. Active individual cognitive strategies have been proposed as the underlying rationale for this variability [e.g. Ferguson, 1973; Vihman, 1992]. In contrast, we have proposed a phonetic motivation for patterns observed in early acquisition. An alternative proposal for variability in first words may be found in phonetic patterns for serial sequences predicted by our hypothesis. In this study, we have emphasized consistent production patterns within and across infants without systematic analysis of variability related to the predictions of our model. Examination of variability in lexical types should be evaluated as a further potential source of evidence for cognitive versus phonetic influences in this period.

Conclusion

We have considered two approaches to the understanding of the acquisition of speech production, the frame content hypothesis as an example of a biological/functional approach at the performance level, and generative/phonological approaches at the competence level. We focused on several phenomena of early speech: intrasyllabic CV co-occurrence patterns, intersyllabic patterns including a tendency towards a labial-coronal consonant sequence, and word level patterns of serial organization. We suggested a biological/functional explanation of the basic mouth open-close as an explanatory principle underlying both intrasyllabic and intersyllabic phenomena in the form of a frame consisting of mandibular oscillation evolving from ingestive mandibular cyclicities. Its basic form was reflected in 'pure frames' consisting of labial consonant-central vowel alternations. Preferred intrasyllabic CV relations between lingual consonants and vowels were considered to result from tongue inertia. The intrasyllabic labial-coronal sequence effects suggest a self-organizational response based on biomechanics, movement initiation constraints and the culturally induced problem of interface of the lexicon with the motor system. Initiation and termination effects showed basic tendencies in infants and languages in the predominance of consonant onsets and vowel terminations. Word-level patterns reflected final position as a site for increase in diversity, in contrast to languages where initial position carries most diversity.

Within the 'embodiment' perspective, which is becoming increasingly important in modern cognitive science [e.g. Clark, 1997; Lakoff and Johnson, 1999], mental representation cannot be fully understood without consideration of activities available to the body for building such representation. Competence, in this view, is the end point rather than the beginning point of development of adult capacity for speech production. This paper may be a step in making embodiment an increasingly viable alternative to the classical essentialist model of modern linguistics, where the starting point is an assumption of innate mental entities.

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Appendix. Description of subjects and data analyzed

Child	Chronological age		Gender	Siblings	Sessions	Types	Tokens	Segments		Syllables, %				
	first session	final session						C n	V n	C %	V %	mono-	di-	poly-
C	10	14	F	1	14	138	656	855	903	49	51	66	27.4	6.5
R	9	21	F	1	26	190	2,130	3,272	3,118	51	49	45.2	45.6	9.2
N	14	36	M	1	23	398	2,727	722	767	48	52	54.5	43.5	1.9
P	17	23	M	1	17	78	526	643	739	46	54	67.7	26.5	5.7
M	15	21	M	1	9	125	648	345	396	47	53	50.8	44.2	4.8
H	15	24	M	0	9	76	278	1,122	1,016	52	45	45.9	33.7	20.3
J	12	19	F	1	14	144	581	983	946	51	49	61.6	35.9	2.4
K	15	19	F	1	10	119	319	426	463	48	52	75.1	24.5	0.4
A	20	25	M	0	11	89	249	428	441	49	50	55.4	37.8	6.8
B	20	25	M	0	13	122	306	368	429	46	54	64.6	21.5	1.3
Mean										48.7	50.9	58.7	34.1	5.9
SD										2.1	2.9	9.9	8.8	5.8

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