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THE DEVELOPMENT OF ACCURACY IN EARLY SPEECH ACQUISITION: RELATIVE CONTRIBUTIONS OF PRODUCTION AND AUDITORY PERCEPTUAL FACTORS

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THE DEVELOPMENT OF ACCURACY IN EARLY SPEECH ACQUISITION: RELATIVE CONTRIBUTIONS OF PRODUCTION AND AUDITORY PERCEPTUAL FACTORS

by

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To Joe,

who has walked this path with me, hand in hand

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THE DEVELOPMENT OF ACCURACY IN EARLY SPEECH ACQUISITION: RELATIVE CONTRIBUTIONS OF PRODUCTION AND AUDITORY PERCEPTUAL FACTORS

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Production system and auditory perceptual factors form a system-based foundation for intelligible speech. The production system contributes motor capacities for producing sounds and sequences. The auditory system provides information about ambient language characteristics of word targets. The child must utilize both to achieve accuracy by matching sounds they can produce with salient word targets. To fully understand the process by which children acquire intelligible speech, we must consider both production system and auditory perceptual factors and how these factors affect behavioral change over time.

Acquisition of accuracy for single words was examined in two groups of children differing in auditory history: 4 normal hearing (NH) children and 4 profoundly hearing-impaired children who received cochlear implants (CI) before age 2 years. The developmental process was analyzed via changes in accuracy and error patterns over time. Data was collected monthly in 1-hour recording sessions for 6 months following onset of meaningful words. Words were transcribed with broad phonetic transcription. Consonants and vowels were described by word position and in sequential patterns within and across syllables.

Segments and sequences produced most frequently were also most accurate across groups and sessions. Lexical targets reflected more diverse phonetic patterns than child production patterns. Both groups performed similarly on all measures except consonant accuracy, where the NH group omitted fewer final consonants. Both groups improved accuracy over time. Consonants changed most dramatically, shifting from omissions in early sessions to correct productions in later sessions. Vowels and consonant-vowel sequences within syllables improved from "partially correct" (i.e., matching some but not all characteristics) to "correct". Sequences with partial omissions (i.e., isolated vowels) improved to code the correct number of segments within and across syllables.

Overall accuracy of segments and sequences in single words increased over the period of the study for both groups. Despite different perceptual histories, they looked very similar in development of early speech accuracy. These findings suggest a stronger influence of the production system than auditory perception on phonetic accuracy in early words, thereby supporting early implantation as a means to achieve speech and language milestones without significant disruption in the process of acquiring accuracy.

Table of Contents

List of Tables

List of Figures

Chapter 1:
Literature Review

Production and auditory perceptual factors form a system-based foundation for intelligible speech. The production system contributes motor capacities for producing sounds and sequences. The auditory system provides information about ambient language characteristics of word targets. The child must utilize both to achieve accuracy by matching sounds they can produce with salient word targets. As the child matures, these two systems support a more complex interface between perception and action, resulting in greater accuracy. To fully understand the process by which children acquire intelligible speech, we must consider both production system and auditory perceptual components and their effect on phonetic accuracy over time.

Behavioral patterns of the production system depend on anatomical and physiological changes of the oral movement system. Hearing children favor labial and coronal consonants and low, mid, front, and central vowels (Boysson-Bardies & Vihman, 1991; Kent & Bauer, 1985). Preferred segments do not include dorsal consonants and back vowels, which require basic regulation of tongue motor control, particularly shaping of the tongue dorsum (Dinnsen, 1992; Kent, 1992). Rather than occurring in isolation, consonants and vowels are combined in sequences as the jaw moves from a closed (consonant) to an open (vowel) position. Within-syllable consonant-vowel pairings tend toward articulatory compatibility, sharing anterior-posterior tongue position (e.g., labial consonant-central vowel, /ba/). Co-occurrences with articulatory compatibility dominate babbling and first words in diverse perceptual environments including various languages (see Davis & MacNeilage, 2002 for a review) and hearing loss (Davis, Morrison, von Hapsburg, & Warner-Czyz, 2005; Davis, Tobey, & Moore, 2004; McCaffrey, Davis, MacNeilage, & von Hapsburg, 1999; Warner-Czyz, Davis, & Morrison, 2005c; Warner-Czyz, Davis, & Morrison, 2005b). The strength of these favored patterns suggests a powerful effect of the production system on observable behavioral patterns (e.g. Boysson-Bardies, 1993; Davis & MacNeilage, 1995; Davis & MacNeilage, 2002).

In addition to production system influence, auditory perceptual input impacts the nature of early speech output (Lindblom, 1992; Oller & Eilers, 1988; Stoel-Gammon & Otomo, 1990). Children with severe-profound hearing loss cannot fully access the acoustic properties of speech. Resulting vocalization patterns reflect a blend of other intact feedback systems (i.e., visual and kinesthetic) with production system properties. Segmental repertoires are characterized by consonants with more visible (i.e., labials) and tactile cues (i.e., nasals) and vowels with neutral qualities (i.e., mid and central) (Ertmer, 2001; Ertmer & Mellon, 2001; Blamey, Barry, & Jacq, 2001). Within-syllable patterns rarely occur but, when present, are comparable to patterns produced by hearing children (Davis et al., 2004; Davis et al., 2005; MacNeilage et al., 1997; von Hapsburg, 2003).

The integration of audition positively impacts vocal development outcomes (Gillis, Schauwers, & Govaerts, 2002; Yoshinaga-Itano, 2002). Cochlear implants (CI) afford children with severe-profound hearing loss access to frequency, intensity and durational characteristics of speech via a coded signal (Skinner et al., 1994). With appropriate and consistent input from CI, consonant and vowel inventories expand and sequential patterns emerge to mirror those of hearing infants (Ertmer, 2001; Ertmer & Mellon, 2001; Blamey, Barry, & Jacq, 2001; McCaffrey et al., 1999). However, the children require auditory experience to trigger speech development.

Vocal behaviors in hearing children and in those with hearing loss detail effects of production and perception on early phonetic output patterns. Understanding the emergence of accuracy requires comparison of the child's productions with salient language-based targets. Available data on production accuracy in early words has emphasized either correct productions or error patterns without following both types of acquisition patterns longitudinally. Developmental studies must describe not only the end result, but also changes in behavioral patterns over time to enlighten the *process* by which children achieve more complex behaviors like speech accuracy (e.g., Ford & Lerner, 1992; Port & van Gelder, 1995; Thelen & Smith, 1994;). The child may successfully match certain aspects of word targets (e.g., consonant place <u>or</u> manner) before achieving a completely correct production. These "partial" successes, evident in error patterns of substitutions (e.g. /bɪg/ for /pɪg/) and omissions (e. g. /ba/ for /bal/), may afford insight as to *how* young children attain phonetic accuracy in early words (Davis & MacNeilage, 1990; Davis, MacNeilage, & Matyear, 2003; French 1989).

The impact of context, or phonetic environment, is another aspect of understanding the process of achieving early accuracy. Children's patterns differ with respect to word position and sequences within and across syllables on early accuracy. Research across different aspects of development has shown that children use the resources available to the system to progress to more complex behaviors (e.g., Clark, 1997; Gibson & Pick, 2000; Smith & Katz, 1996; Thelen & Smith, 1994). Acquisition of phonetic accuracy proves no exception to this use of available resources principle.

Children are more accurate on the most frequently produced segments (Davis et. al., 2003; French, 1989) and sequences (i.e., with articulatory compatibility) (Davis & MacNeilage, 1990; Davis et al., 2003; Warner-Czyz et al., 2005b). In addition, they often use favored segments and sequences in substitution patterns (Davis et al., 2003; French, 1989). Word position impacts accuracy, too, with more correct productions in initial than final position (Davis & MacNeilage, 1990; Shibamoto & Olmsted, 1978; Warner-Czyz et al., 2005b). Learning from regularities in the auditory signal also is evident in the child's ability to match targets. Typically developing children achieve more correct productions of common than uncommon sequences in the ambient language, as shown in older children (e. g. Storkel, 2001).

Production and auditory perceptual systems both impact early speech patterns. However, their effects on the acquisition of accuracy in early words are unclear. Comparison of children at similar development levels with different hearing histories can help to illuminate the role of these two systems in early acquisition of lexical accuracy. Similarities between groups will point to dominance of the production system. Differences in the pattern of vocal development could clarify the role of audition emergence of accuracy in early words.

Additionally, the developmental process can be characterized as change over time. Full understanding of the nature of accuracy requires observation of at closely spaced intervals. This continuous rather than stage-based approach to analysis can reveal potentially unique profiles in these two groups. Acquisition of lexical accuracy for single words was analyzed in two groups of children: normal hearing and young CI recipients. The goal of the study was to understand better the relative contributions of production and auditory perceptual factors to acquisition of accuracy in the first phase of acquiring intelligible speech.

Understanding the development of phonetic accuracy in early words requires knowledge of the foundation from which these words emerge. Infants demonstrate considerable overlap in favored phonetic patterns from the onset of speech-like vocalizations, termed *canonical babbling*, through the single word period (Vihman, Ferguson, & Elbert, 1986). Establishing a coherent link between phonetic tendencies and production accuracy in children differing in auditory status could help to understand interdependent relations of production and auditory perception as a function of developmental time. Typical behavioral correlates of acquisition in normally hearing infants and children who are deaf or hard of hearing provide background for this study.

Acquisition of Speech in Hearing Infants

In infants with normal auditory and visual perception abilities, increased articulatory control contributes to changes in speech patterns. For example, proportion of variegated syllables increases while proportion of reduplicated syllables concomitantly decreases across the course of development (Davis & MacNeilage, 1995; Mitchell & Kent, 1990; Robb, Bauer, & Tyler, 1994; Roug, Landburg, & Lundburg, 1989; Smith, Brown-Sweeney, & Stoel-Gammon, 1989). Studies of typical vocal acquisition have outlined the nature of speech production patterns during the first eighteen months of life across languages (Davis & MacNeilage, 1995; Kent & Bauer, 1985; Koopmans-van Beinum & van der Stelt, 1986; Oller, 1980; Stark, 1980; Stoel-Gammon & Cooper, 1984; Vihman et al., 1986; Zmarich & Lanni, 1998). Results show that infants produce reflexive vocalizations and vocal play without meeting the rhythmic requirements for speech-like vocalization during the first six months of life (Oller, 1980; Stark, 1980). Infants with normal hearing sensitivity begin to produce rhythmic, syllable-like canonical babbling around 7-8 months of age and continue producing babbling behaviors through the first word period until approximately 18 months of age (Davis & MacNeilage, 1995; Oller, 2000; Stark, 1980).

Phonetic characteristics in early words exhibit continuity with patterns in babbling (Davis & MacNeilage, 1995; Elbers & Ton, 1985; MacNeilage & Davis, 1997; Oller, Wieman, Doyle, & Ross, 1975; Stoel-Gammon, 1985; Stoel-Gammon & Cooper, 1984; Vihman et al., 1986; Vihman, Macken, Miller, Simmons, & Miller, 1985). The numerous phonetic similarities between babbling and early words persist in studies of a variety of languages (Boysson-Bardies & Vihman, 1991; Locke, 1983; Roug et al., 1989; Gildersleeve-Neumann, 2000, Teixeira & Davis, 2000, Zmarich & Lanni, 1998). These similarities in vocal qualities may represent universal aspects of early speech acquisition based on characteristics of infant production system development. These continuities can be described via segmental consonant and vowel characteristics, serial ordering patterns, and phonetic accuracy in the early vocal acquisition of hearing infants

Segmental Characteristics

Segmental inventories, which describe types and frequencies of consonants and vowels, have been widely reported in studies across languages (e.g. Boysson-Bardies, Vihman, Roug-Hellichus, Durand, Landberg, & Arao, 1992; Davis & MacNeilage, 1995; Davis & MacNeilage, 2002; Ingram, 1976; Kent & Bauer, 1985; MacNeilage, Davis, & Matyear, 1997; Stoel-Gammon, 1985; Stoel-Gammon & Cooper; Vihman, 1992; Vihman et al., 1985). Assessment of segmental inventories can include analyses of horizontal (i.e., consonant place, vowel front-back) and/or vertical (i.e., consonant manner, vowel height) characteristics. Although several researchers have focused on specific aspects of consonants or vowels, few have examined both comprehensively.

Kent and Bauer (1985) reported on phonetic properties of simultaneous babbling and word-based utterances of 5 13-month-old English-learning infants. A 1-hour recording session was collected from each child and coded using narrow phonetic transcription. Labial, coronal, and stop consonants occurred most frequently, but manner types differed by word position. Stops dominated initial position while all consonant manners were represented in medial position. Vowel inventories included a preference for front (42%) over central (31%) or back (28%) vowels. Mid vowels occurred more frequently (55-60%) than low (23-32%) or high (8-14%) productions, although high vowels were more prevalent in word final position.

Boysson-Bardies and Vihman (1991) examined longitudinal data for consonants in early words and concurrent babbling of 20 children in four language environments at four lexical data points: 0 words, 4 words, 15 words, and 25 words. The children were audio and video-recorded for 30 minutes twice a month. Data from the English-learning participants will be reviewed here. Labial consonants (46%) predominated in the single word period, followed by coronal (34%) and dorsal consonants (10%). Place distribution broadened as the children diversified their vocabulary, resulting in a lower proportion of labials and a higher proportion of coronal and dorsal consonants. Stops comprised 70% of consonants in first words, followed by nasals (15%) and fricatives (10%). Although this study did not specify patterns by word position, overall findings converge with the cross-sectional outcomes of Kent and Bauer (1985).

Kent and Bauer (1985) and Boysson-Bardies & Vihman (1991) provide detailed information about consonant and vowel repertoires during the single word period. Although production propensities in early vocal acquisition show substantial consistency, differences *do* exist (e.g. regression from the coronal sounds in babbling, which match ambient language characteristics, to labial sounds, which do not). Therefore, the inclusion of concurrent babbling in analyses (Boysson-Bardies & Vihman, 1991; Kent & Bauer, 1985) might preclude an accurate picture of early phonetic-lexical connections. This particular difference between the two stages has been attributed to either ease of production (MacNeilage et al., 1997), increased cognitive load (Boysson-Bardies & Vihman, 1991; Vihman, 1993; Vihman, 1996; Vihman et al., 1986), or both (MacNeilage & Davis, 2000) in first words compared to babbling. In either case, the advent of a new intrinsic factor – the attachment of a sound-meaning relationship via the production system – might potentially invoke a change in segmental or serial production patterns

(MacNeilage and Davis, 1999). Focus on lexical items rather than all productions (word and non-word) could enable a more precise understanding to lexical patterns.

Davis et al. (2002) analyzed consonant and vowel inventories in CVC and CVCV for 1,611 lexical utterances during the first word period in 10 English-learning infants. One-hour data sessions were collected weekly for 6 infants and biweekly for 4 infants. Similar to Boysson-Bardies and Vihman (1991), labials dominated early word attempts in both word positions. Dorsals occurred with higher frequency in C2 position. Consonant manner included predominance of oral stops (55%), nasals (22%) and glides (9%), with the greatest diversity in word final position (C2 of CVC). Vowel analysis in CVCV utterances revealed the dominance of central vowels in the front-back dimension in both syllable positions, occurring twice as frequently as front vowels and four times as frequently as back vowels. Vowels in the initial syllable included 46% low, 37% mid, and 17% high vowels. The distribution shifted to 23% low, 36% mid, and 41% high vowels in the second syllable. Overall results suggest that infants exhibit greater variety of both consonant and vowel qualities in absolute final position in first words.

Overall, hearing infants favor labial and coronal stop consonants. Low and mid, front and central vowels dominate, except in the word-final position in CVCV utterances where high vowels are more frequent. Except for Davis et al. (2002), these investigations evaluated segmental inventories without considering the phonetic environment surrounding consonants and vowels.

Serial Ordering Patterns

Fewer studies have examined serial ordering patterns, the relations between consonants and vowels within and across syllables (Boysson-Bardies, 1993; Davis & MacNeilage, 1995). *Intrasyllabic* patterns refer to the co-occurrences of consonants and vowels within a syllable. *Intersyllabic* patterns describe the relationship between consonants and vowels across syllables in terms of reduplication and variegation. Together, intrasyllabic and intersyllabic patterns form the basis for the evaluation of context-dependence.

Intrasyllabic sequences. According to the Frame/Content Theory of MacNeilage and Davis (Davis & MacNeilage, 1995; MacNeilage & Davis, 1990; MacNeilage & Davis, 1993), speech-like vocal patterns emerge as a result of rhythmic jaw movement accompanied by phonation with little independent movement of other articulators (i.e., lips, tongue, and velum) within syllables. Mandibular oscillation is seen as the basis for syllable production in canonical babbling (Davis & MacNeilage, 1995) and early speech (Davis et al., 2002). Predicted consonant-vowel (CV) co-occurrences are characterized by biomechanical inertia (lack of movement) rather than perceptual distance (maximal movement) to achieve perceptual distinctiveness (Ohala, 1983) between closed and open portions of syllables. For example, mandibular oscillation accompanied by phonation with a neutral tongue position results in the co-occurrence of labial consonants with central vowels (i.e., /ba/). Coronal consonant-front vowel pairings (i.e., /di/) result from a fronted tongue position. A dorsal consonant-back vowel combination (i.e., /gu/), is produced when the tongue is in a backed position at utterance onset. Although infants may produce diverse CV patterns, data supports predominance of predicted CV pairings at levels above chance in infant corpora in several languages in both canonical babbling and first words (Boysson-Bardies, 1993; Davis & MacNeilage, 1995; Locke, 1983; Oller & Steffans, 1993; Stoel-Gammon, 1985; Vihman, 1992). [See Davis & MacNeilage, 2002, for a summary of cross-language data on intrasyllabic patterns in infants.]

Davis and MacNeilage (1995) examined CV pairings in 6 typically developing infants over the babbling period. They computed the ratio of observed to expected occurrences of labial, coronal, and dorsal consonants with front, central, and back vowels. Expected values were calculated from the overall proportion of particular consonant and vowel types in the corpus. If 60% of all consonants were labial consonants and 60% of all vowels were central vowels, then the expected frequency of labial-central co-occurrence would be 0.6*0.6 = 0.36, or 36% of all CV combinations. Patterns were subjected to a χ^2 analysis to compare the distribution of observed frequencies to that of expected frequencies for each of 9 potential patterns outlined in the Frame/Content theory (MacNeilage & Davis, 1990; MacNeilage & Davis, 1993). If the observed value equals the expected value, the ratio would be 1.0. Analyses confirmed above-chance incidence of 18 predicted CV co-occurrences (3 predictions x 6 children). Chi square analysis revealed a significant difference between relative frequency of predicted (18/18) versus non-predicted CVs (9/36) (p = 0.001), suggesting that most of the articulatory variation within syllables in babbling is frame-related.

Davis et al. (2002) found a similar pattern for predicted CV co-occurrences in the first words of 10 infants. After eliminating 2 dorsal analyses due to low volubility, 27 of the 28 predicted associations were confirmed. The difference between predicted (27/28) and non-predicted (15/58) results was significant. Results corroborated the persistence of frame-dominated CV productions (i.e., labial-central, coronal-front, and dorsal-back pairings) in the early words of these infants.

Intersyllabic sequences. Intersyllabic patterns describe the relationship between non-contiguous consonants and vowels across syllables. Serial vocalizations of more than one syllable can occur as reduplicated (e.g., /baba/) or variegated syllables (e.g., /babi/). Reduplication and variegation can be described via horizontal (consonant place, vowel front-back) or vertical (consonant manner, vowel height) dimension or both. Both reduplicated and variegated syllable types co-occur from the onset of canonical babbling (Davis & MacNeilage, 1995; Mitchell & Kent, 1990; Robb et al., 1994; Roug et al., 1989; Smith et al., 1989).

The Variegation hypothesis of the Frame/Content theory (MacNeilage & Davis, 1990) proposes that changes in the amplitude (i.e., the vertical dimension) of the mandibular cycle should guide the types of consonant and vowel changes rather than changes in anterior-posterior tongue position (i.e., the horizontal dimension) [See MacNeilage & Davis, 2002, for a comprehensive summary of intersyllabic patterns predicted by the Frame/ Content theory.]. That is, intersyllabic patterns will more likely result in reduplication of consonant place and vowel frontness and variegation of consonant manner and vowel height. Davis and MacNeilage (1995) conducted a longitudinal babbling study of 6 typically developing hearing infants from approximately

7 to 12 months. Vowel changes across syllables typically involved vowel height (84%) and consonant manner (61%), confirming variegation predictions.

Researchers have studied intersyllabic sequences in early words as well (Davis et al., 2002; Kent & Bauer, 1985; Shibamoto & Olmsted, 1978). Shibamoto and Olmsted (1978) examined consonant patterns in 4 infants from the onset of first words through the 50th word. Infants reduplicated consonant place (44%), particularly for labial (43%) or coronal (48%) types. Variegations were typified by "fronting" patterns (74%), in which the first consonant is produced with a more anterior place of articulation than the second consonant. Consonant manner and vowel patterns were not analyzed.

Kent and Bauer (1985) studied intersyllabic patterns in CVCV utterances in first words and concurrent babbling in 5 13-month-old infants. One-third of productions involved total syllable reduplication. Consonant reduplication (60%) occurred more than variegation, primarily involving repetition of labial (65%) or coronal (20%) place. Vowel variegation (56%) occurred more frequently than reduplication. Specific intersyllabic patterns for consonant manner, vowel height or front-back were not reported.

Davis et al. (2002) also found concurrent use of reduplication (58%) and variegation (42%) in CVC and CVCV utterances in first words. Their 10 infants produced 75% consonant reduplication, primarily involving labial (58%) and coronal (31%) place or stop (73%) and nasal (26%) manner. Consonant place variegations most frequently occurred as labial-coronal (LC, 44%) and labial-dorsal (LD, 22%) sequences. "Fronting" patterns (e.g., LC, LD, and CD) occurred three times more often than the reverse pattern (e.g., CL, DL, and DC), consistent with Shibamoto and Olmsted's (1978) findings. Detailed relationships of manner variegation and total consonant variegation (change in both place and manner characteristics) were not included.

Intersyllabic vowel patterns have not been a focus of many studies. Davis et al. (2002) found more front-back reduplication (58%), particularly for front (41%) and central (53%) vowels. When infants variegated, they typically produced the first vowel at a more anterior location than the second (71%). Vowel height variegations outnumbered reduplications (55% vs. 45%). Height changes predominantly included "raising" patterns (e.g., MH, LM, LH) (84%) chiefly due to the use of high vowels in V2 position. Reduplication patterns were equally distributed for the three vowel heights.

Overall, children reduplicate intersyllabic patterns in the horizontal dimension (consonant place, vowel front-back) and variegate in the vertical dimension (consonant manner, vowel height). Labial and stop manner reduplication as well as “fronting” variegation patterns (i.e., C1 produced in a more anterior place than C2) typified consonant patterns. Vowel variegation exceeded vowel reduplication, particularly for vowel height. These results conform to the assessment by Vihman (1996) and the Variegation Hypothesis of the Frame/Content theory (MacNeilage & Davis, 1990) that amplitude changes of the mandibular cycle (i.e., the vertical dimension) guide phonetic variegation rather than anterior-posterior changes (i.e., the horizontal dimension).

Children favor labial and coronal stop consonants and low, mid, front and central vowels in early words. Intrasyllabic sequences reflect articulatory compatibility, the combination of consonants and vowels with similar anterior-posterior tongue position (i.e., labial-central, coronal-front, and dorsal-back), as predicted by the Frame/Content Theory. Intersyllabic patterns feature variegation of consonant manner and vowel height, as predicted by the Variegation Hypothesis of the Frame/Content Theory.

Simultaneous analysis of segments on both dimensions in the description of inventories and intersyllabic patterns will define better the context-dependent relations between consonants and vowels in early vocal development. Additionally, available studies did not link the child’s productions to their intended lexical target. By examining the child’s output without consideration of the lexical objective, we learn about vocal patterns based on characteristics of the child’s production system but nothing about the effect of these production patterns on accuracy or error patterns in early words.

Development of Accuracy in First Words in Hearing Infants

Fewer studies have detailed acquisition of accuracy in typically developing children in early words (Davis & MacNeilage, 1990; Davis et al., 2003; French, 1989; Otomo & Stoel-Gammon, 1992; Schumacher, McNeil, Vetter, & Yoder, 1986;

Shibamoto & Olmsted, 1978). Assessment of accuracy involves three main properties: target characteristics, correct productions, and error patterns.

Target characteristics refer to the segmental properties and serial organization of the intended word (i.e., the lexical target) and can be compared with the child's actual utterances to determine accuracy. *Correct productions* describe the child's ability to match the intended target. The child can match horizontal (consonant place, vowel front-back) and/or vertical (consonant manner, vowel height) dimensions of a target in individual phonetic segments or serial patterns. *Error patterns* refer to systematic substitution (e.g. b/d) or omission (e.g. -/d) patterns to complement the analysis of correct productions. Does the infant methodically err on one dimension (e.g., match consonant manner but not place characteristics) or omit particular segments and sequences?

Systematic investigations of error patterns in the early lexicon are more sporadic than studies of production accuracy (Otomo & Stoel-Gammon, 1992). This paucity of research in the earliest linguistic (i.e., single word) period is in direct contrast to the plethora of studies involving phonological strategies used by children after two years of age. Studies of older children report simplification of syllabic complexity via final consonant deletion, substitution with stops, and cluster reduction (e.g. Bernhardt & Stoel-Gammon, 1994; Locke, 1983). Therefore, the limited research investigating error distribution in the single word period is surprising since error patterns – in tandem with phonetic inventories – can provide a fuller description of the child's earliest stages of acquisition of adult forms (Bernhardt & Stoel-Gammon, 1994). Simultaneous examination of all three measures of accuracy – with target characteristics serving as the foundation by which to assess correct productions and error pattern types - will allow an interactive rather than parallel evaluation of phonetic accuracy in the single word period.

Phonologists have emphasized the importance of cognitive strategies in developing target accuracy (Garnica & Edwards, 1977; Ingram, 1976; Menn, 1979; Vihman; 1996). Vihman proposed the construct of "word templates" that the child adapts to produce new word forms in his expanding vocabulary. Early in the second year, the child experiences a release from production-based dominance and makes systematic changes in the reproduction of target segments, sequences, and syllable shapes, known as phonological processes (Menn, 1971; Ingram, 1976). Related explanations have sought to account for segment variability, including “local scatter” (Menn, 1979) and trade-offs in production (Garnica & Edwards, 1977; Leonard, Rowan, Morris, & Fey, 1982). Local scatter posits that the child executes articulatory instructions with a greater range of tolerance than an adult. Trade-offs refer to sound simplification in one word with correct production in another word at the expense of a different sound or syllable structure (Garnica & Edwards, 1977; Leonard et al., 1982). The trade-offs are suggested as occurring due to an overload of the speech system with respect to the organization of components into a single pattern.

The development of production accuracy may relate more directly to production characteristics of the infant system as evidenced by methodical error and omission tendencies in segmental and serial organization patterns (MacNeilage et. al., 1997). For instance, the cognitive rule of final consonant deletion can alternatively be described as a preference for closure (i.e., consonant) at initiation and open jaw (i.e., vowel) at termination (e.g. bat-> [pæ]). Similarly, the phonological rule using stop consonants as substitutions for other consonants can instead be described as a preference for complete closure of the oral cavity in babbling and first words (e.g. sock -> [tak]). This section focuses on segmental and syllabic patterns in accuracy during the first word period.

Segmental Characteristics

Accuracy of phonetic segments has been studied in the single word period with greater focus on issues related to consonants (Ferguson & Farwell, 1975; French, 1989; Paschall, 1983; Shibamoto & Olmsted, 1978; Vihman et al., 1994) than vowels (Davis & MacNeilage, 1990; French, 1989; Paschall, 1983; Shibamoto & Olmsted, 1978) in typically developing children.

Vihman, Kay, Boysson-Bardies, Durand, & Sundberg (1994) compared segmental inventories and target characteristics of consonants in early words in 5 English-learning infants from 9 months to the acquisition of a 50-word vocabulary (described in Boysson-Bardies & Vihman, 1991). Children both produced more labials and coronals (48% and

35%, respectively) and attempted targets with more labials and coronals (36% and 43%, respectively) than dorsals. A similar trend was found for consonant manner with stops dominating inventories (75%) and word target characteristics (55%). The predominance of labials, coronals, and stops in both child productions and target characteristics agrees with previous research by Ferguson (Ferguson & Farwell, 1975; Ferguson, Peizer, & Weeks, 1973) that segmental properties for attempted words tend to conform to typical child production patterns. However, the authors did not directly compare target characteristics with the child's productions to determine accuracy.

Shibamoto and Olmsted (1978) explored early word accuracy in 4 infants. Word position affected the ability to match consonant place with greater accuracy in word-initial position (80%) than word-final position (53%). The authors did not specify *which* place of articulation the infants attempted or consonant manner accuracy. Vowel results revealed greater accuracy in the initial syllable (73%) than the second syllable (53%). Children matched front and central vowel qualities more often than back vowels (21-34% versus 3-11%). Individual vowel analyses showed that /i/ and /a/ were produced most accurately in all word positions. Vowel height accuracy was not analyzed separately.

Reporting diary data, French (1989) monitored the target characteristics and error patterns of first words in Andrew, a monolingual English speaker, between 16 and 23 months. Andrew often correctly matched word-initial consonants but not vowel qualities. French suggested that this child tailored target characteristics by avoiding "difficult" initial consonants (i.e., nasals, aspirated plosives, fricatives other than /s/, consonant clusters) to achieve more accuracy for consonants he attempted in word-initial position (i.e., stops). Andrew's error patterns included final consonant deletion in monosyllables and syllable reduplication in disyllables rather than consonant substitutions. The vowel /a/ was produced most frequently and most accurately overall, although accuracy for other vowels improved over time. French's observation concurs with Shibamoto & Olmsted (1978) that /a/ is one of the earliest vowels produced accurately. Vowel error patterns revealed incorrect vowels were predominantly realized as /a/. This tendency suggests that Andrew utilized available production capacities (e.g., experience with /a/) to achieve vowel accuracy and to substitute for vowels that he could not produce accurately. This is consistent with Ferguson and Farwell (1975). Overall, French's findings support the interactive nature of production capacities and lexical factors since Andrew's target characteristics contained his most accurate consonants in initial position.

Davis and MacNeilage (1990) focused on accuracy and error patterns of vowels in one child (B) between 14 and 20 months. Data were audio-recorded weekly for 2-hour periods until the child produced about 50 words in a session; twice weekly thereafter. All meaningful speech utterances occurring at least twice in a session were transcribed using broad phonetic transcription. Fewer than 60% of vowel attempts at adult words were accurate, ranging from less than 30% correct for /ə, ɚ, ɛ/ to greater than 75% correct for /i, ɪ, o, u/. Contrary to French (1989), who found the child was *more* correct on the most frequently produced phonetic segments, B was *less* accurate on the most commonly occurring vowels. Of the three most accurate vowels in each word position, only two coincided with the most frequently produced vowels: /a/ in disyllables (V1) and /i/ in disyllables (V2). Vowel error patterns typically included either neighboring vowels in the vowel space and neutralization of vowels. Additionally, Davis and MacNeilage (1990) found higher accuracy in the initial syllable.

Vihman et al. (1994) compared consonant production preferences with targets attempted, but did not evaluate accuracy. Shibamoto & Olmsted (1978) addressed general accuracy of productions as well as the horizontal dimension (consonant place, vowel front-back) by word position, but neglected the vertical dimension (consonant manner, vowel height) and error patterns. Davis & MacNeilage (1990) analyzed vowel front-back and height characteristics in child productions, accuracy, and error patterns, but not target characteristics. French (1989) analyzed target characteristics, accuracy, and error patterns, but generalization may be limited because of lack of descriptive statistics and use of a diary method with one participant.

Other studies have examined the acquisition of consonant and vowel accuracy in older children (Hare, 1983; Otomo & Stoel-Gammon, 1992; Paschall, 1983). Paschall (1983) studied 20 18-month-old infants' ability to match segmental targets in spontaneous speech. She found more correct productions of central (71%) than front (56%) or back vowels (62%), and higher accuracy for high (71%) and mid (66%) than low vowels (54%). Error type distributions showed six times more vowel substitutions than omissions. Consonant analysis revealed greater accuracy for labials (80%) than coronals or dorsals. Children produced stops, nasals, and glides occurred with greater than 60% accuracy. Liquids, fricatives, and affricates were less than 25% correct. Consonant omissions occurred more frequently than substitutions, a pattern that differs from the tendency toward substitutions in vowel error patterns.

Otomo and Stoel-Gammon (1992) examined vowel accuracy in 6 typically developing toddlers aged 22 to 30 months in a longitudinal study. Each child participated in a monthly naming task targeting 26 mostly monosyllabic words focused on 6 unrounded American English vowels: /i/, /I/, /e/, /ɛ/, /æ/, and /a/. The children produced /i/ and /a/ most accurately at all three data points (22, 26, and 30 months), confirming the findings of Shibamoto and Olmsted (1978) and French (1989). Mid vowels /I/ and /ɛ/ were produced least accurately, often with lowered height, potentially due to the need to establish and maintain phonological contrasts between phonemes. The children generally matched vowel front-back characteristics (80-90%) more often than height (67-78%).

The investigations by Davis and MacNeilage (1990), Otomo and Stoel-Gammon (1992), and Paschall (1983) concentrated on correct productions and error patterns in early vowel development, which allowed a more in-depth analysis of accuracy patterns. However, none of the studies separately examined target characteristics, which could describe the types of words attempted by children. Additionally, only one study (Davis & MacNeilage, 1990) investigated a child in the earliest linguistic phase while the others examined older children, who might function at higher cognitive levels than infants beginning to produce first words.

Infants demonstrate overall trends in their ability to match consonant and vowel qualities in early words. Labial and stop consonants were both attempted and produced most accurately. Front and central vowels, particularly /i/ and /a/, were matched most frequently across studies. However, no studies have concomitantly reported on target characteristics, accuracy, and error patterns for both consonants and vowels. To fully understand the acquisition process of phonetic accuracy, analysis should include all three accuracy measures for both types of segments during this very early linguistic stage.

Serial Ordering Patterns

Intrasyllabic sequences. Davis, MacNeilage and colleagues have completed an initial examination of the accuracy of intrasyllabic patterns in the 50-word period of typically developing children (Davis et al., 2003). Audio sessions were recorded semi-monthly for 4 of the infants and semi-weekly for the fifth infant for a total of 97 sessions. Observed to expected ratios were calculated to determine patterns for targets, correct productions, and substitutions in CV co-occurrences. Four intrasyllabic CV sequences in word targets occurred at levels above chance: coronal-back (1.38), dorsal-front (1.27), labial-central (1.25), and coronal-front (1.02). Only two of these CV patterns (labial-central, coronal-front) are predicted by the Frame/Content theory to occur more frequently in babbling. All three predicted CV associations (MacNeilage & Davis, 1990) were accurate at above-chance levels (labial-central = 1.38, coronal-front = 1.07, dorsal-back = 1.14). When the infants did not match the adult CV target, they often used predicted CV pairings as substitutions at levels greater than chance (labial-central = 1.19, coronal-front = 1.35, dorsal-back = 1.38).

The authors concluded that children may attempt word targets with more diverse CV patterns, but they are more accurate on articulatory compatible CV co-occurrences predicted by Frame/ Content theory. Error patterns reveal preferential use of predicted co-occurrences in substitutions. These results concur with the vowel substitution patterns in French (1989), suggesting that infants may use pre-existing patterns of syllabic movement in canonical babbling as a springboard transition to early words.

Intersyllabic sequences. Harmony refers to the influence of one sound on the production of another non-contiguous sound so that the two agree in horizontal (consonant place, vowel front-back) and/or vertical (consonant manner, vowel height) dimensions, regardless of the difference between the two segments in the intended target word. Pater (1997) compared child productions to the intended target, describing intersyllabic tendencies for consonant harmony. He distinguished between progressive (*duck*: [dʌk] → [dʌt]) or regressive (*duck*: [dʌk] → [gʌk]) directionality and involvement of each of the three main places of articulation: labial, coronal, and dorsal. His analysis of two male children demonstrated the presence of dorsal dominant harmony, in which coronals and labials assimilate to dorsals. However, Pater did not analyze the relationship between labial and coronal consonants, manner of articulation, or vowel harmony.

In conclusion, the bulk of available research implies that infants with hearing sensitivity within normal limits can achieve accuracy for segmental and intrasyllabic characteristics during the early lexical period. However, the majority of studies have collapsed data across the whole period to obtain mean values without describing individual session values (Davis et al., 2003; Hare, 1983; Paschall, 1983; Vihman et al., 1994). Most studies reporting session-to-session changes in accuracy were case studies (Davis & MacNeilage, 1990; French, 1989) although two followed several infants (Otomo & Stoel-Gammon, 1992; Shibamoto & Olmsted, 1978). Application of these studies to the developmental process of accuracy serves more as a description of end stages and does not characterize intra-stage changes. No study has detailed accuracy of both segmental and serial characteristics in early lexical development. No studies examine target characteristics. Such data could detail how infants use production system capacities to achieve accurate productions with respect to ambient language targets.

Acquisition of Speech in Children with CI

Relative to hearing infants, infants with profound hearing loss have limited access to the acoustic properties of speech sounds. They exhibit difficulties in development of normal speech movements and the typical repertoire of speech patterns. Although other intact feedback systems (e.g., visual and kinesthetic systems) can provide cues to placement and movement of articulators, these systems are limited due to incomplete visual access to particular articulatory characteristics (e.g., tongue position) and inability of the child to interpret kinesthetic cues. Perkell et al. (2000) notes that, “To acquire normal speech (adult-established), children need to hear” (p. 249), suggesting that reduced auditory perceptual capabilities may significantly contribute to limited speech production acquisition in hearing-impaired infants.

With the development and availability of multi-channel CI devices, children with profound hearing loss have been allowed access to consistent auditory input in the speech spectrum. Many of these children have developed competent oral communication more commensurate with that of hearing children (Blamey, Barry, & Jacq, 2001; Blamey, Barry, Bow, Sarant, Paatsch, & Wales, 2001; Chin, 2002; Chin, & Pisoni, 2000; Ertmer, 2001; Ertmer & Mellon, 2001; McCaffrey et al., 1999; Moore & Bass-Ringdahl, 2002; Tobey, Geers, & Brenner, 1994; Tye-Murray, Spencer, & Woodworth, 1995).

A CI electrically stimulates remaining basal ganglion cells of auditory nerve fibers so that the child has access to sound. Externally worn hardware consisting of a microphone and speech processor converts speech and other environmental sounds into a code that preserves the frequency, intensity, and duration of the input signal. This electronic code is transmitted transdermally to an electrode array surgically implanted into the cochlea. The speech processor divides the input signal into different frequency bands, which are subsequently assigned to the electrodes in the array to maximize the tonotopic (i.e., frequency-specific) organization of the afferent auditory nerve (Brookhouser, Beauchain, & Osberger, 1999). The electrodes directly stimulate the cochlear neurons of the auditory nerve, which sends the signal to the central auditory pathways (Brookhouser et al., 1999; Chin, 2002; Chin & Pisoni, 2000).

Because CI technology allows better perceptual retrieval of the speech spectrum than conventional amplification systems, children with profound hearing loss who receive these devices can integrate audition into their communication system to develop more intelligible speech. Therefore, children with profound hearing impairment receiving CI provide a natural population in which to examine the impact of audition on early lexical acquisition. Even though the child may respond essentially within normal limits to acoustic stimuli, CI devices do not provide the child with the equivalent of normal hearing sensitivity. Rather, the child must learn to interpret the compromised auditory signal allowed by the CI to develop vocal communication skills.

Children with hearing loss generally develop vocal communication (i.e., phonetic inventories and serial patterns) quantitatively and qualitatively different from hearing infants. Access to the conversational speech spectrum and the auditory feedback loop allows young children with hearing loss to monitor their own speech, thereby improving orally intelligible speech over time. However, patterns identical to those of hearing children may not emerge (Chin, 2002; Higgins, Carney, McCleary & Rogers, l996). Comparison of early speech patterns produced by young children with hearing loss with that of hearing infants can provide a background to understand the relative roles of audition and oral production propensities during babbling and first words.

Babbling

Infants with hearing loss do not babble on average until 11 months of age, 3 to 4 months later than hearing children, with no overlap in the onset distribution of canonical babbling between the two groups (Eilers & Oller, 1994; Oller & Eilers, 1988). When they begin babbling, they often do so with lower volubility than the 300 syllables per hour typical of young hearing children (Davis et al., 2005; McCaffrey et al., 1999), with less consistency, and with canonical babbling comprising less than 20% of total vocalizations per session (Eilers & Oller, 1994; Oller & Eilers, 1988). Diversity of consonant and vowel inventories is often limited compared to their hearing contemporaries (Davis et al., 2005). Vocal output differs with respect to the regularity of syllable timing expected in canonical babbling (Davis et al., 2005; Oller et al., 1985). Rather than maintaining a rhythmic speech-like cadence, infants with hearing loss often employ either prolongation of sounds or rapid rises and falls in amplitude, which creates irregular, inappropriately timed vocal patterns (Davis et al., 2005; Oller & Eilers, 1988; Oller et al., 1985).

Moore and Bass-Ringdahl (2002) examined 12 children acquiring Nucleus 24M CI devices between 18 and 20 months. Average age of onset of canonical babbling was 6.5 months post-activation, coinciding with the 6 to 10 month average time frame for hearing infants. This finding is consistent with the concept of maturational “thawing” of a sensory, perceptual, or motor system (Eggermont, Ponton, Don, Waring, & Kwong, 1997; Ponton, Don, Eggermont, Waring, Kwong, & Masuda, 1996; Ponton, Don, Eggermont, Waring, & Masuda, 1996; Ponton, Moore, & Eggermont, 1999). According to Ponton, Eggermont, and colleagues, the onset of deafness "freezes" development of the auditory cortex at a particular maturational state. Once stimulation is received, maturation can proceed at a rate more consistent with typical development. Auditory access to the speech signal via a CI may result in a maturational delay of the auditory cortical system, followed by progression at rates similar to normal hearing individuals.

However, the "thawing" metaphor might not adequately describe acquisition of speech by younger CI recipients. Gillis et al. (2002) investigated babbling in 9 infants whose Nucleus 24 CI device was activated between 6 and 21 months chronological age (M = 12 months, SD = 5.1 months). The cause of deafness was genetically based (e.g. Connexin 26, N = 5) in all cases in which diagnosis of etiology was possible. Canonical babbling began 1.6 to 4 months after activation. Compared to hearing infants, babbling onset emerged at an earlier "hearing age" in these young CI users. The compressed time frame for babbling onset in very young CI recipients suggests that earlier implantation and activation could potentially lead to an abbreviated "thawing" period with closer temporal approximations of typical speech milestones.

Young children with hearing loss generally attain babbling milestones differently than hearing infants. When they babble, vocal patterns often deviate from hearing infants, evident in a restricted formant frequency range, limited phonetic inventories for consonant and vowel qualities, longer segmental durations, and fewer syllable based vocalizations meeting the timing requirements for speech. Available evidence suggests that some time is needed to achieve babbling milestones following amplification, although the length of this period is unclear.

Segmental Characteristics

Children with profound hearing loss often exhibit different segmental inventories of babbling and early words compared to hearing infants (Blamey, Barry, & Jacq, 2001; Ertmer & Mellon, 2001; Locke, 1983; McCaffrey et al., 1999; Osberger & McGarr, 1982; Stoel-Gammon, 1988; Stoel-Gammon & Otomo, 1986; Yoshinaga-Itano, Stredler-Brown, and Jancosek, 1992; von Hapsburg, 2003). Auditory access to speech via appropriate intervention devices (e.g., CI) sparks expansion of phonetic repertoires. Studies of children with profound hearing loss receiving CI between 2 years (Ertmer, 2001; Ertmer & Mellon, 2001; Robinshaw, 1996) and 5 years (Blamey, Barry, & Jacq, 2001; Hesketh, Fryauf-Bertschy, & Osberger, 1991; Osberger, Robbins, Berry, Todd, Hesketh, & Sedey, 1991) show these differences.

Hesketh and colleagues (1991) studied the emergence of consonants and vowels in a congenitally deaf child who received a Nucleus 22 CI at 5 years of age. A 6-minute spontaneous speech sample was collected pre-implantation (after 24 months of tactile aid experience) and at 6 and 12 months post-implantation. Labial and nasal consonants were produced most frequently pre-implant. She diversified her consonant repertoire after 1 year of CI use to include coronal and dorsal place as well as fricative, glide and liquid manner. Vowel inventories expanded from primarily central and back vowels pre-implant toward increased use of front vowels post-implant.

Osberger et al. (1991) found similar results for segmental inventories in 14 pediatric CI users. The age at implantation ranged from 2.5 years to 10.1 years (*M* = 5.1 years). Seven children used a 3M/House implant and seven wore a Nucleus 22 device. Labial and stop consonants dominated the corpus at both pre-implant and 12 months post-implant, although coronal place and fricative, liquid, and glide manners emerged after 1 year of experience. Vowel repertoires included an overabundance of central and back vowels throughout the study. Mid vowels were more common pre-implant, but post-implant productions contained an equal distribution of all three vowel heights.

Hesketh (1991) and Osberger et al. (1991) concurred on emergence of segmental inventories. They studied children implanted at an average of 5 years of age or older using more primitive CI devices. Recent research focused on the influence of implantation age has shown that children implanted prior to 5 years tend to perform better on both speech production measures (Ertmer, 2001; Ertmer & Mellon, 2001; Kirk & Hill-Brown, 1985; McCaffrey et al., 1999; Tobey et al., 1991; Tye-Murray & Kirk, 1993; Tye-Murray et al., 1995; Warner-Czyz & Moore, 2002) and speech perception tasks

(Cheng, Grant, & Niparko, 1999; Fryauf-Bertschy, Tyler, Kelsay, Gantz, & Woodworth, 1997; Waltzman & Cohen, 1998).

Ertmer (2001) and Ertmer and Mellon (2001) described diversification of consonant and vowel inventories over time in a very young child receiving a CI. Identification of profound sensorineural hearing loss occurred at 5 months. She received a Clarion CI with CIS processing strategy at 19 months. Monthly data collection occurred in 30-minute sessions pre-implant through 12 months post-implant and was coded using broad transcription. Early productions were characterized by high front and central vowels. Vowels differentiated over time with inventories at 1 year post-activation including similar proportions of front and central (42-48%) as well as high and mid (42-48%) vowels. Labial consonants were produced almost exclusively until 11 months post-activation, when a "spike" in dorsal consonants occurred (56%). Nasals and glides dominated early inventories, but stops, fricatives, and liquids emerged after 6 months of CI experience. Later productions included both stops and nasals.

Blamey, Barry, & Jacq (2001) examined the rate of acquisition of phonetic inventories in nine children receiving a Nucleus CI before the age of five. Five of the children had congenital hearing losses due to unknown etiology (*N* = 4) or rubella (*N* = 1); the others developed profound hearing loss as a result of meningitis (*N* = 3) or unknown etiology (*N* = 1) between 14 and 57 months of age. Average duration of deafness was 31 months (*SD* = 18 months) and average age at implantation was 45 months (*SD* = 11 months). Annual data were collected via conversational samples and analyzed using narrow phonetic transcriptions excluding consonant clusters. Labials predominated through 2 years post-activation, although coronal and dorsal consonants appeared consistently by 6 months and 2 years post-activation, respectively. Stops, nasals, and glides were the most common consonant manners through 18 months post-activation, at which point fricatives entered the inventory. Vowel inventories primarily included central and front, low and mid vowels. Almost all participants incorporated back and high vowels by 12 months post-activation.

The younger cohorts examined by Ertmer (2001; Ertmer & Mellon, 2001), and Blamey and colleagues (2001) exhibited expansion patterns for both consonants and vowels similar to the older children studied by Hesketh et al. (1991) and Osberger et al. (1991). Pre-implantation inventories were dominated by labial consonants, a pattern differing from the high proportion of coronal consonants in hearing infants. However, post-implant inventories were more consistent with consonant patterns of hearing children (Blamey, Barry, & Jacq, 2001; Ertmer & Mellon, 2001; Locke, 1983; McCaffrey et al., 1999; Osberger & McGarr, 1982; Stoel-Gammon, 1988; Stoel-Gammon & Otomo, 1986; Yoshinaga-Itano et al., 1992; von Hapsburg, 2003). Two main changes that occur with CI experience are reduction of nasal consonants and expansion of the vowel space.

Participants across studies dramatically decreased nasals while concurrently increasing oral production as they gained auditory experience. The prevalence of nasal consonants in children with hearing loss differs from typical vocal patterns for hearing infants and may relate to decreased visual access to the tongue and velum position as well as restricted acoustic cues for place and nasality. Without acoustic information to signal change from the velum's resting position, infants with hearing loss do not learn to consistently elevate the velum to close the velopharyngeal port for oral productions (Davis & MacNeilage, 2000; Locke, 1983; McCaffrey et al., 1999; Osberger & McGarr, l982; Stevens, Nickerson, Boothroyd, & Rollins, 1976). Another proposal related to the nasal production mode in children who are deaf or hard of hearing has been tactile stimulation in an attempt to create feedback through a non-auditory modality (Locke, 1983; Stevens et al., 1976; Stoel-Gammon, 1988).

Both acoustic and transcription studies have reported a restricted vowel space in children with hearing loss (Blamey, Barry, & Jacq, 2001; Ertmer, 2001; Ertmer & Mellon, 2001; Kent, Osberger, Netsell, & Hustedde, 1987; Osberger et al., 1991; Robinshaw, 1996; Yoshinaga-Itano et al., 1992). The propensity to neutralize vocalic segments results in a higher proportion of central vowels. Gaining auditory access to the speech spectrum via CI allows these children to expand their repertoire to include front, high, mid, and low vowels.

While available studies have described general trends in the acquisition of segmental inventories, not all studies precisely described consonant and vowel proportions in text or figures (e.g. Hesketh et al., 1991; Osberger et al., 1991). As a result, comparison to other findings relative to the development of segmental properties over time in either young CI recipients or typically developing children is difficult. Additionally, the effect of word position on consonant and vowel frequencies was not always reported. This is surprising since studies of segmental inventories in hearing children have shown consonant and vowel diversity in syllable and word final position (Davis et al., 2002; Kent & Bauer, 1985).

Finally, comparison of segmental inventories of CI recipients to hearing children may seem logical with respect to the starting point (i.e., predominance of labials) and end point (i.e., expanded phonetic repertoire). However, examination of phonetic inventories via transcription analysis focuses more on the *product* rather than the *process* of speech development, which may not accurately represent speech acquisition in this population. Higgins et al. (1996) has reported that children with hearing loss – particularly those identified later, implanted later, and those with profound hearing losses – can develop maladaptive speech production strategies based on the relative contributions of their perceptual systems (e.g., visual, kinesthetic, auditory). Chin (2002) similarly found that older Nucleus 22 CI recipients using SPEAK processing strategy developed consonant inventories with additional non-English stops.

Ingressive labial stops (Higgins et al., 1996) and non-native stop contrasts (Chin, 2002) indicate that, although these children may produce the percept of a /b/, the technique used to articulate the phoneme may not match hearing children. Consequently, the assumption of identical developmental processes may not accurately describe early speech acquisition in hearing and hearing-impaired children. These two groups might differ not only in auditory levels, but also in levels of physical and cognitive maturation as well as dependence on kinesthetic cues and movement patterns.

Serial Ordering Patterns

Intrasyllabic sequences. Serial ordering patterns of young children with hearing loss seem to mirror that of hearing children, particularly after they gain auditory experience through hearing instruments, assistive listening devices, or CI. Infants with hearing loss often produce more isolated consonants and vowels before intervention (Davis et al., 2005; Eilers & Oller, 1994; Ertmer, 2001; McCaffrey et al., 1999; Oller & Eilers, 1988; Osberger et al., 1991; von Hapsburg, 2003), but an increased proportion of in syllables after intervention (Davis et al., 2005; McCaffrey et al., 1999). The CV pairings in infants with different levels of hearing loss tend to mimic the predicted patterns in hearing children (Davis et al., 2005; MacNeilage et al., 1997).

Davis et al. (2005) investigated three children identified at birth with varying degrees of hearing loss (i.e., mild, moderate decreasing to profound, and profound). The infants were chronologically seven to nine months at the onset of the study, the approximate onset age for syllable-based canonical babbling in hearing infants (Oller, 1980). Data collection began at 4 to 6 months hearing age (i.e., experience with amplification) and continued through 15-16 months hearing age. Only the infant with a mild hearing loss produced a sufficient number of CV alternations per session to allow for an intrasyllabic analysis. He favored labial-central and coronal-front patterns at levels greater than chance, consistent with patterns in hearing infants during babbling and first words. These CV patterns were proposed as being based on rhythmic mandibular movements (Davis & MacNeilage, 1995; Davis et al., 2002).

McCaffrey and colleagues (1999) found similar results in a young CI recipient. Activation of the Nucleus 22 CI device occurred at 25 months with 19 electrodes receiving stimulation using the SPEAK strategy in the common ground mode. Data were collected from videotapes over a 14-month period in 5 1-hour recording sessions at 3 months and 1 month pre-implantation and at 2, 7, and 9 months post-implantation, with corresponding chronological ages of 22, 24, 27, 32, and 34 months. The child's few pre-implant monosyllabic productions followed the Frame/Content prediction of labial-central CV co-occurrences (66%). As coronal place of articulation emerged and frequency of syllable-like vocalizations increased post-implant, she began to produce coronal-front CV associations (14%) in addition to labial-central co-occurrences (55%). Low incidence of dorsals precluded analysis for dorsal-back vowel co-occurrences. Overall, her intersyllabic patterns began to reflect those observed in hearing infants.

Warner-Czyz et al. (2005c) examined CV co-occurrences in 5 young implant users in the first word period. All CI devices (Nucleus: N = 3; Med El: N = 3) were fully inserted and activated between 12 and 24 months (M = 18 months). Twenty 1-hour audio-video sessions were compiled from the children between 5 to 13 months post-CI activation. Patterns predicted by Frame/Content were produced at above-chance levels (labial-central = 1.32; coronal-front = 1.24). Results converge with Davis et al. (2005) and McCaffrey et al. (1999), suggesting little difference in CV production patterns based on the inclusion or exclusion of concurrent babbling in the early word period.

Davis et al. (2004) conducted a study of early vocal development in young CI recipients. They collected two baseline and monthly 1-hour recordings in a home or clinical intervention setting. All children received their first implant device between 12 and 28 months of age (M 18.7, SD 7.96). Within the first 6 months of implantation, the children produced few CV sequences. After 6 to 8 months of auditory experience with a CI, CV co-occurrence ratios resembled those previously reported for normal hearing children across languages. Converging evidence across different sites, investigators, participants, and implant devices suggested the emergence of early speech behaviors resembles those of normal hearing children post CI.

Overall, labial-central and coronal-front co-occurrences were present at levels above chance across studies, a pattern similar to hearing infants. These patterns existed regardless if analyses included babbling and words (Davis et al., 2005; McCaffrey et al., 1999) or only words (Warner-Czyz et al., 2005c). Finely grained session-by-session analyses detailed the emergence of CV alternations both before and after amplification in the Davis and McCaffrey studies. However, Davis et al. reported data from a child with mild hearing loss who did not receive a CI. Since previous research has described differences in speech production ability in children wearing hearing instruments versus CI, the developmental trajectory might differ between the two groups.

Intersyllabic sequences. Very few studies have explored how infants with hearing loss incorporate intersyllabic sequences in early speech. Davis, McCaffrey and colleagues have examined reduplication and variegation patterns of 4 children with hearing loss ranging from mild to profound degree (Davis et al., 2005; McCaffrey et al., 1999).

The three children examined by Davis et al. (2005) showed different intersyllabic speech patterns. The child with mild hearing loss used total reduplication most frequently at the beginning of utterances (78%). Variegations typically involved changes in the vowel (81%) chiefly in the height dimension. Consonant variegation was infrequent, but when it happened, it occurred in the manner dimension. Both the child whose hearing loss progressed from moderate to profound and the child with profound hearing loss exhibited total reduplication of consonants and vowels throughout the study.

The young CI recipient studied by McCaffrey et al. (1999) exhibited consonant reduplication for place (44%) over manner (25%). Reduplications typically involved labial, stop or nasal consonants. Variegations followed "fronting" patterns (e.g., LC, LD, CD), just like hearing infants. Vowel variegation increased over time from 0% pre-implant to 48% at 9 months post-implant. Total variegation of both consonant and vowel characteristics (e.g., [badi]) remained consistent at 20-30% over the course of the study.

Both studies found a prominence of reduplication in early sessions that gradually decreased. Vowel variegation typically occurred earlier and more frequently than consonant variegation. Variegations for either type of segment tended to involve changes in the vertical dimension (i.e., vowel height, consonant manner), consistent with data on hearing infants and the Variegation hypothesis of the Frame/Content theory (MacNeilage & Davis, 1990). Nevertheless, more research on the relation between consonants and vowels across syllables is needed because these studies emphasized the periodic development of only a few children, only one of whom uses a CI.

Overall, children with hearing loss produce more visible consonants (i.e. labials) than less visible ones (i.e. coronals and dorsals). They use a limited vowel inventory and reduced vowel space, producing mostly neutralized vowel qualities prior to amplification. Segmental inventories expand with auditory experience. CV co-occurrence patterns, when syllable vocalizations are present, tend to conform to the Frame-Content hypothesis (MacNeilage & Davis, 1990; MacNeilage & Davis, 1993). Intersyllabic sequences reflect predominant use of reduplication for entire syllables and also for consonant and vowel types. When these children variegate, they vary the amplitude of the mandibular cycle (consonant manner, vowel height). Serial organization in children with hearing loss appears to mirror that of hearing infants at similar developmental stages.

These studies have described consistent patterns with respect to segmental inventories and serial ordering patterns. However, they typically included a diverse range of ages (Osberger et al., 1991; Tye-Murray & Kirk, 1993), a small number of participants (Ertmer, 2001; Ertmer & Mellon, 2001; Hesketh et al., 1991; McCaffrey et al., 1999; Robinshaw, 1996; Warner-Czyz et al., 2005c), or participants without CI devices (Davis et al., 2005; von Hapsburg, 2003). Even when CI users serve as participants, the vocal development level (i.e., canonical babbling vs. early words) of the children is not always reported (Blamey, Barry, & Jacq, 2001; Ertmer, 2001; Ertmer & Mellon, 2001; Hesketh et al., 1991; Osberger et al., 1991), which decreases the opportunity to compare results with typically developing hearing infants. Finally, most have entailed longitudinal data collection, but sampling intervals exceeded 6 months in all but four studies (Davis et al., 2005; Ertmer, 2001; Ertmer & Mellon, 2001; McCaffrey et al., 1999).

Phonetic repertoire and serial ordering patterns of larger samples of children with CI devices should be investigated at regular intervals (i.e., less than every 3 months) longitudinally particularly because of the high variability often associated with this population (Kirk, 2000). Additionally, investigations should compare the child's output with their intended lexical target to determine correct and incorrect production patterns.

Development of accuracy in first words in children with CI

Investigations of segmental inventories and serial ordering patterns have detailed the production propensities of young children with CI, but do not compare the child's production with the intended lexical target. The ability to explore phonetic accuracy begins with the onset of first words when output is intelligible enough for analysis of target characteristics, correct productions, and error patterns. Blamey (Blamey, Barry, and Jacq, 2001; Blamey, Barry, Bow et al., 2001; Serry & Blamey, 1999), Ertmer (Ertmer, Kirk, Sehgal, Riley & Osberger, 1997), Tye-Murray (Tye-Murray & Kirk, 1993; Tye-Murray et al., 1995) and Warner-Czyz, Davis, & Morrison (2005b, 2005c) have studied of the acquisition of accuracy of segmental properties and intrasyllabic patterns in young CI recipients. At present, accuracy of intersyllabic reduplication and variegation patterns has not been examined in children with hearing loss.

Segmental Characteristics

As in hearing children, young CI recipients require production experience prior to achieving phonetic accuracy (Blamey, Barry, Bow et al., 2001; Blamey, Barry, & Jacq, 2001; Ferguson & Farwell, 1975; Warner-Czyz et al., 2005b, 2005c). Early segmental forms consist mainly of labial consonants and central vowels. Not surprisingly, these phonetic categories represent the most accurately produced phonetic segments in early words in young CI users (Tobey et al., 1994; Tye-Murray & Kirk, 1993; Tye-Murray et al., 1995; Warner-Czyz et al., 2005c). Error patterns have received less attention, but Tye-Murray & Kirk's (1993) vowel study suggests a tendency to either omit vocalic segments or replace them with a central vowel. Target characteristics have been the least studied of segmental characteristics in the pediatric CI population (except see Warner-Czyz et al., 2005c).

Blamey, Barry, and Jacq (2001) examined inventory development of 9 children learning Australian English who received CI before 5 years of age. They looked at two production measures: (a) production propensities, which required two phonetically recognizable productions of a phone in spontaneous speech; and (b) accuracy criterion, which required at least two correct productions of the phone in recognizable words and 50 percent accuracy. Results from conversational samples collected annually over 6 years suggested that the children could physically produce a phone (i.e., production propensities) before integrating it into a meaningful linguistic context (i.e., accuracy). This pattern held true for monophthongs, diphthongs, consonants, and consonant clusters, mirroring findings of Ferguson and Farwell (1975) that phonetic segments emerge in a child's inventory prior to the attachment of a sound-meaning relationship in early words.

A subsequent study by Blamey, Barry, Bow et al. (2001) evaluated growth in production accuracy via linear regression analysis and a generalized linear model. The children obtained a mean accuracy score of 92% for monophthongs, 82% for diphthongs and consonants, and 43% for consonant clusters after 6 years of CI experience. Annual rates of improvement differed by phonetic segment with a steeper trajectory for accuracy of consonants and diphthongs (9.9% and 8.9%, respectively) than for consonant clusters and monophthongs (5.8%). These results may indicate general trends in phonetic accuracy, but not specific contexts (i.e., horizontal or vertical dimensions, word position, and serial ordering patterns) in which the children achieved correct productions or produced errors. Analysis of individual data for correct productions via generalized linear model showed typical variability for all measures except diphthongs, in which significant differences existed between the participants.

Warner-Czyz and Moore (2002) also examined change over time in consonant place accuracy in 45 young CI recipients before and after implantation. The children were implanted with either a Nucleus 22 or 24 device before age 12 years (M = 61.82 months, SD = 27.04 months) and grouped according to age at implantation (before 5 years, N = 24; after 5 years, N = 21). Data were collected from annual videotape recordings of a story re-tell task over a 10-year period. Multilevel statistical modeling, which was used to account for child-specific patterns, included CI experience, activation age, linear, and quadratic effects to most closely match the data (r = 1.04). Overall results supported an interaction effect of implant experience and age at implantation on production accuracy in pediatric CI recipients. Although the older children were 10% more accurate than the younger children pre-implant, the younger children improved 1.5 times more quickly than the older children, surpassing the older group's average place accuracy scores by 4 years post-activation. The younger group continued to improve their scores up to 11 years post-implant whereas the older group's asymptote occurred closer to 7 years post-implant. Although this study did not specify *which* place of articulation was most accurate, results suggest that younger CI recipients not only demonstrated better end outcomes, but they reached these outcomes more quickly than the children implanted at ages greater than 5 years.

Tye-Murray et al. (1995) also examined correct consonant productions of 28 CI recipients grouped according to age at implantation: 2-4 years (*N* = 12), 5-8 years (*N* = 9), and 9-15 years (*N* = 7). All participants had at least 24 months of implant experience (*M* = 36 months, *SD* = 13.5 months) although the older group had somewhat less experience (*M* = 29 months) than the younger groups (*M* = 37 and 40 months for the 2-4 and 5-8 year groups, respectively). Labial consonants were produced more accurately (72-81% correct) than less visible consonants (33-47% correct). Central vowels (70%) were more correct than front vowels (50%), back vowels (58%), or diphthongs (54%).

Tobey et al. (1994) studied the speech production skills of 39 children with profound hearing impairment using different types of auditory prostheses (i.e., hearing instruments, tactile aids, CI). Only the data from the CI group (*N* = 13) will be reviewed here. Eleven vowels and 5 diphthongs were evaluated annually using an imitation task, which requires the child to listen carefully before mimicking the model. The children achieved correct productions of back vowels (greater than 90%) more often than diphthongs (approximately 70%) or front vowels (approximately 60%) after 3 years of CI experience. The CI recipients performed best on stop (80%) and nasal (65%) consonants at 3 years post-implant. Consonant place analyses suggested a general trend of greater accuracy for visible sounds like labial consonants (90% correct) over less visible sounds (i.e., 75% dentals, 50% palatals).

Warner-Czyz et al. (2005b) studied the development of consonant and vowel accuracy in a young child whose CI was activated at 25 months (described in McCaffrey et al., 1999). This child increased volubility and attempted more productions in babbling before improving in phonetic accuracy, confirming Blamey, Barry, and Jacq (2001). She best matched labial consonant targets across sessions (range 45-78%). Nasal consonants were most accurate in earlier sessions (76-88%), but stop and glide consonants emerged at 7 and 9 months post-implant (67-72%). However, word position influenced her accuracy patterns, with greater accuracy in initial position than in medial and final positions, similar to the pattern in hearing infants (Shibamoto & Olmstead, 1978). Low front (66%) and mid central vowels (69%) were most accurate pre-implant. She increased her ability to match vowel targets by 9 months post-implant, achieving the correct vowel category at least 50% for high back, high front, low central, low front, mid back, and mid central vowels. Overall vowel accuracy exceeded consonant accuracy for this child, similar to Ertmer (2001). This may correspond to the acoustic highlighting of vowels over consonants as a result of increased intensity, prolonged production (e.g., 300 versus 100 ms), and the steady state quality of vowels (Pickett, 1999).

All of these studies found more correct productions for visible over less visible consonants. Tye-Murray et al. (1995) and Tobey et al. (1994) did not differentiate utterances based on word position or consonant manner. Warner-Czyz and colleagues (2005b) analyzed these dimensions, providing measures that suggest a more comprehensive way to examine phonetic accuracy, but reported results for only a single participant. Although these studies described correct production of consonants, vowels, or both, they addressed neither error patterns nor characteristics of the intended targets.

Tye-Murray and Kirk (1993) explored how error patterns evolved over time in 8 pre-lingually deafened children who received the Nucleus CI. Age at implantation ranged from 3;10 to 7;5 (years;months). Phonetic transcriptions were completed for the first 100 words of each spontaneous speech sample, collected pre-implant and at 6, 12, 18, and 24 (or 36) months post. Omissions decreased over time with a concurrent increase in production of the correct vowel front-back category, particularly for front vowels. Central vowels often served as substitutes for front vowels and diphthongs pre-implant. By 24/36 months, the most common replacement for front vowels was another front vowel, particularly /i/ for /I/. This error pattern might relate to the maximal separation of the first (F1) and second formants (F2) for high front vowels, which translates to a maximally distinct electrode pattern stimulated for this vowel category. The pediatric CI users either omitted vowels or produced mid central vowel substitutions. This pattern diverges from hearing infants, who typically use more vowel substitutions than omissions (Paschall, 1983). After 2 to 3 years of CI experience, the CI users exhibited more substitution patterns, with a greater likelihood of matching at least vowel front-back characteristics.

Comparison of child productions and lexical targets in the early words of young CI recipients suggests that accuracy improves with auditory experience. Tye-Murray and Kirk’s (1993) analysis of error patterns suggests that children are more likely to omit the target sound or substitute with frequently produced segments before gaining accuracy for the vowel front-back dimension. However, this study involved older CI recipients, who might demonstrate different acquisition patterns than their younger counterparts (Warner-Czyz & Moore, 2002). Neither production error patterns for consonants nor segmental target characteristics have been detailed in this population.

There is a dearth of studies concurrently detailing consonants and vowels with respect to target characteristics, correct productions, and error patterns. Present findings describe phonemic accuracy without consideration of word position or the phonetic environment (i.e., intrasyllabic and intersyllabic sequences). Each of these phonetic contexts could influence children’s ability to accurately produce phonetic segments.

Serial Ordering Patterns

Intrasyllabic Sequences. Study of target characteristics, correct productions, and error patterns in attempts at intrasyllabic sequences can help to describe the potential role of rhythmic mandibular oscillations in early words (Davis & MacNeilage, 1995; MacNeilage & Davis, 1990; MacNeilage & Davis, 1993). Due to their change in perceptual status, children who receive CI, form a unique group enabling study of the relative role of intrinsic and extrinsic influences on CV patterns. Similarities in CV co-occurrences between young CI users and hearing children may suggest intrinsic influence of the production system (e.g., rhythmic mandibular oscillations) while differences may support extrinsic effects of differences in auditory access to the speech spectrum.

Warner-Czyz et al. (2005b) compared CV targets to actual productions in one young CI recipient. Accuracy required a correct production of both consonant and vowel components (/ba/ as both the labial-central lexical target and child utterance). Nearly 80% of pre-implant CVs in lexical targets were realized as partial omissions (i.e., singleton vowels) or omissions. The proportion of partial omissions decreased (18%) in the 7-month post-implant session, suggesting a positive effect of auditory experience on her ability to produce a CV in lieu of a singleton vowel. In later sessions, labial-central syllables were produced most correctly with 57-58% CV accuracy and 79-84% CV category accuracy (i.e., producing a labial-central CV but not necessarily the correct one). All other CV syllables were produced correctly less than 50%.

A subsequent study by Warner-Czyz et al. (2005c) explored intrasyllabic CV accuracy in 5 pediatric CI users across the first word period. Although the participants attempted more diverse CV sequences (55%), they produced (59%) and matched (68%) sequences based on articulatory compatibility more often than sequences requiring additional tongue movement. Labial-central co-occurrences (81%) were the most accurate CV sequence overall. The diversity in targets implies that young CI recipients learn from ambient language patterns from the auditory system, but use production system propensities as a means to bootstrap to intelligible speech in early words.

The most accurate intrasyllabic CV patterns in both studies were sequences predicted by Frame/Content as a general production system foundation of early canonical syllables once the child has auditory access to the speech spectrum (Davis & MacNeilage, 1995; MacNeilage & Davis, 1990; MacNeilage & Davis, 1993). These studies consider target characteristics and accuracy of CV sequences, but do not describe the full range of error patterns over the course of development. Particularly in hearing-impaired children, who tend to produce more omissions and substitutions, analysis of error patterns should help to determine if co-occurrences predicted from frame dominance are produced more frequently as substitutions for other CV pairings.

Some studies of young CI users have begun to analyze the connection between vocal output and lexical targets via measures of production accuracy. Young CI recipients generally match labial, stop and nasal consonant characteristics best. Vowel accuracy precedes consonant accuracy, particularly for mid and central vowel qualities. The most frequently produced intrasyllabic CV sequences also tend to be the most accurate. However, these investigations often involve few participants (Ertmer, 2001;

Ertmer & Mellon, 2001; McCaffrey et al., 1999; Warner-Czyz et al., 2005b) and children with diverse etiologies of deafness (Blamey, Barry, and Jacq, 2001), age at implantation (Tye-Murray et al., 1995), and CI experience (Tye-Murray & Kirk, 1993). Studies with more participants do not consider phonetic context (Blamey, Barry, and Jacq, 2001; Blamey, Barry, Bow et al., 2001; Serry & Blamey, 1999; Tye-Murray & Kirk, 1993; Tye-Murray et al., 1995), and/or employ statistical analyses that may not approximate the course of developmental growth over time (Blamey, Barry, & Jacq, 2001; Blamey, Barry, Bow et al., 2001).

Review of the current literature on acquisition of phonetic accuracy in both hearing infants and young CI recipients has illuminated a few methodological issues regarding data collection, data analysis, and statistical analysis. While some studies gather longitudinal data on a semi-monthly or monthly basis (Davis & MacNeilage, 1990; Davis et al., 2003; Ertmer, 2001; Ertmer & Mellon, 2001; French, 1989; Otomo & Stoel-Gammon, 1992; Shibamoto & Olmsted, 1978), others report results at 6-month or 12-month time periods (Blamey, Barry, & Jacq, 2001; Blamey, Barry, Bow et al., 2001; Osberger et al., 1991; Tye-Murray & Kirk, 1993; Warner-Czyz & Moore, 2002) or at irregular intervals (Warner-Czyz et al., 2005b, 2005c). In pediatric populations, changes in speech output can occur relatively quickly (Prather, Hedrick, & Kern, 1975). Extending the intervals at which data are collected might overlook subtle differences in production accuracy or production error characteristics as they emerge over time. Therefore, data should be collected on a regular, more frequent basis than every 6 months, particularly for young CI users.

In addition to the issue of data collection schedules, present measures utilized to assess production accuracy and errors might not offer a complete picture of the developmental process. They often disregard the phonetic context such as word position, intrasyllabic, or intersyllabic sequences. Very few studies have considered the phonetic environments in which consonants and vowels are produced in either hearing (Davis & MacNeilage, 1990; Davis et al., 2003; Shibamoto & Olmsted, 1978) or hearing-impaired infants (McCaffrey et al., 1999; Warner-Czyz et al., 2005b, 2005c). This lack of specificity of the phonetic context is surprising since studies have shown that hearing children achieve more correct productions of initial segments than medial or final segments (Davis & MacNeilage, 1990; Shibamoto & Olmsted, 1978; Warner-Czyz et al., 2005b), more correct productions of predicted than non-predicted CV co-occurrences (Davis & MacNeilage, 1990; Davis et al., 2003; Warner-Czyz et al., 2005b, 2005c), and more frequent substitutions using the predicted CV co-occurrences than other combinations (Davis et al., 2003). Phonetic environment must be considered to achieve an adequate developmental account of production accuracy in early words.

Error patterns are related to the measures of production accuracy. Several studies have described substitution and omission patterns as phonological processes (Menn, 1971; Ingram, 1976), but few have directly tied the trends in errors to the improvements in phonetic accuracy across time (French, 1989; Otomo & Stoel-Gammon, 1983; Tye-Murray & Kirk, 1993). Connecting these two measures in a single study will allow a more straightforward definition of *how* infants acquire phonetic precision relative to lexical targets using favored production patterns and lexical target characteristics in the early word period. In conclusion, regular and frequent data collection, consideration of phonetic environment, and influence of auditory status to adequately depict the developmental process of production accuracy in early words.

Nature of Development

Development is defined as the study of changes in behavioral and physical growth correlated with age. Such changes have been described routinely using discontinuous rather than continuous measures (Howe & Rabinowitz, 1991; Howe & Rabinowitz, 1994; Port & van Gelder, 1995; Sternberg & Okagaki, 1989; Thelen & Smith, 1994). Researchers focusing on discontinuous change support the existence of developmental "stages," or the step-like acquisition of behaviors over time (Cole, 1999; Lamb, Bornstein, & Teti, 2002; Oller, 1980; Stark, 1980). These "stages" reflect stable interactions between the child and environment that result in robust behaviors across infants. In contrast, focus on developmental continuity emphasizes transitions between these "stages" (Baumrind, 1989; Ford & Lerner, 1992; Port & van Gelder, 1995;

Sternberg & Okagaki, 1989; Thelen & Smith, 1994; Turkewitz & Devenny, 1993). Examining shifts in behavior over time may better explain changes in components leading to specific behavioral milestones. To accurately describe developmental change over time, descriptions of speech acquisition should depict both developmental "stages" and the patterns of change from one stage to another (Smith & Thelen, 1993; Thelen & Smith, 1994; van Gelder & Port, 1995).

Koopmans van Beinum and van der Stelt's (1986) cross-sectional investigation of early phonatory and articulatory development across the first year of life typifies the study of stage-like developmental patterns. Early vocal behaviors as reported by parents for 69 infants between 6 and 52 weeks of age were classified into 6 developmental stages: uninterrupted phonation, interrupted phonation, one articulatory movement, phonatory variations, chains of reduplicated articulations, and meaningful words. This hierarchical construct of stages in speech acquisition helped delineate developmental milestones in a manner consistent with previous research (Holmgren, Lindblom, Aurelius, Jalling, & Zetterstrom, 1986; Oller, 1980; Stark, 1980) and has been used for comparison in subsequent research (Robb et al., 1994; Roug et al., 1989).

Stage descriptions, like that of Koopsman van Beinum and van der Stelt, concentrate on the average change across individuals for a given attribute to describe the systematic "endpoints" of a behavior. However, stages cannot specify the *process* by which the individuals achieve these endpoints. Thelen and Smith's body of research challenges stage-like descriptions by exploring interim patterns to inform how infants attain developmental milestones (Smith & Katz, 1996; Smith & Thelen, 1994; Thelen, 1995; Thelen & Smith, 1994). Thelen (1986; Thelen & Ulrich, 1991) proposed that infants possess some of the components necessary to achieve upright locomotion (i.e., coordinated alternating stepping patterns, separate flexion of the hip and knee) earlier than the stage-like milestone at 1 year, but are limited by other factors (i.e., lack of adequate postural control and leg strength). That is, postural control and leg strength impede the infant's ability to walk independently. When supported upright via a harness to eliminate dependence on postural control and leg strength, seven-month-old infants perform regular, alternating stepping on a small, motorized treadmill. Their rate of development was limited by the biomechanical control and strength necessary to maintain stability on one leg while moving another, demonstrating the importance of dynamic interdependence of input components in the development of behaviors.

A stage perspective might view only the end results from Thelen and Ulrich, which would suggest a discontinuity in skill acquisition since children do not walk independently at 7 months but can do so at 12 months. However, some aspects of upright locomotion are present early; just the relative contributions of these skills change over time. Consideration of the context-dependent nature of development suggests that infants *are* capable of performing this milestone if given the appropriate environment. That is, a specific context (i.e., supported on a treadmill) promotes successful "walking" based on the child's current abilities whereas the traditional environment (i.e., no support on a motionless surface) encumbers walking patterns. In this sense, walking independently is not a dichotomous action but a continuous transition over time (Clark, 1997; Smith & Thelen, 1993; Thelen & Smith, 1994; van Gelder & Port, 1995).

Thelen's work suggests that infants may use the resources available to the system (e.g., alternating stepping patterns, individual control of hip and knee flexion, postural control, leg strength) to transition between "stages" to achieve higher levels of function (e.g., Clark, 1997; Gibson & Pick, 2000; Smith & Katz, 1996; Thelen & Smith, 1994). The notion that infants explore their available intrinsic and extrinsic capacities to produce more complex behaviors over time might aptly describe the interaction of perceptual input and production constraints on the acquisition of early word accuracy. Previous research has suggested that children are more accurate both on the most commonly produced sounds and sequences (Davis et al., 2003; Warner-Czyz et al., 2005b, 2005c) and the most common patterns in the ambient language (Storkel, 2001). How these two tendencies combine in hearing infants and in young CI recipients during the single word period has not yet been tested.

Collection of data at intermediate time points pooled across participants can help define the average trend on a particular behavioral measure. Plotting a mean path can provide points of comparison for rates of acquisition based on the average participant. However, examining only the mean trajectory does not consider the impact of *inter-individual (individual) differences* that compare states in different persons on the same variables (Baumrind, 1989; Fenson, Dale, Reznick, Bates, Thal, & Pethick, 1994; Ford & Lerner, 1992; Giani, Filosa, & Causa, 1996; Leonard et al., 1982; Port & van Gelder, 1995; Sternberg & Okagaki, 1989; Thelen & Smith, 1994; Turkewitz & Devenny, 1993). Additionally, "true" developmental change, as defined by Ford and Lerner (1992), results from *intra-individual differences,* assessed by comparing states of an individual on the same variables on successive occasions, rather than occurring as step-like stages or individual differences (Baumrind, 1989; Ford & Lerner, 1992; Giani et al., 1996; Leonard et al., 1982; Port & van Gelder, 1995; Turkewitz & Devenny, 1993), Individual paths of different children persist over time, do not correlate to pathological events, and envelop the growth process of a particular individual (Ford and Lerner, 1992; Stern, 1998; Vaal, van Soest, & Hopkins, 2000). Statistical models must accommodate within-participant trends and differences to accurately depict how development unfolds over time.

Incorporating "partial successes," like the ability of very young infants to walk when on a treadmill (Thelen & Ulrich, 1991) can describe the nature of development. It has implications for evaluation of phonetic accuracy in the early word period. Can we detail patterns of change based on changes in the levels of accuracy and error patterns over time? Do they correctly produce horizontal characteristics (i.e., consonant place, vowel front-back) before vertical characteristics (i.e., consonant manner, vowel height)? Do substitution and omission patterns differ for consonants and vowels? These questions require a more thorough longitudinal examination of target characteristics, correct productions, and error dispersion over time than has been done before in order to better describe accurately patterns of change over time.

Stage theories have provided information about the sequence, but not the process of development. Often, the process is not linear. If development evolves as a nonlinear process with periods of acceleration and deceleration, then linear statistical methods such as linear regression analysis might not accurately capture the estimation of growth.

Rather, non-linear statistical methods such as growth curve modeling (Bryk & Raudenbush, 1992; Hox, 1995; Singer, 1998) and the general estimating equation (Liang & Zeger, 1986; Zeger & Liang, 1986) may better match the nonlinear aspects of developmental growth. Also, significant individual differences may require the addition of multilevel modeling (Bryk & Raudenbush, 1992) that allows the examination of both general trends and individual differences over time.

Theoretical frameworks also should incorporate nonlinearity and individual differences as they occur across the developmental process. Embodiment perspectives support the importance of context and use (Clark, 1997; Davis & MacNeilage, 2002) as a foundation for early developmental patterns. In contrast, linguistic theorists (Chomsky & Halle, 1968; Jakobson, 1968) assert universality of speech acquisition patterns with little importance attached to the acquisition process or individual differences.

In addition to exploring the general developmental trajectory of correct productions in early words, examination of change in error patterns over time may inform the influence of production and perception on vocal communication patterns. If children with hearing loss possess input systems similar to hearing infants, then they should include the intact production, visual, and kinesthetic systems with a restricted auditory system. Although Higgins et al. (1996) and Chin (2002) documented aberrant speech production patterns in *older* pediatric CI users, these patterns may relate to attempts to create feedback through the kinesthetic system as a replacement for auditory feedback cues. The role of these production patterns as a foundation of early vocal acquisition in very young children with profound hearing impairment who receive CI should be understood more precisely. Overall, developmental perspectives, including dynamic systems theory, provide a means by which to evaluate skill acquisition based on intrinsic and extrinsic sources, nonlinearity, and context-dependence.

Purpose and Research Questions

Production system and auditory perceptual factors have been shown to impact early speech patterns, but their effect on early phonetic accuracy has not been explicitly evaluated. The most frequently produced segments and sequences are generally most accurate, suggesting the impact of production propensities on speech accuracy in the single word period. Vocal patterns of children with hearing loss differ from hearing children but may converge once they gain auditory access to the speech signal, supporting the influence of audition on early word accuracy. Children acquire accuracy much like any other developmental process, with different levels of improvement over time. However, no study to date has simultaneously explored correct productions and error patterns of segmental inventories and serial patterns to obtain a complete picture of early phonetic accuracy. This work aimed to define more clearly the impact of production propensities and auditory perception in early speech accuracy as a function of time.

Production and auditory perceptual effects on development of phonetic accuracy were explored in the first six months of the single-word period. Accuracy was used as a metric to examine (a) two groups differing in auditory history; and (b) change over time, as shown by trends in correct productions and error patterns from early to later sessions.

Group

The development of phonetic accuracy in early words was evaluated in two populations differing in auditory background (i.e., hearing infants and young CI recipients) to allow clarification of the effect of auditory perceptual input. Auditory deficits often lead to reduced vocalization output with limited consonant and vowel inventories. Segments are typically single-appearing rather than combined in sequences like hearing infants. CI devices afford consistent auditory access to the speech spectrum, providing an impetus toward expansion of segmental repertoires and emergence of sequential patterns more consistent with those of hearing infants.

How well and how quickly young CI recipients integrate their expanded speech patterns to attain phonetic accuracy relative to hearing infants could follow one of three trajectories. Longitudinal changes may reflect a “thawing period” (Eggermont et al., 1997; Ponton et al., 1999) such that once the system receives auditory stimulation, phonetic accuracy proceeds at the same rate as in hearing individuals. Similar acquisition and error patterns between the two groups with differing auditory histories would indicate the production system as integral to developing early speech accuracy.

Developmental trajectories may mirror the findings of Gillis et al. (2002), who found an accelerated onset in the babbling of very young CI recipients compared to hearing infants with similar auditory experience. Results supporting this view would show higher accuracy scores for the CI group, particularly in early sessions, due to older chronological ages than the NH group.

Results may indicate lower accuracy scores and/or maladaptive production patterns (Chin, 2002; Higgins et al., 1996). Such output patterns would suggest that provision of auditory experience via CI devices may lead to improved vocal acquisition, but not necessarily typical speech development.

Time

Early phonetic accuracy provides comparison of behaviors at different times. Whereas accurate productions yield stage-like milestones for accuracy, exploration of substitution and omission error patterns may better inform the process by which accurate and stable speech patterns emerge across time.

Children improve their ability to match adult word targets over time. Thus, it is expected that both the hearing and the CI groups will increase segmental and sequential accuracy. However, the process by which the two groups achieve accuracy may differ. Attempts at consonant targets tend to shift from omissions, particularly in final position, to correct productions. Hearing children often use substitutions as a transition to accurate vowel productions, but older CI recipients instead have used omissions. Few studies have examined longitudinally the role of context (i.e., word position, sequences within and across syllables) on phonetic accuracy, although limited results suggest greater accuracy in initial position and for sequences with articulatory compatibility.

This study will detail phonetic accuracy and error patterns in early words over the single word developmental period in two groups of children differing in hearing history. The following research questions will be addressed:

1. What is the effect of auditory perceptual access on early speech accuracy?
2. What is the effect of change over time on early speech accuracy and types of error patterns?

Chapter 2
Method

Participants

Participants with Hearing Sensitivity within Normal Limits (NH)

Data from 4 typically developing hearing infants (NH) who participated in a larger study of early speech acquisition (Davis & MacNeilage, 1995) were analyzed for comparison with the CI participants. All 4 NH children were at the single word developmental stage, matching the vocal development age of the CI group. This stage occurred at approximately 11 to 13 months chronological age in these NH children.

Participants with Profound Hearing Impairment (CI)

Four infants with severe-profound hearing impairment (pure-tone threshold average in the range 71-110 dB HL) who had received cochlear implants (CI) participated. Description of the type and severity of hearing loss was obtained from each child's case history and medical records available from parents and educational personnel. All participants had hearing parents who use an oral communication mode. Audiological data for the CI children are displayed in Table 1.

The CI group had full insertion of their devices and at least 6 months experience with the cochlear implant before data collection began. Participation was not limited based on type of device or speech processing strategy because previous studies have found no evidence of differences in speech development based on cochlear implant device (e. g. Davis et al., 2004). Table 2 describes the CI devices used by the participants. The average age at implantation was 16 months (*SD* = 4.2 months). Chronological ages ranged from 18 to 31 months at the onset of data collection. The CI infants were located by referral from professionals in The Callier Center at The University of Texas at Dallas and The University of Texas at Austin.

Table 1

Audiological Data

Child	Condition	Ear	Speech	Frequency (Hz)						
				250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz
CI1	Unaided	SF	NR 85	NR 95	NR 105	NR 105	NR 105		NR 115	NR 110
	Aided	SF	NR 85	NR 95	NR 105	NR 105	NR 105		NR 115	NR 110
	Implanted (6 months)	R		30		35			45	
	Implanted (12 months)	R				35			45	
CI2	Auditory Brainstem Response	L			NR	NR	NR		NR	NR
	Unimplanted	L	NR		NR	NR	NR		NR	NR
	Implanted (6 months)	L	SDT 25		35	35	35	35	30	
	Implanted (12 months)	L	SDT 25		30	30	25		30	
CI3	Auditory Brainstem Response	R			NR 92	NR 92			NR (CLICK)	
	Unimplanted	R	NR	NR	NR	85	NR		NR	
	Implanted (6 months)	R	30	45	40	35	40	40	40	40
	Implanted (12 months)	R	30	35	35	30	25	35	35	40
CI4	Auditory Brainstem Response	R L			NR		NR		NR (CLICK)	
	Unimplanted									
	Implanted (6 months)	L	20	35	30	30	30	35	30	35
	Implanted (12 months)	L		30	30	30	35		30	

Table 2

Description of CI Devices

	Cochlear implant system specifications							
Pt.	Manu-facturer	Internal array	Active electrodes	External process.	Dynamic range	Stim. mode	Process. strategy	Speech process.
CI1	MedEl	Combi 40+	12	Combi 40+	M=20	Mono-polar	CIS+	TEMPO
CI2	Cochlear	Nucleus 24 Contour	8	Sprint (Body)	M = 30	MP1+2	ACE	ADRO
CI3	MedEl	Combi 40+	12	Combi 40+	M=20	Mono-polar	CIS+	TEMPO
CI4	MedEl	Combi 40+	12	Combi 40+	M=20	Mono-polar	CIS+	TEMPO

Cognitive, Visual, and Developmental History

Infants with mild-to-moderate cognitive or motor disabilities were included in the CI group since many infants with hearing impairment have some degree of motor or cognitive involvement (Yoshinaga-Itano & Apuzzo, 1998). These mild conditions do not affect vocalization output significantly. Infants with suspected severe levels of motor, cognitive, or visual disabilities, as determined by medical records, were excluded from participation due to the likelihood of significantly affecting vocalization output (Yoshinaga-Itano & Apuzzo, 1998).

Data Collection

Recording Procedures

Data was collected monthly in 1-hour recording sessions for 6 months following the onset of meaningful words. Word onset was established when both the parent and observer agreed on the use of one to three phonetic forms in a clearly recognized communicative context (e.g. /ba/ while requesting a ball). An observer was always present during recording sessions and interacted with the parent and child in a natural manner. Recordings were made of ordinary household activities and play routines between parent and child.

Vocalizations were recorded using a Canon XL1 digital camcorder with an Audio Technica FM wireless omni-directional microphone clipped to the child’s shoulder to maintain a relatively consistent mouth-to-microphone distance. The FM transmitter was placed in a pouch secured at the child's waist. Sessions were also videotaped to disambiguate intent and content of productions during transcription. Data collections schedules for the CI and NH children are shown in Tables 3 and 4, respectively.

Table 3

Participant Characteristics for the CI children

Participant	Gender	Age at CI activation	Session	Chronological age	Hearing age (CI experience)
CI1	M	1 y 10 m 13 d	1	2 y, 7 m, 26 d	0 y, 9 m, 12 d
			2	2 y, 9 m, 7 d	0 y, 10 m, 24 d
			3	2 y, 10 m, 6 d	0 y, 11 m, 23 d
			4	2 y, 11 m, 26 d	1 y, 1 m, 12 d
			5	3 y, 0 m, 23 d	1 y, 2 m, 10 d
CI2	F	0 y 11 m 22 d	1	1 y, 6 m, 4 d	0 y, 6 m, 13 d
			2	1 y, 6 m, 24 d	0 y, 7 m, 5 d
			3	1 y, 7 m, 27 d	0 y, 8 m, 5 d
			4	1 y, 8 m, 24 d	0 y, 9 m, 3 d
			5	1 y, 9 m, 21 d	0 y, 9 m, 30 d
			6	1 y, 10 m, 26 d	0 y, 11 m, 5 d
CI3	M	1 y 5 m 19 d	1	2 y, 4 m, 16 d	0 y, 10 m, 27 d
			2	2 y, 5 m, 13 d	0 y, 11 m, 24 d
			3	2 y, 6 m, 0 d	1 y, 0 m, 11 d
			4	2 y, 8 m, 13 d	1 y, 2 m, 24 d
			5	2 y, 9 m, 19 d	1 y, 3 m, 30 d
			6	2 y, 10 m, 21 d	1 y, 5 m, 2 d
CI4	F	1 y 0 m 26 d	1	1 y, 8 m, 2 d	0 y, 7 m, 6 d
			2	1 y, 10 m, 6 d	0 y, 9 m, 10 d
			3	1 y, 10 m, 17 d	0 y, 9 m, 21 d
			4	1 y, 11 m, 10 d	0 y, 10 m, 14 d
			5	2 y, 0 m, 12 d	0 y, 11 m, 16 d
			6	2 y, 1 m, 3 d	1 y, 0 m, 7 d

Table 4

Participant Characteristics for the NH Children

Participant	Gender	Session	Chronological Age
NH1	F	1	0 y, 8 m, 27 d
		2	0 y, 10 m, 2 d
		3	0 y, 10 m, 29 d
		4	0 y, 11 m, 26 d
		5	1 y, 0 m, 23 d
NH2	M	1	1 y, 3 m, 21 d
		2	1 y, 5 m, 2 d
		3	1 y, 6 m, 2 d
		4	1 y, 6 m, 29 d
		5	1 y, 8 m, 1 d
		6	1 y, 9 m, 7 d
NH3	M	1	1 y, 5 m, 9 d
		2	1 y, 6 m, 6 d
		3	1 y, 7 m, 5 d
		4	1 y, 7 m, 25 d
		5	1 y, 8 m, 22 d
		6	1 y, 9 m, 25 d
NH4	F	1	1 y, 0 m, 2 d
		2	1 y, 1 m, 9 d
		3	1 y, 2 m, 2 d
		4	1 y, 3 m, 6 d
		5	1 y, 4 m, 24 d

Transcription Procedures

The author coded all word tokens occurring during the sessions using the International Phonetic Alphabet (IPA) system of notation via broad transcription methods. Utterances were classified as word attempts if the parent and observer agreed that the child exhibited a consistent sound-meaning correspondence, not necessarily corresponding to the adult form. As in Jasuta (1987) and Davis et al. (2002), a word was counted as established when used spontaneously on two different occasions. Onomatopoeic forms without CV structure, vegetative, and reflexive sounds were excluded from analysis.

Utterances. All vocalizations were transcribed according to the following method: A canonical syllable consisted of a sequencing of a closant or consonant-like sound followed by a vowel-like sound or vice versa (i.e., CV or VC) (Oller, 2000). Precanonical utterances referred to utterances with perceptually vowel-like or consonant-like qualities that did not meet the criteria for a syllable (i.e., singleton consonants (C) or singleton vowels (V)) (Oller, 2000). Reflexive vocalizations were not analyzed. Analyses included only vocalizations corresponding to a word target.

Transcription Agreement. Two transcribers familiar with infant vocalizations analyzed data from the primary transcriber for reliability. Ten percent of each infant's tokens were re-transcribed. Reliability was calculated as percentage agreement between the first and second transcriptions for (a) consonant place and manner, and (b) vowel height and front-back. Consonant reliability was 79% for place and 84% for manner. Vowel reliability was 57% for height and 76% for front-back. Reliability was consistent across groups except for vowel height, in which transcription reliability for the NH group (63%) exceeded that of the CI group (51%).

Data Analysis

Transcribed data was analyzed using the Logical International Phonetics Program (LIPP, Oller and Delgado, 1990). The LIPP analysis included transcribable utterances that corresponded to lexical targets. To provide a baseline measurement, inventories for segments and sequences were developed for the two groups.

Segmental Analysis

Phonetic inventories, describing types and frequencies of consonant and vowel phones, were developed for each infant. Descriptions of consonant place and manner categories are shown in Appendix A. Voicing distinctions were not analyzed due to lack of evidence of accuracy differences in voiced or voiceless consonants (Dillon, Cleary, Pisoni, & Carter, 2004; Dawson et al., 1995; Sehgal, Kirk, Svirsky, Ertmer, & Osberger, 1998). Vowel front-back and height dimensions are described in Appendix B.

Sequential Analysis

Sequential analysis involves analysis of both intrasyllabic organization (i.e., CV co-occurrences) and intersyllabic organization (i.e., consonant and vowel reduplication and variegation patterns). Intrasyllabic effects were explored through analysis of CV and VC co-occurrence patterns in which consonant and vowel sequences were characterized according to Appendices A and B. Consonants were categorized based on place of articulation (i.e., labial, coronal, dorsal) and vowels were grouped according to the front-back continuum (i.e., front, central, back). Phones not commonly heard in American English were transcribed with the appropriate IPA symbol. A χ^2 analysis was employed to compare observed to expected frequencies for each of the 9 potential patterns, based on predictions of the Frame/Content theory (MacNeilage & Davis, 1990; MacNeilage & Davis, 1993). Frame/Content predictions are intrasyllabic CV co-occurrences based on articulatory compatibility, including labial-central, coronal-front, and dorsal-back patterns for CV and central-labial, front-coronal, and back-dorsal patterns for VC. Intersyllabic sequences were analyzed as reduplication and variegation of both consonants and vowels. The phonetic segments were categorized according to (a) the *horizontal* dimension, the anterior-posterior tongue position (i.e., consonant place, vowel front-back); and (b) the *vertical* dimension, or tongue/jaw amplitude (i.e., consonant manner, vowel height). Voicing characteristics were not considered due to the limits of phonetic transcription when applied to infant vocalizations (Vihman & McCune, 1994).

Production – Lexical Function

The emergence of developmental trajectories during the first 6 months of the first word period was evaluated via accuracy analyses based on the transcribed data for both groups. Accuracy analyses compared the children's productions to lexical targets for consonants and vowels. A *correct production* described a match of *both* horizontal and vertical characteristics without regard for voicing distinctions.

Additionally, phonetic accuracy was analyzed with respect to phonetic environment. This analysis included characterizations of patterns by word position, as well as intrasyllabic co-occurrences and intrasyllabic sequences. Word position was analyzed separately for initial, medial, and final position. Intrasyllabic CV and VC co-occurrences were divided into nine groups based on place of articulation (labial, coronal, dorsal) for consonants and front-back dimension (front, central, back) for vowels. Correct productions of CV targets required a match of both horizontal and vertical dimensions for both consonant and vowel (/ba/ as the labial consonant-central vowel target and /ba/ as the labial consonant-central vowel production). Intersyllabic reduplication and variegation patterns were analyzed for the potential effects of consonant harmony and the influence of production preferences. C1-C2 and V1-V2 sequences were analyzed according to horizontal and vertical dimensions of consonants and vowels.

Percent accuracy was determined by dividing the number of accurate productions by the number of attempts at a particular phonetic segment or intrasyllabic sequence. The percent correct calculations for consonants, vowels, intrasyllabic combinations, and intersyllabic sequences formed the basis for assessing the development of speech production accuracy during the early lexical period at successive time points.

Production – Perception

All transcribed data were compared between the NH and CI groups to assess the interaction of auditory sensory access and behavioral correlates of the production system.

Continuous Nature of Development

Error patterns were examined in conjunction with correct productions to investigate the process of achieving phonetic accuracy. Exploration of error dispersion included partially correct responses (i.e., matching *either* the horizontal or vertical dimension), incorrect productions (i.e., matching no sound characteristics), partial omissions (i.e., omitting one of two segments in a sequence), and omissions.

Statistical Analysis

Due to the repeated measures within subjects and the categorical nature of the outcome, all analytical procedures were performed using SAS PROC GENMOD, explained in more detail below. The ordered categorical dependent variable was level of accuracy for child realizations of segments and sequences corresponding to an identified lexical target. Child realizations were ranked in six levels organized by magnitude of error. They ranged from correct to omission as follows: (a) correct productions, a match of both horizontal and vertical dimensions; (b) correct category, a match of consonant place and vowel front-back but no consonant manner or vowel height in intrasyllabic sequences; (c) partially correct productions, a match of either horizontal or vertical dimensions of segment(s); (d) incorrect productions, a match of syllable shape but neither horizontal nor vertical dimensions; (e) partially omitted realizations, deletion of a segment in a context-dependent sequence to result in singleton consonant or vowel; and (f) omitted, absence of either the segment or the sequence as realized by the child.

Independent variables included (a) hearing level, a comparison of children with hearing sensitivity within normal limits (NH) and those with severe-profound hearing impairment using CI (CI); (b) time, a measure of the degree to which accuracy changed over the course of the study; (c) tongue position, the impact of horizontal or vertical dimension on correct productions; (d) word position, or the effect of initial, medial, or final position on accuracy; and (e) articulatory compatibility, the relationship between segments within and across syllable boundaries. The final variable related to the predictions of the Frame/Content hypothesis.

The statistical significance of differences within and across groups was evaluated using Generalized Estimating Equations (GEE) (Liang & Zeger, 1986; Zeger & Liang, 1986), an extension of Generalized Linear Models. Generalized Linear Models are the foundation of Analysis of Variance and regression statistical methods. It has been adapted for categorical data. The GENMOD procedure in SAS version 9.1.3 (SAS Institute, Inc., Cary, North Carolina) was selected to accommodate repeated measures in an ordered multinomial model. GEE with repeated measures have been used in empirical studies of progressive hearing loss (Santos et al., 2005), treatment effectiveness (Hedrick et al., 2003; Warner et al., 2005), and environmental and ecological survival (Sweeney, Czapka, & Yerkes, 2002; Biro, Post, & Parkinson, 2003).

A cumulative logit model was fit with levels of accuracy as the dependent variable. The analysis produces a likelihood ratio test for each main effect and interaction, with significance values based on the chi-square distribution. Significant effects were further explored using follow-up custom contrasts with Wald chi-square tests. Odds ratios were used to compare the multiplicative increase (or odds) of more accurate responses according to different levels of the independent variables. For example, comparison of VC accuracy for initial versus medial position revealed an odds ratio of 5.7. This means that VC sequences in initial position were 5.7 times more likely to be correct than those in medial position. An odds ratio of 3.5 is considered a moderate effect and an odds ratio of 9.0 is considered a large effect (Hopkins, 2002).

Chapter 3
Results

The research questions in this study focus on comparisons between the CI and NH groups (*group*) and change over time (*time*). Results are organized according to group (i.e., CI vs. NH) and time (i.e., early versus later sessions) for both segmental and serial patterns. In both sections, percentages will be reported as two numbers separated by a forward slash (e.g. 60/75%). In the first section, the first number will represent the CI group and the second number will represent the NH group. For example, 60/75% accuracy means that the CI children achieved 60% correct and the NH children 75% correct on a particular measure.

Inventory, target characteristics, and accuracy results are described within each main section. Consonant and vowel inventories provide information regarding the children's production capacities for elements in the production system. Target characteristics demonstrate the kinds of phonetic patterns the children are attempting. Accuracy for targets illustrates the ways that these two groups of children employ production capacities to achieve lexical accuracy. Simultaneous examination of word targets and child accuracy describes relationships between targets and accuracy.

Group (CI vs. NH)

Both the CI and the NH groups showed common patterns with respect to production propensities, characteristics of word targets attempted, and individual variability across analysis categories. Although the NH group produced sounds and sequences with greater frequency and greater accuracy than the CI group, the only statistically significant difference between the groups occurred in the consonant category.

Consonants

Inventory. The corpus contained 4,485 consonants. There were 2,067 from the CI group (M = 516.80, SD = 303.50) and 2,418 from the NH group (M = 604.50, SD = 245.80). Labial (49/47%) and coronal (35/41%) place dominated both groups. Stops (49/56%) and nasals (35/28%) were the most frequently produced consonant manner. All other place and manner categories occurred less than 10%. Table 5 shows the relationship between inventories, target characteristics, and accuracy for consonants for both groups.

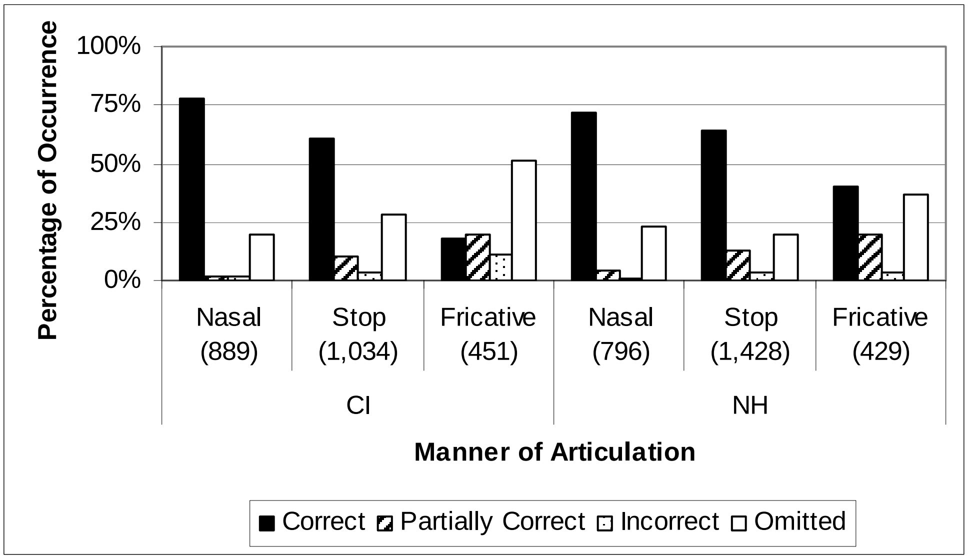
Target characteristics. Participants attempted a total of 5,027 consonants in word targets. The CI and NH groups attempted 2,374 (M = 593.50, SD = 200.77) and 2,653 (M = 663.25, SD = 167.88) consonants, respectively (shown in Table 5). The incidence of consonant targets varied by place, manner, and word position, but was consistent across the two groups. Labial (46/45%) and coronal (37/37%) consonant place of articulation comprised the majority of word targets attempted. Stops (44/54%) were the most frequently attempted manner followed by nasals (37/30%) and fricatives (19/16%). Initial consonants accounted for one-half of all word targets (51/48%) while medial (27/26%) and final (22/26%) consonant targets occurred with equal frequency.

Accuracy. The NH group produced more accurate consonants and less severe errors than the CI group ($\chi^2 = 4.15$, $p < .05$) (Table 5). The NH group matched consonant characteristics 62% and omitted 23% of targets. The CI group achieved 59% accuracy with 29% omissions. Partially correct consonants typically included correct manner (57%) over correct place (43%) across groups. Incorrect consonants rarely occurred.

Consonant manner impacted the level of accuracy ($\chi^2 = 7.00$, $p < .05$). Findings will be reported globally since results were independent of group ($\chi^2 = 2.41$, $p > .10$). Nasal consonants (78/71%) were more likely to be correct than stops and fricatives (odds ratio = 2.9, $\chi^2 = 16.7$, $p < .0001$). Stop accuracy exceeded 60% (61/64%). Fricatives (18/40%) were 6 times more likely to be inaccurate than stops and nasals (odds ratio = 6.3, $\chi^2 = 69.7$, $p < .0001$). As shown in Figure 1, both groups followed similar patterns of accuracy and omissions for manner categories analyzed. However, CI children exhibited more stop and fricative omissions and lower fricative accuracy than NH children.

Figure 1

Accuracy for Consonants by Manner of Articulation

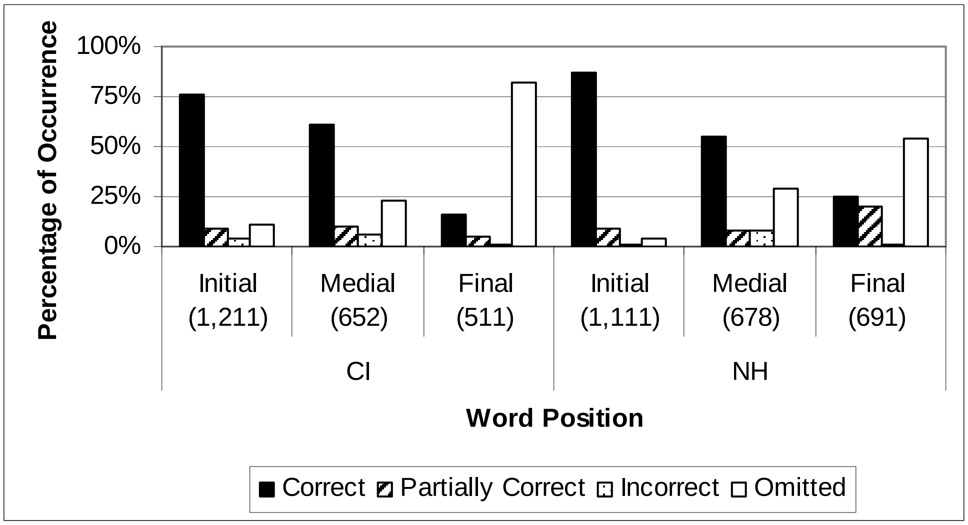


Labial place of articulation was produced with similar rates of accuracy (79/74%) and omissions (16/18%) in the two groups. The NH children produced coronal consonants more accurately (40/57%) and with fewer omissions (44/24%) than the CI children. Overall, participants produced dorsals with lower accuracy (23/24%) and a higher rate of omissions (50/51%). Even though these patterns persisted across groups, consonant place only marginally affected accuracy ($\chi^2 = 7.11$, $p < .10$).

Word position significantly influenced consonant accuracy ($\chi^2 = 7.17$, $p < .05$). Overall scores are reported because patterns for level of accuracy were consistent across groups (see Figure 2 for group-specific percentages). Initial consonants were produced with greatest accuracy (76/87%) and fewest omissions (11/4%). Final consonants occurred with the lowest accuracy (16/25%) and most omissions (82/54%). Medial consonants fell in between with 61/55% accuracy and 23/29% omissions. The most evident difference between the groups occurred in final consonant position. CI children produced fewer correct or partially correct consonants and omitted more final consonants than NH children.

Figure 2

Accuracy for Consonant by Word Position



Overall, the NH group outperformed the CI group on consonant accuracy controlling for manner, place, and word position. The most frequently produced and attempted consonants (i.e., stop, nasal, labial) were also the most accurate across groups. Consonant accuracy in initial position was better than in medial and final positions.

Table 5

Inventory, Targets, and Accuracy for Consonants by Group

Consonant					Levels of Accuracy			
Gp	Dimension	Type	Inventory (N)	Targets (N)	Correct	Partially Correct	Incorrect	Omitted
CI	Manner	Nasal	725	889	78%	1%	2%	20%
		Stop	1,006	1,034	61%	10%	3%	28%
		Fricative	183	451	18%	20%	11%	51%
	Place	Labial	1,019	1,093	79%	5%	2%	16%
		Coronal	724	887	40%	13%	4%	44%
		Dorsal	40	168	23%	22%	3%	50%
		Glottal	284	226	63%	0%	15%	22%
NH	Manner	Nasal	681	796	71%	4%	1%	23%
		Stop	1,351	1,428	64%	13%	3%	20%
		Fricative	147	429	40%	20%	3%	37%
	Place	Labial	1,132	1,201	74%	8%	0%	18%
		Coronal	980	985	57%	15%	4%	24%
		Dorsal	149	340	24%	17%	8%	51%
		Glottal	157	127	98%	0%	0%	2%

Note. Gp = Group.

Vowels

Inventory. Segmental inventories included 4,492 vowels from all participants. The CI (N = 2,469, M = 617.30, SD = 273.63) and NH (N = 2,473, M = 618.30, SD = 224.13) groups produced vowels with almost equal frequency. Mid central (34/29%) and low central (24/23%) vowels were produced with greatest overall frequency by both groups, as shown in Table 6. Central (59/51%) and mid (53/45%) vowel qualities occurred most often in segmental inventories across groups and individual participants.

Target characteristics. Participants attempted 5,456 vowels in word targets across sessions. The CI children attempted 2,670 vowels (M = 667.50, SD = 356.59) compared to 2,786 vowels (M = 678.00, SD = 252.80) by the NH children. Vowel target distribution did not vary considerably across groups. Proportions were balanced between front, central, and back types. Mid (53/42%) vowels were the most commonly attempted vowel height (See Table 6). Members of both groups attempted more vowel targets in medial (64/61%) than final (21/29%) or initial (15/10%) word position.

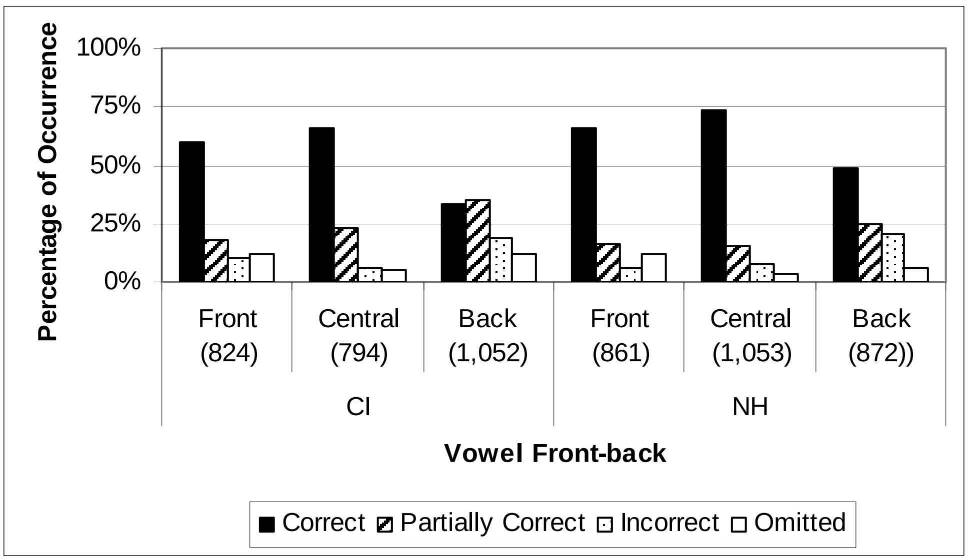
Accuracy. Children across groups mainly produced correct vowels (i.e. matching both front-back and height dimensions) or partially correct vowels (i.e., matching either front-back or height dimensions). Only 12% of vowel attempts in the corpus were incorrect and 8% were omitted. Table 6 details levels of vowel accuracy by group.

The NH children achieved more correct vowels than the CI children (63/51%). The proportion of partially correct (26/19%), incorrect (12/11%), and omitted (10/7%) realizations did not differ between the two groups. The main effect for group was not significant ($\chi^2 = 2.24$, $p > .10$). Participants in both groups demonstrated greater vowel accuracy in medial (80/86%) than initial (45/61%) or final (59/64%) positions. The effect of word position on accuracy approached statistical significance ($\chi^2 = 5.75$, $p < .10$).

Vowel front-back characteristics significantly influenced accuracy rates (χ^2 = 6.89, $p < .05$) (shown in Figure 3). Central vowels were most accurate (66/73%). Front vowels occurred with slightly lower accuracy (60/66%) and more omissions (12/12%). Back vowels occurred with lower accuracy (33/49%) but more partially correct (35/25%) and incorrect (19/21%) productions than central or front vowels. Overall, central vowels were twice as likely to be accurate than either front or back vowels (odds ratio = 1.78, χ^2 = 94.86, $p < .0001$) and front vowels were twice as likely to be more accurate than back vowels (odds ratio = 2.2, $\chi^2 = 94.86$, $p < .0001$). Group marginally affected accuracy in the front-back domain ($\chi^2 = 4.73$, $p < .10$). The NH children were two times more likely than the CI group to match front-back characteristics for back (odds ratio = 2.2, χ^2 = 14.28, $p < .001$) and central (odds ratio = 1.8, $\chi^2 = 7.23$, $p < .001$) vowels.

Figure 3

Front-back Vowel Accuracy by Group



The most frequently attempted vowel height was not the same as the most accurate height. Participants in both groups attempted mid vowels most often, but low vowels were produced more accurately (67/77%) with fewer omissions (3/1%). Mid vowels followed with 45/57% accuracy and 32/27% partial accuracy (i.e., matched height). High vowel accuracy (52/60%) matched that of mid vowels but the children showed more omissions (21/17%).Despite these differences in accuracy, the effect of vowel height did not reach statistical significance ($\chi^2 = 4.51$, $p > .10$).

No group difference was found for vowel accuracy. Both groups matched front-back tongue position, vowel height, or both dimensions in approximately 80% of the time. Participants produced vowels, attempted vowels in word targets, and achieved vowel accuracy more often for central, mid, and low vowels. Back and high vowels were least accurate. High front vowels were omitted most frequently.

Table 6

Inventory, Targets, and Accuracy for Vowels by Group

Group	Vowel Category	Inventory (N)	Targets (N)	Levels of Accuracy			
				Correct	Partially Correct	Incorrect	Omitted
CI	HB	346	297	43%	16%	16%	22%
	MB	206	755	29%	43%	20%	8%
	LC	143	399	65%	27%	5%	3%
	MC	845	395	66%	19%	7%	8%
	HF	603	466	57%	16%	7%	20%
	LF	68	92	73%	20%	5%	2%
	MF	258	266	60%	21%	17%	2%
NH	HB	354	378	52%	8%	28%	11%
	MB	142	494	46%	38%	15%	1%
	LC	200	507	82%	15%	2%	1%
	MC	714	546	66%	17%	12%	5%
	HF	557	455	67%	6%	6%	21%
	LF	242	264	68%	29%	3%	1%
	MF	264	142	61%	25%	11%	3%

Note. HB = High back; MB = Mid back; LC = Low central; MC = Mid central; HF = High front; LF = Low front; and MF = Mid front.

Intrasyllabic CV Sequences

Inventory. The CI group produced 1,038 (M = 259.501, SD = 147.57) and the NH group produced 1,583 (M = 395.75, SD = 123.33) CV syllables for a total of 2,621. The left side of Table 7 displays the number of syllables per participant and the right side shows observed to expected frequencies in each cell. Because the expected value is 1.0, any ratio greater than 1.0 indicates occurrence at above-chance levels. The boldfaced ratios along the diagonal of each of the eight individual tables represent the 24 CV co-occurrences predicted by the Frame/Content theory (i.e. labial-central, coronal-front, dorsal-back). A maximum of 12 predicted sequences (3 predictions for each of 4 participants) and 24 non-predicted sequences could occur for each group. One dorsal analysis was removed from each group (CI1, NH3) due to low number of occurrences.

For the CI group, 6/11 predicted co-occurrences were confirmed versus 9/22 non-predicted associations. For the NH group, 8/11 predicted associations were confirmed versus 5/22 non-predicted co-occurrences. The difference between the relative frequency of above-chance occurrences in predicted and non-predicted co-occurrences was significant for the NH group ($\chi^2 = 4.65$, $p < .05$) but not the CI group ($\chi^2 = 0.30$, $p > .10$).

Table 7

Ratio of Observed to Expected Occurrences of Child CV Productions by Group

		Consonants		
Participant	Vowels	Coronal	Labial	Dorsal
CI1	Front	**0.71**	1.10	-
N = 156	Central	1.20	**0.93**	-
	Back	1.38	0.87	-
CI2	Front	**2.04**	0.53	2.54
N = 276	Central	0.45	**1.26**	0.00
	Back	0.60	1.15	**1.31**
CI3	Front	**0.99**	0.63	14.40
N = 144	Central	0.80	**1.24**	0.00
	Back	1.40	0.60	**0.00**
CI4	Front	**2.48**	0.23	3.51
N = 462	Central	0.49	**1.26**	0.16
	Back	0.58	1.23	**0.00**
NH1	Front	**1.20**	0.89	0.86
N = 440	Central	0.79	**1.13**	0.95
	Back	1.57	0.61	**1.43**
NH2	Front	**1.91**	0.21	0.34
N = 456	Central	0.32	**1.68**	0.56
	Back	0.51	0.74	**8.69**
NH3	Front	**0.47**	3.01	-
N = 212	Central	0.82	**1.68**	-
	Back	1.24	0.10	-
NH4	Front	**0.89**	1.00	0.86
N = 475	Central	0.93	**1.01**	1.57
	Back	1.34	0.86	**0.00**

Target Characteristics. The corpus contained 3,878 CV targets containing relatively equal contributions from the CI and NH groups (see Table 8). The CI children attempted 1,844 CV sequences (M = 461.00, SD = 229.51) and the NH children attempted 2,034 (M = 508.50, SD = 190.72). Table 8 displays the frequency of attempts for intrasyllabic CV sequences. The most commonly attempted CV targets across groups included labial-central, coronal-back, and coronal-front. The majority of CV syllables occurred in initial position (63%) followed by final (19%) and medial (18%) position.

Table 8

Ratio of Observed to Expected Occurrences of CV Targets by Group

		Consonants		
Participant	Vowels	Coronal	Labial	Dorsal
CI1	Front	**0.73**	1.17	0.00
N = 200	Central	0.96	**1.02**	2.33
	Back	1.72	0.59	**0.00**
CI2	Front	**1.63**	0.57	1.82
N = 508	Central	0.48	**1.38**	0.00
	Back	0.64	1.23	**0.81**
CI3	Front	**0.98**	0.84	3.61
N = 388	Central	0.25	**2.23**	1.88
	Back	1.43	0.34	**0.00**
CI4	Front	**2.10**	0.31	2.48
N = 748	Central	0.61	**1.25**	0.34
	Back	0.69	1.18	**0.78**
NH1	Front	**0.87**	1.15	0.49
N = 526	Central	0.68	**1.18**	1.41
	Back	1.88	0.40	**0.90**
NH2	Front	**1.45**	0.39	1.45
N = 748	Central	0.38	**1.87**	0.32
	Back	1.16	0.74	**1.29**
NH3	Front	**0.83**	2.31	0.00
N = 284	Central	0.69	**2.13**	2.73
	Back	1.19	0.28	**0.00**
NH4	Front	**0.92**	1.07	0.87
N = 476	Central	1.10	**0.91**	1.31
	Back	1.03	0.98	**0.97**

Target CV syllables with diverse intrasyllabic pairings outnumbered those predicted CV co-occurrences based on articulatory compatibility across groups (see Table 10 for description of specific CV patterns in targets). Observed to expected ratios for predicted CV (CI: 6/12; NH: 5/12) versus non-predicted CV associations in word targets (CI: 10/24; NH: 12/24) revealed that children did not select lexical targets based on their own production propensities (see Table 10) (CI: $\chi^2 = 1.33$, $p > .10$; NH: $\chi^2 = 0.18$, $p > .10$).

Accuracy. Participants typically matched exact CV patterns or the CV category for 56% of CV targets. Partially correct realizations accounted for 29% of attempts across group. CI children produced correct (40%) and partially correct (33%) CV patterns with relatively equal frequency. NH children produced more correct (56%) than partially correct (24%) CV targets. Although the NH group exhibited higher overall accuracy for CV targets, no systematic effect for group was found ($\chi^2 = 2.31$, $p > .10$). Word position also did not affect accuracy of CV co-occurrences ($\chi^2 = 3.87$, $p > .10$). Participants in both groups accomplished higher accuracy on CV sequences predicted by the Frame/Content theory (55/61%) than non-predicted sequences (27/45%) ($\chi^2 = 3.58$, $p < .10$). No significant difference existed between the observed to expected accuracy of predicted and non-predicted CV co-occurrence patterns for either CI or NH children ($\chi^2 = 0.78$, $p < .10$).

The group variable did not significantly impact intrasyllabic CV accuracy. Children in both groups favored CV co-occurrences based on articulatory compatibility in their own productions. Although participants as a whole attempted more diverse CV targets, they exhibited higher overall accuracy and less severe error patterns for CV co-occurrences based on articulatory compatibility.

Table 9

Ratio of Observed to Expected Occurrences in Accurate CV Productions by Group

		Consonants		
Participant	Vowels	Coronal	Labial	Dorsal
CI1	Front	**0.50**	0.13	-
N = 107	Central	1.41	**0.78**	-
	Back	2.41	0.22	**-**
CI2	Front	**1.51**	0.65	1.37
N = 158	Central	0.40	**1.42**	0.00
	Back	0.79	1.10	**2.29**
CI3	Front	**1.31**	0.28	3.96
N = 198	Central	0.15	**2.42**	1.20
	Back	1.46	0.30	**0.00**
CI4	Front	**2.25**	0.04	3.12
N = 278	Central	0.35	**1.49**	0.00
	Back	0.85	1.17	**0.00**
NH1	Front	**1.25**	0.86	0.90
N = 294	Central	0.65	**1.21**	0.92
	Back	2.01	0.36	**1.59**
NH2	Front	**1.53**	0.33	1.60
N = 464	Central	0.24	**1.98**	0.00
	Back	1.02	0.88	**1.72**
NH3	Front	**0.74**	3.27	-
N = 157	Central	0.80	**2.77**	-
	Back	1.09	0.18	**-**
NH4	Front	**0.51**	1.25	1.44
N = 219	Central	0.97	**0.99**	1.62
	Back	1.62	0.70	**0.00**

Table 10

Inventory, Targets, and Accuracy for Intrasyllabic CV by Group

Gp	CV	Inventory (N)	Targets (N)	Levels of accuracy: Correct	Corr. CV cat.	Partially correct	Incorrect	Partially omitted	Omitted
CI	LF	113	177	46%	6%	29%	3%	12%	3%
	LC	513	531	52%	16%	18%	2%	8%	5%
	LB	63	327	13%	2%	77%	0%	7%	1%
	CF	154	301	51%	13%	10%	2%	16%	8%
	CC	122	142	42%	15%	25%	4%	14%	1%
	CB	46	306	36%	1%	45%	5%	13%	0%
	DF	24	36	47%	14%	28%	6%	3%	3%
	DC	2	12	17%	8%	33%	25%	0%	17%
	DB	1	12	8%	0%	17%	50%	17%	8%
NH	LF	195	278	56%	8%	24%	1%	5%	7%
	LC	540	462	70%	15%	5%	0%	6%	3%
	LB	87	201	28%	1%	52%	2%	16%	0%
	CF	271	348	70%	9%	11%	1%	4%	5%
	CC	246	210	53%	1%	27%	5%	11%	3%
	CB	183	388	49%	2%	38%	3%	4%	4%
	DF	13	61	54%	2%	38%	0%	2%	5%
	DC	31	52	19%	0%	40%	0%	37%	4%
	DB	17	34	21%	0%	50%	29%	0%	0%

Note. Gp = Group; Corr. CV cat. = Correct CV category; LF = Labial-Front; LC = Labial-Central; LB = Labial-Back; CF = Coronal-Front; CC = Coronal-Central; CB = Coronal-Back; DF = Dorsal-Front; DC = Dorsal-Central; and DB = Dorsal-Back.

Intrasyllabic VC Targets

Inventory. Participants produced a total of 202 intrasyllabic VC sequences. The NH group produced 152 VC co-occurrences (M = 38.00, SD = 37.66) and the CI group produced 50 (M = 12.50, SD = 1.73). NH2 produced the majority (N = 87) of VC syllables in the NH group, primarily favoring predicted sequences (N = 59). In general, VC patterns predicted by the Frame/ Content theory occurred most often in the corpus (74/60%). Central-labial (36/26%) and front-coronal (36/32%) co-occurrences were produced most frequently. Three participants (CI2, NH2, and NH4) produced predicted and non-predicted sequences with equal frequency.

Table 11 displays observed to expected ratios for VC co-occurrences based on chi square analysis. Similar to CV inventory results, both groups favored VC co-occurrences predicted by Frame/Content. Chi square for difference in relative frequencies could not be calculated validly due to insufficient observations per cells.

Table 11

Ratio of Observed to Expected Occurrences of Child VC Productions by Group

		Consonants		
Child	Vowels	Coronal	Labial	Dorsal
CI	Front	**1.63**	-	-
N = 50	Central	0.65	**1.55**	-
	Back	-	-	-
NH	Front	**1.40**	-	1.38
N = 152	Central	0.61	**2.00**	0.58
	Back	1.15	-	-

Target characteristics. The corpus contained 1,796 intrasyllabic VC targets. The CI children attempted 966 intrasyllabic VC targets (*M* = 241.50, *SD* = 183.94). The NH children attempted 830 (*M* = 207.50, *SD* = 90.87). The majority of VC targets occurred in final position (67/62%) followed by medial (22/22%) and initial (11/16%) positions.

VC pairings requiring additional tongue movement accounted for the majority (70/67%) of all VC targets. The most frequently attempted VC patterns in word targets across groups included back-coronal (39/29%), front-coronal (26/16%), and central-coronal (15/26%), as shown in Table13. The NH group also attempted 13% central-labial targets, which differs from the CI group (4%). All other VC sequences comprised less than 10% of the corpus, with vowel-dorsal patterns attempted least often (13/13%). Observed to expected ratios for intrasyllabic VC patterns showed a significant difference between VC targets with (8/11) and without articulatory compatibility (8/15) for NH children ($\chi^2 = 36.36$, $p < .01$) but not for CI children ($\chi^2 = 1.57$, $p > .10$) (see Table 12).

Table 12

Ratio of Observed to Expected Occurrences of VC Targets by Group

		Consonants		
Child	Vowels	Coronal	Labial	Dorsal
CI1	Front	**0.91**	-	-
$N = 104$	Central	0.87	**1.69**	-
	Back	1.14	-	-
CI2	Front	**0.88**	-	2.68
$N = 207$	Central	0.69	**7.36**	-
	Back	1.12	-	-
CI3	Front	**1.07**	-	-
$N = 145$	Central	0.94	-	-
	Back	0.94	-	-
CI4	Front	**1.18**	0.75	0.45
$N = 541$	Central	0.50	**1.24**	2.73
	Back	1.28	0.99	-
NH1	Front	**1.16**	-	2.25
$N = 278$	Central	0.79	**1.85**	0.45
	Back	1.23	-	**1.30**
NH2	Front	**1.08**	-	1.75
$N = 256$	Central	0.73	**2.64**	0.91
	Back	1.20	-	**0.63**
NH3	Front	**1.21**	-	-
$N = 76$	Central	0.92	**1.33**	-
	Back	1.05	0.83	-
NH4	Front	**0.78**	-	1.92
$N = 220$	Central	1.29	**1.31**	-
	Back	0.99	1.85	**0.74**

Accuracy. Participants across groups typically realized VC patterns as a singleton vowel with consonant omission (76/63%). All other categories occurred less than 10%.

Group impacted VC accuracy ($\chi^2 = 3.63$, $p < .10$) with the NH children more than twice as likely to match intrasyllabic VC patterns (odds ratio = 2.40, $\chi^2 = 12.35$, $p < .001$). The NH group achieved correct VC co-occurrences 9% and partially omitted the VC target 58%. The CI group performed more poorly with more partial omissions (74%)

and fewer correct (3%) or correct category realizations (3%). Details by specific VC co-occurrence pattern are shown in Table 13.

Articulatory compatibility also influenced VC accuracy ($\chi^2 = 5.58$, $p < .05$). Although sequences illustrating intrasyllabic movement in tongue position comprised the majority of target attempts, VCs with congruent tongue position (i.e., front-coronal, central-labial, back-dorsal) were 60% more likely to be more accurate than non-predicted patterns (odds ratio = 1.60, $\chi^2 = 23.43$, $p < .0001$). Specifically, VC patterns predicted by Frame/Content occurred with greater accuracy (9/25% vs. 0/5%) and fewer partial or total omissions (80/52%) than non-congruent patterns (92/82%). This effect persisted across group ($\chi^2 = 2.32$, $p > .10$). Observed to expected ratios could not be calculated for VC accuracy due to inadequate frequencies to conduct a valid chi square analysis.

Table 13

Inventory, Targets, and Accuracy for Intrasyllabic VC by Group

Gp	VC	Inventory (*N*)	Targets (*N*)	Levels of accuracy					
				Correct	Corr. VC cat.	Partially correct	Incorrect	Partially Omitted	Omitted
CI	FC	18	250	6%	0%	1%	5%	65%	23%
	FL	1	11	9%	0%	9%	0%	73%	9%
	FD	0	28	0%	0%	0%	25%	71%	4%
	CC	11	142	1%	1%	1%	1%	81%	15%
	CL	18	35	26%	3%	0%	29%	43%	0%
	CD	0	95	0%	0%	0%	2%	98%	0%
	BC	0	381	0%	0%	2%	5%	81%	12%
	BL	1	19	0%	0%	16%	11%	74%	0%
	BD	1	5	0%	0%	40%	0%	60%	0%
NH	FC	48	135	30%	1%	3%	7%	48%	10%
	FL	0	1	0%	0%	0%	100%	0%	0%
	FD	10	59	0%	0%	17%	3%	76%	3%
	CC	25	216	5%	0%	1%	4%	79%	12%
	CL	39	112	13%	1%	1%	44%	41%	0%
	CD	5	15	13%	7%	20%	7%	47%	7%
	BC	17	242	7%	0%	6%	8%	68%	11%
	BL	4	20	5%	0%	5%	5%	85%	0%
	BD	4	30	3%	0%	13%	13%	70%	0%

Note. Gp = Group; Corr. VC Cat. = Correct VC Category; FC = Front-Central; FL = Front-Labial; FD = Front-Dorsal; CC = Central-Coronal; CL = Central-Labial; CD = Central-Dorsal; BC = Back-Central; BL = Back-Labial; and BD = Back-Dorsal.

The ability to match VC characteristics also differed by word position ($\chi^2 = 6.51$, $p < .05$). Although overall accuracy was low, participants committed less severe errors in initial position than medial (odds ratio = 5.7, $\chi^2 = 124.66$, $p < .0001$) or final position (odds ratio = 3.9, $\chi^2 = 22.39$, $p < .0001$). Final VC sequences were more accurate than those in medial position (odds ratio = 1.5, $\chi^2 = 4.36$, $p < .05$). This most likely relates to the prevalence of partial omissions in medial position (82/84%) compared to final (73/56%) and initial (58/26%) positions.

The NH group matched VC co-occurrence patterns in word targets better than the CI group. Child productions reflected Frame/Content predictions with more central-labial and front-coronal sequences. VCs with articulatory compatibility were attempted less frequently but achieved more accurately than non-predicted patterns. VC syllables were most accurate in initial position and least accurate in medial position.

Intersyllabic Vowel Relationships in CVCV Contexts: Front-Back Dimension

Inventory. A total of 503 intersyllabic vowel sequences were attempted with 190 (M = 47.50, SD = 26.90) from the CI children and 313 (M = 78.25, SD = 79.45) from the NH group. Frequency of front-back reduplication (69%/83%) exceeded that of front-back variegation overall. Front-front (37/52%), central-central (31/29%), and central-front (24/11%) sequences were produced most frequently by both groups. Child productions of intersyllabic vowel sequences are displayed in Table 14.

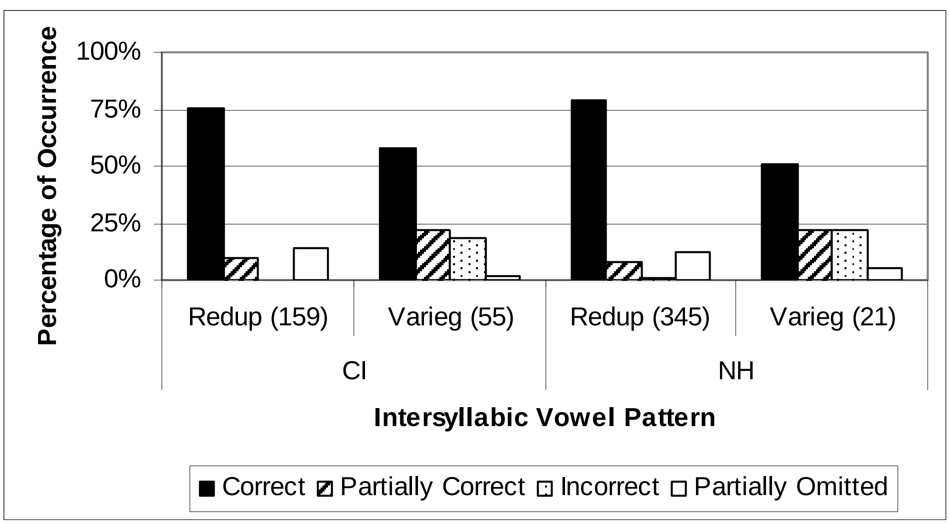
Target characteristics. Of the 567 CVCV words analyzed, the CI group attempted 214 (M = 53.50, SD = 33.15) and the NH group attempted 353 (M = 88.25, SD = 85.85), as shown in Table 14. Vowel sequences with reduplication in the front-back dimension were attempted more frequently (74/88%) than variegated sequences (26/12%). Both CI and NH children most frequently attempted word targets with front-front (48/61%), central-central (26/26%), and central-front (20/7%) sequences.

Accuracy. Correct front-back characteristics for both V1 and V2 accounted for the majority of attempts (71/76%) at intersyllabic vowel sequences (see Table 14). Approximately 10% of attempts were realized as partially correct (13/9%) with a preference to match V2 characteristics twice as often as a correct first vowel. This pattern was more robust in the CI group (odds ratio = 3.9, $\chi^2 = 3.50$, $p < .10$). Partially omitted sequences (11/12%), primarily V2 omission, accounted for approximately 10% of CVCV word attempts. Incorrect productions occurred infrequently. Overall results yielded a marginally significant group effect ($\chi^2 = 2.85$, p < .10) most likely due to the higher proportion of partially correct and incorrect productions in the CI cohort.

Intersyllabic vowel reduplication (75/79%) was more accurate than variegation patterns (58/51%). The most frequently produced and attempted VV sequences were also among the most correct. The most accurate for both groups was front-front (66/74%), central-central (93/90%), and central-front (76/72%). Error patterns varied by type of intersyllabic vowel pattern (Figure 4). Children across groups realized reduplicated sequences as either partially correct (10/8%) or partially omitted (14/12%). In contrast, variegated sequences were more likely to be either partially correct (22/22%) or incorrect (18/22%) rather than partially omitted. Aside from these differences, the effect of reduplication versus variegation did not reach statistical significance ($\chi^2 = .71$, $p > .10$).

Figure 4

Accuracy of Reduplicated and Variegated Vowel Targets by Front-back by Group



Incidence of front-back reduplication exceeded variegation in all measures of intersyllabic vowel sequences. Front-front, central-central, and central-front sequences were the most frequently produced, attempted, and accurate intersyllabic vowel patterns across groups. Error patterns differed by type of intersyllabic sequences. Participants were more likely to partially omit reduplicated sequences, especially V2, and more likely to produce two incorrect vowels for variegated sequences.

Table 14

Inventory, Targets, and Accuracy for Intersyllabic Vowel Front-Back Sequences by Group

				Levels of Accuracy			
Gp	VV type	Inventory (N)	Targets (N)	Correct	Partially Correct	Incorrect	Partially Omitted
CI	FF	71	103	66%	13%	0%	21%
	FC	6	0				
	FB	0	8	0%	50%	50%	0%
	CF	45	42	76%	7%	14%	2%
	CC	59	56	93%	5%	0%	2%
	CB	2	0				
	BF	1	5	0%	100%	0%	0%
	BC	4	0				
	BB	2	0				
NH	FF	162	215	74%	10%	1%	14%
	FC	5	0				
	FB	3	0				
	CF	33	25	72%	20%	0%	8%
	CC	91	93	90%	2%	0%	8%
	CB	8	0				
	BF	4	16	19%	25%	56%	0%
	BC	1	0				
	BB	6	4	75%	0%	25%	0%

Note. Gp = Group; F = Front; C = Central; and B = Back.

Intersyllabic Vowel Relationships in CVCV Contexts: Height Dimension

Inventory. The corpus contained 95 intersyllabic vowel sequences. There were 68 (*M* = 17.00, *SD* = 23.41) from the CI children and 27 (*M* = 6.75, *SD* = 8.38) from the NH children. Height variegation dominated child productions (74/67%) in contrast to the prevalence of front-back reduplication in vowel sequences. Intersyllabic patterns moving to a higher vowel (i.e., mid-high, low-high, and low-mid) each accounted for 18-25% of sequential productions in both groups, as shown in Table 15.

Target characteristics. Of 567 CVCV target word forms, the CI group attempted 214 (M = 53.50, SD = 33.15) and the NH group attempted 353 (M = 88.25, SD = 85.85). Sequences with variegated height comprised 90% of word targets in both CI and NH children's lexicon, which contrasts the predominance of front-back reduplication. Two-thirds of variegations in targets involved a change from a lower to a higher vowel (i.e., low mid, low high, mid high). Table 15 describes levels of accuracy for intersyllabic vowel sequences by height.

Accuracy. The two groups performed similarly regarding the ability to match vowel height targets in intersyllabic contexts ($\chi^2 = 1.07$, $p > .10$) (see Table 15). The majority of V1-V2 attempts were produced with correct height for either one (24/20%) or both (59/65%) of the vowels in the intersyllabic sequence. Partially correct responses were evenly split between correct V1 and correct V2 and chiefly occurred with variegated types (N = 114 of 123). Partial omissions occurred in 11% of target attempts for both groups. Ninety-five percent of partial omissions involved deletion of the second vowel and occurred only in variegated sequences, particularly those moving from a lower to a higher vowel.

Reduplicated and variegated patterns were matched with relatively equal frequency by both sets of children (67/57% and 59/66%, respectively). Differences between the CI and NH groups emerged when error patterns were considered, as shown in Figure 5. The CI group was equally likely to produce a partially correct (19%) or incorrect (14%) reduplicated vowel height sequence. In contrast, the NH group produced incorrect realizations twice as often as partially correct productions (30% versus 14%). No differences in error patterns existed in levels of accuracy for variegation patterns.

Figure 5

Accuracy of Reduplicated vs. Variegated Vowel Targets by Height by Group

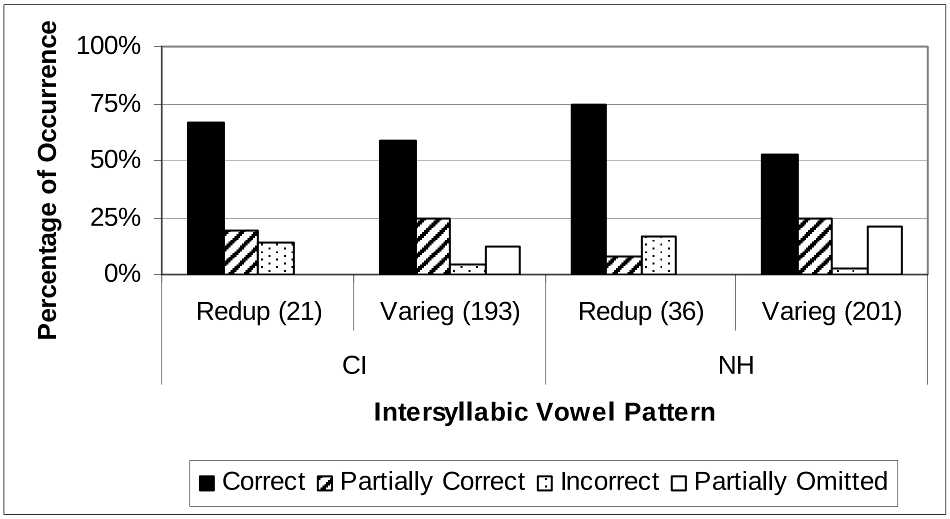


Table 15

Inventory, Targets, and Accuracy for Intersyllabic Vowel Height Sequences by Group

Gp	VV type	Inventory (N)	Targets (N)	Levels of Accuracy			
				Correct	Partially Correct	Incorrect	Partially Omitted
CI	HH	6	4	25%	75%	0%	0%
	HM	4	0				
	HL	0	0				
	MH	16	100	50%	21%	7%	22%
	MM	6	13	77%	0%	23%	0%
	ML	1	0				
	LH	17	44	80%	18%	0%	2%
	LM	12	49	57%	39%	2%	2%
	LL	6	4	75%	25%	0%	0%
NH	HH	0	6	33%	17%	50%	0%
	HM	0	0				
	HL	0	0				
	MH	6	107	44%	20%	3%	34%
	MM	6	14	79%	0%	21%	0%
	ML	1	0				
	LH	5	34	74%	18%	3%	6%
	LM	6	60	55%	37%	2%	7%
	LL	3	16	88%	13%	0%	0%

Note. Gp = Group; H = High; M = Mid; and L = Low.

Height variegation, particularly patterns moving from a lower to a higher vowel, occurred more frequently in inventory, targets, and accuracy of intersyllabic vowel sequences. Reduplication and variegation patterns were produced with equal accuracy by both groups. The NH children were twice as likely as the CI children to produce an incorrect versus a partially correct height sequence.

Participants attempted intersyllabic vowel sequences in CVCV contexts with front-back reduplication and height variegation. Participants matched vowel characteristics of both vowels in intersyllabic contexts, particularly in reduplicated sequences. Partially correct productions typically contained an accurate second vowel. Partially omitted sequences typically involved deletion of the second vowel.

Intersyllabic Consonant Relationships in CVC and CVCV Contexts: Place

Inventory. A total of 433 intersyllabic consonant sequences were produced (see Table 16). The CI group produced 116 (*M* =7.25, *SD* = 8.78) and the NH group produced 317 (*M* =19.81, *SD* = 31.41). Frequency of reduplicated sequences (89/89%) surpassed variegated sequences (11/11%) in both groups. The most common sequences were labial-labial (69/49%) and coronal-coronal (20/37%) across groups.

Target characteristics. The corpus contained 1,308 intersyllabic consonant sequences combining labial, coronal, and dorsal place of articulation. The CI children attempted 540 (*M* =135, *SD* = 110.94) and the NH children attempted 768 (*M* =192, *SD* = 96.81) CVC or CVCV word targets, as shown in Table 16. Labial-labial (27/38%) and coronal-coronal (18/24%) were the most commonly attempted reduplications in word targets across groups. Labial-coronal (50/17%) sequences were the most frequently attempted variegated pattern in the lexicons of both groups.

The corpus contained 788 CVC words (*M* =98.50, *SD* = 63.65) and 520 CVCV words (*M* =65.00, *SD* = 63.65). Intersyllabic consonant patterns varied by word shape. Variegated sequences dominated CVC forms (78/58%) largely due to the prevalence of labial-coronal targets (91/40% of all variegated sequences). Contrastingly, CVCV words tended toward consonant reduplication (96/90%). Participants most frequently attempted labial-labial (79/60%) and coronal-coronal (21/35%) sequences.

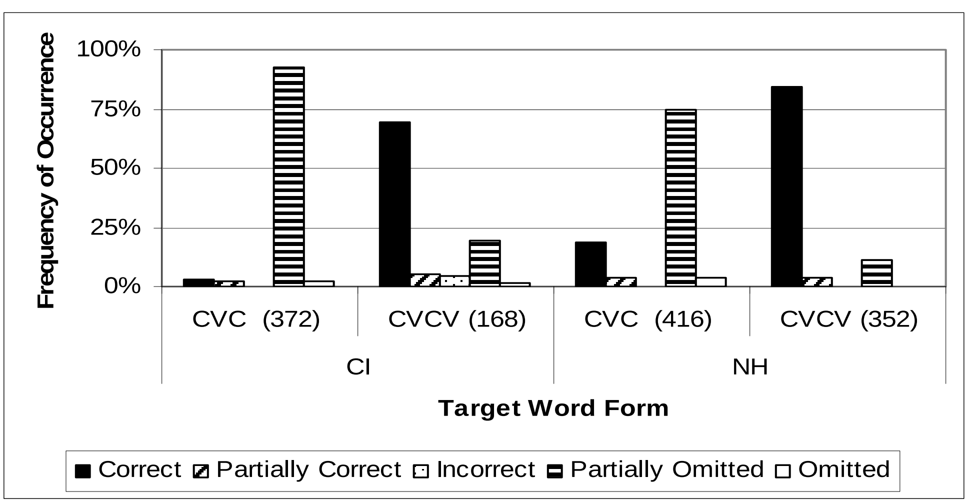
Accuracy: Partial omissions constituted 56% of word attempts with intersyllabic consonant sequences. Ninety percent of partial omissions involved deletion of C2. Thirty-nine percent of attempts were realized with correct place accuracy for both consonants.

The NH children were more accurate than the CI children, matching both consonants more frequently (24/49%) and producing partially omitted sequences less frequently (64/39%) than the CI group. The effect of group did not reach statistical significance ($\chi^2 = 1.16$, $p > .10$). Both groups matched reduplicated (50/64%) better than variegated (3/21%) sequences ($\chi^2 = 3.11$, $p < .10$). The CI group matched words with labial-labial patterns most frequently (63%). Children in the NH group achieved at least 55% correct productions of place reduplication (see Table 16 for details).

Word shape did affect intersyllabic consonant place accuracy with higher scores for CVCV than CVC targets ($\chi^2 = 4.19$, $p < .05$). Figure 6 shows that participants in both groups achieved correct consonants in CVCV words (70/85%) more often than in CVC words (3/19%). Partial omissions, especially elimination of the second consonant, occurred significantly more frequently in CVC (93/74%) than CVCV (20/11%) contexts (odds ratio = 181.0, $\chi^2 = 76.20$, $p < .0001$). Partially correct, incorrect, and omitted realizations each accounted for less than 6%. No systematic interaction effect was found between word shape and group ($\chi^2 = .79$, $p > .10$).

Figure 6

Levels of Accuracy for CVC and CVCV Word Forms by Group



Place reduplication patterns were produced, attempted, and matched more frequently than variegation patterns in intersyllabic contexts. Even though more CVC targets were attempted, the children achieved greater accuracy and omitted the second consonant less frequently in CVCV forms.

Table 16

Inventory, Targets, and Accuracy for Intersyllabic Consonant Place Sequences by Group

Gp	CC Type	Inventory (N)	Targets (N)	Levels of Accuracy				
				Correct	Partially Correct	Incorrect	Partially Omitted	Omitted
CI	LL	80	145	63%	3%	5%	28%	1%
	LC	9	268	1%	2%	0%	95%	1%
	LD	0	2	0%	0%	0%	100%	0%
	CL	2	9	33%	22%	0%	44%	0%
	CC	23	98	31%	2%	0%	62%	5%
	CD	1	5	20%	20%	0%	60%	0%
	DL	0	1	0%	0%	0%	100%	0%
	DC	1	11	0%	9%	0%	91%	0%
	DD	0	1	0%	0%	0%	100%	0%
NH	LL	156	290	59%	3%	0%	38%	1%
	LC	12	127	21%	4%	0%	75%	1%
	LD	2	29	24%	21%	0%	55%	0%
	CL	18	65	25%	3%	0%	69%	3%
	CC	116	185	69%	0%	1%	30%	0%
	CD	0	17	35%	24%	0%	41%	0%
	DL	2	6	33%	17%	17%	33%	0%
	DC	1	31	3%	10%	0%	58%	29%
	DD	10	18	100%	0%	0%	0%	0%

Note. Gp = Group; L = Labial; C = Coronal; and D = Dorsal.

Intersyllabic Consonant Relationships in CVC and CVCV Contexts: Manner

Inventory. A total of 487 intersyllabic patterns containing stop, nasal, or fricative consonant manner were produced. The CI group produced 114 (M = 28.50, SD = 23.29) of which 62 came from CI4. The NH group produced 373 (M = 93.25, SD = 96.00) of which 233 came from NH2. Both groups preferred reduplication (90/87%), particularly stop-stop (46/61%) and nasal-nasal (44/25%) sequences. See Table 17 for details.

Target characteristics. Table 17 shows differences in the number of word targets with 217 (*M* = 54.25, *SD* = 34.07) from the CI group and 494 (*M* = 123.50 *SD* = 107.82) from the NH group. Most targets were of CVCV (71%) rather than CVC (29%) form.

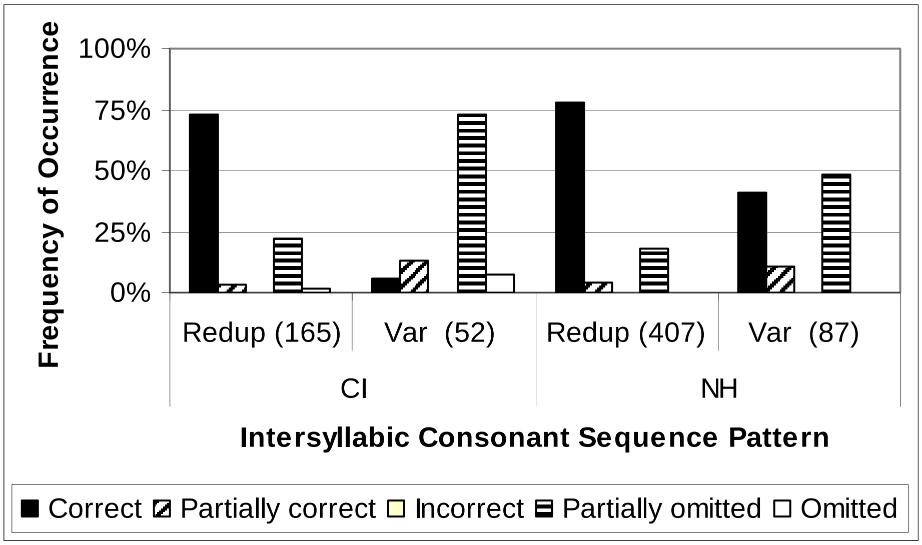
Participants were more likely to attempt sequences with reduplicated (76/82%) than variegated manner (24/18%). The most common reduplication patterns involved stops (56/70%) and nasals (43/26%). Variegation patterns in word targets differed by group. The CI children mainly attempted fricative-stop sequences (85%) whereas the NH children attempted more diverse word targets such as nasal-stop (37%), stop-nasal (31%), and fricative-nasal (20%). The only exception to the prevalence of reduplicated over variegated word targets involved word shape. CI children attempted more consonant variegation in CVC (73%) but more consonant reduplication in CVCV (100%).

Accuracy. Participants across group either matched manner for both consonants or omitted one member of the sequence. The NH group exhibited greater accuracy (57/71%) and fewer partial omissions (35/23%), but no systematic effects were found for group on accuracy of intersyllabic consonant manner sequences ($\chi^2 = 1.14$, $p > .10$) (see Table 17).

Reduplicated targets were not only attempted more frequently overall, but also more accurately than variegated targets ($\chi^2 = 3.00$, $p < .10$). Correct productions of reduplicated sequences (73/78%) exceeded those of variegated sequences (6/41%) in both groups. Most variegated sequences were realized as partially omitted productions (73/48%), as shown in Figure 7. The most accurate manner sequences coincided with those attempted most frequently, with one exception. The NH group attempted CVCV words with stop reduplication more frequently than nasal reduplication (61% and 29%, respectively) but achieved equal accuracy on both patterns (86% and 89%, respectively).

Figure 7

Accuracy of Consonant Manner Reduplication and Variegation by Group



Participants in both groups exhibited greater intersyllabic consonant manner accuracy for CVCV than CVC word shapes. Correct productions accounted for 77/86% of CVCV words compared to 33/15% of CVC words. All children were more likely to delete one member of the consonant sequence in CVC than CVCV contexts. Partial omissions generally involved the deletion of C2 (93%) and were significantly more likely to occur in CVC versus CVCV contexts (odds ratio = 39.0, $\chi^2 = 6.59$, $p < .01$). Although word shape significantly affected which consonant in the sequence was omitted, CVC and CVCV did not differ with regard to overall accuracy ($\chi^2 = 1.02$, $p > .10$).

For both groups, manner of articulation in intersyllabic consonant relationships revealed a preference for reduplicated targets, particularly stop-stop combinations. Variegated targets differed by group. CI children preferred fricative-stop CVCV and NH children tended toward nasal-stop and stop-nasal variegated targets. Intersyllabic patterns attempted most frequently were generally most accurate. The most common error type involved omission of C2, principally in CVC sequences.

Table 17

Inventory, Targets, and Accuracy for Intersyllabic Consonant Manner Sequences by Group

Gp	CC type	Inventory	Targets	Level of accuracy: Correct	Partially correct	Incorrect	Partially omitted	Omitted
CI	NN	50	71	79%	0%	0%	21%	0%
	NF	6	3	0%	0%	0%	100%	0%
	NS	1	0					
	FN	3	2	100%	0%	0%	0%	0%
	FF	0	1	0%	0%	0%	100%	0%
	FS	0	44	0%	16%	0%	75%	9%
	SN	1	3	33%	0%	0%	67%	0%
	SF	0	0					
	SS	53	93	69%	5%	0%	23%	3%
NH	NN	94	107	87%	4%	0%	9%	0%
	NF	0	6	0%	0%	0%	100%	0%
	NS	28	32	81%	9%	0%	9%	0%
	FN	1	0					
	FF	1	14	7%	64%	0%	29%	0%
	FS	4	17	18%	18%	0%	65%	0%
	SN	7	27	22%	11%	0%	67%	0%
	SF	10	5	20%	0%	0%	80%	0%
	SS	228	286	78%	1%	0%	21%	0%

Note. Gp = Group; N = Nasal; F = Fricative; and S = Stop.

Both CI and NH groups showed common patterns across segmental and serial analyses for distribution of child production inventories and target characteristics. Although the NH children demonstrated greater absolute accuracy, this difference only reached statistical significance for one of eight analyses (i.e., consonants).

Time (Early vs. Late)

The time variable was associated with an increase in accuracy during the 6 month course of the study. Although accurate productions show where the child is correct, examination of exclusively correct productions did not fully describe growth in accuracy. Error patterns shifted from either omissions or partially correct productions to correct productions. Time interacted with group in most measures, typically revealing greater accuracy for the NH versus the CI group in both early and later sessions. Similar to the convention used in the previous section, results will be reported with the first number representing early sessions and the second number representing later sessions. If consonant accuracy improved over time (54/65%), then consonants were 54% correct in early sessions and 65% correct in later sessions.

Consonants

Inventory. The early sessions contained 1,409 (M = 176.13, SD = 140.22) and later sessions contained 3,076 (M = 384.5, SD = 192.56) for a total of 4,485 consonants produced across groups. The dominance of labial, coronal, and stop consonants persisted throughout the study, as described in Table 18. Variations from this overall pattern occurred in early sessions. The CI group produced a higher proportion of fricatives (12%) and glottals (17%) and the NH group produced more glides (13%). Results from both groups converged with overall patterns in later sessions.

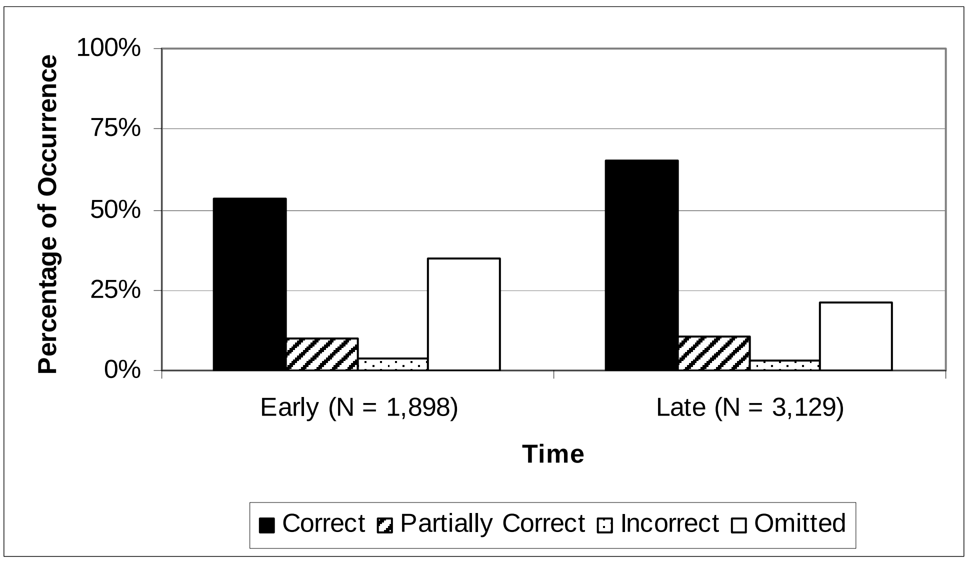
Target Characteristics. Participants attempted word targets containing 5,027 consonants. The CI (N = 946, M = 236.50, SD = 109.66) and NH groups (N = 952, M = 238.00, SD = 81.48) attempted an equivalent number of target word consonants in early sessions. Consonant target frequency diverged in later sessions with a lower frequency of consonant targets for CI (N = 1,428, M = 357.00, SD = 128.06) than the NH group (N = 1,701, M = 425.25, SD = 182.32), as displayed in Table 18. Proportion of occurrence by place and manner were consistent across groups. Early sessions contained more labial (49%) than coronal (29%) targets. Later sessions included a balance between the two places of articulation (44% labials, 42% coronal). Stop (49/49%) and nasal (31/35%) consonants were attempted most frequently in word targets across sessions.

Accuracy. Consonant accuracy improved from early to later sessions (54/65%) (χ^2 = 6.20, $p < .05$), but the effect depended on group (χ^2 = 5.55, $p < .05$) (see Table 18). NH participants were 3 times more likely to be accurate than CI children in early sessions (odds ratio = 3.0, χ^2 = 7.2, p <.01) and 7 times more likely in later sessions (odds ratio = 7.4, χ^2 = 19.1, p <.0001). NH children were 3 times more likely to improve consonant accuracy from early to later sessions (odds ratio = 3.2, χ^2 = 157.1, p <.0001).

Improved consonant accuracy for both groups directly results from the shift from omissions toward correct place and manner over time (see Figure 8). Early sessions were characterized by 54% accuracy and 35% omissions. Percentages of partially correct and incorrect productions remained stable over time. Later sessions showed an 11% increase in correct productions with a concurrent 14% decrease in consonant omissions.

Figure 8

Shift in Levels of Accuracy for Consonants by Time



Trends for levels of accuracy did not change as a function of time. Consonant accuracy was greatest for nasal (71/77%) and stop (55/67%) consonant manners. Fricatives were realized with more omissions over the course of the study. Labial and glottal place were most accurate (i.e., at least 70% correct) with fewest omissions whereas dorsal place was least accurate (12/36%) with most omissions (65/37%).

Both groups improved accuracy for consonant targets over time, primarily transitioning from omissions in early sessions to correct productions in later sessions. NH participants performed significantly better than the CI group in both early and later sessions. Nasal, stop, labial, and glottal consonants were matched most often. Fricative and dorsal consonants were produced with lower accuracy and more omissions.

Table 18

Inventory, Targets, and Accuracy for Consonants by Time

	Consonant				Levels of accuracy			
Sess.	Dimension	Type	Inventory (N)	Targets (N)	Correct	Partially correct	Incorrect	Omitted
Early	Manner	Nasal	435	579	71%	2%	1%	26%
		Stop	734	928	55%	12%	4%	31%
		Fricative	116	391	25%	15%	6%	55%
	Place	Labial	788	927	73%	7%	2%	20%
		Coronal	382	789	33%	14%	3%	50%
		Dorsal	38	428	12%	15%	7%	65%
		Glottal	201	243	77%	1%	9%	14%
Late	Manner	Nasal	1623	1106	77%	3%	1%	19%
		Stop	971	1534	67%	12%	3%	18%
		Fricative	214	489	32%	23%	9%	36%
	Place	Labial	1363	1367	79%	6%	1%	15%
		Coronal	1322	1317	56%	14%	4%	26%
		Dorsal	151	258	36%	22%	5%	37%
		Glottal	240	187	74%	0%	11%	15%

Note. Sess = Session.

Vowels

Inventory. Early sessions contained 1,522 vowels (*M* = 190.25, *SD* = 122.72) and later sessions contained 3,420 vowels (*M* = 427.50, *SD* = 172.00). The prominence of mid (56/89%) and central vowels (67/53%) persisted across sessions. Differences over time included a decreased proportion of low (32/8%) and front vowels (18/4%) and an increased proportion of back vowels (15/40%). Details of vowel inventory in early and later sessions are presented in Table 19.

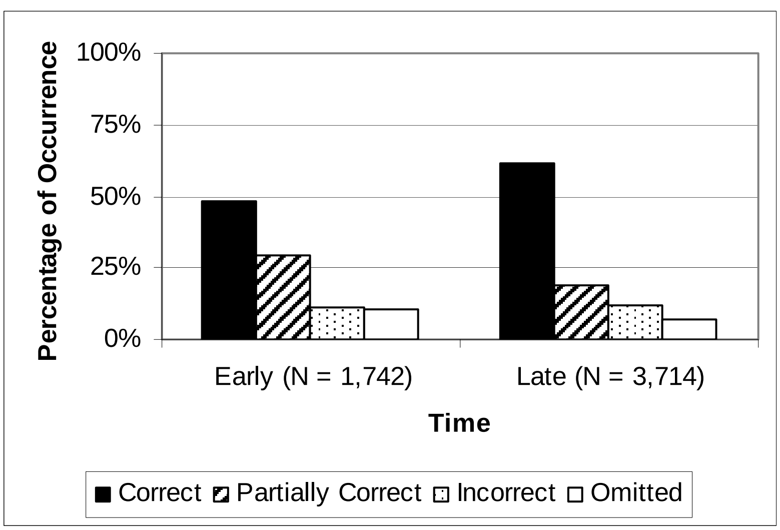
Target characteristics. The frequency of vowels in targets increased over time from 1,742 (*M* = 217.88, *SD* = 144.33) in early sessions to 3,726 (*M* = 465.75, *SD* = 204.20) in later sessions. The proportion of target vowels in each word position remained stable. Specific vowel category distribution in word targets varied by time (see Table 19). Early sessions were characterized by mid back (25%), mid central (23%), and low central (21%) vowels in word targets. Later sessions included more mid back (20%) and high front (19%) vowel targets. Mid height dominated across sessions (54/45%). The front-back dimension contained more central vowel targets (43%) early and equal proportions of front and central vowels in later sessions (39% and 35%, respectively).

Accuracy. Vowel accuracy increased for both the CI group (46/54%) and the NH group (51/68%) ($\chi^2 = 5.39$, $p < .05$). Central vowels were most accurate in early sessions (64/69%). Later sessions showed improvement of front vowel accuracy for the NH children (40/75%) and back vowel accuracy for the CI children (21/40%). Low vowels were most accurate across sessions (63/72%), although later sessions showed the emergence of high vowels (63%). Table 19 details vowel accuracy over time.

Unlike consonants, in which omissions transitioned to correct productions, vowel accuracy shifted from partially correct vowels in early sessions to correct vowel category in later sessions (Figure 9). Children were more likely to achieve correct height (60%) than correct front-back (40%) in partially correct vowel productions ($N = 1{,}231$). Participants were most likely to obtain the correct front-back tongue position for central vowels (odds ratio: 17.9, $\chi^2 = 459.56$, $p < .0001$) and the correct height for mid vowels (odds ratio = 4.3, $\chi^2 = 34.67$, $p < .0001$) in partially correct responses.

Figure 9

Shift in Levels of Accuracy for Vowels by Time



Participants in both groups diversified inventories and word target characteristics for vowels over time. Accuracy improved from early to later sessions, particularly for the most frequently produced and attempted vowels. Whereas consonant accuracy emerged as a function of decreased omissions, vowel accuracy developed as a transition from partially correct productions, primarily correct height qualities.

Table 19

Inventory, Targets, and Accuracy for Vowels by Time

				Levels of Accuracy			
Sess	Vowel Category	Inventory (N)	Targets (N)	Correct	Partially Correct	Incorrect	Omitted
Early	HB	87	188	47%	6%	29%	18%
	MB	92	448	22%	57%	18%	3%
	LC	98	322	66%	29%	3%	2%
	MC	639	381	66%	17%	5%	12%
	HF	384	189	40%	10%	8%	42%
	LF	105	116	56%	37%	5%	2%
	MF	117	98	55%	29%	14%	2%
Late	HB	613	487	49%	14%	21%	15%
	MB	256	801	44%	31%	18%	7%
	LC	245	584	79%	15%	4%	2%
	MC	920	560	66%	18%	14%	3%
	HF	776	732	67%	11%	6%	15%
	LF	205	240	75%	21%	3%	1%
	MF	405	310	62%	21%	15%	2%

Note. Sess. = Session; HB = High back; MB = Mid back; LC = Low central; MC = Mid central; HF = High front; LF = Low front; and MF = Mid front.

Intrasyllabic CV Sequences

Inventory. Early sessions across groups contained 1,106 (M = 119.38, SD = 208.25) and later sessions contained 1,865 (M = 95.81, SD = 110.34) intrasyllabic CV sequences for a total of 2,261 CV syllables. Early inventory of productions converged with Frame/Content predictions with a preference for co-occurrences with articulatory compatibility (63%). Later sessions reflected a more balanced distribution with 54% predicted and 46% non-predicted CV pairings. The most commonly produced sequence across sessions and groups was labial-central (51/34%). Later sessions showed the emergence of coronal-front sequences, increasing from 12% to 19% over time. Patterns were consistent across groups. Individual children (CI1, NH3) also produced several coronal-central pairings (e.g. saying /nʌ/ for /no/). Both early and later sessions include above-chance observed to expected ratios for CV co-occurrences predicted by Frame/Content Theory, as shown in Table 20.

Table 20

Ratio of Observed to Expected Occurrences of Child CV Productions by Time

		Consonants		
Child	Vowels	Coronal	Labial	Dorsal
Early	Front	**1.81**	0.52	2.81
N = 955	Central	0.67	**1.18**	0.52
	Back	1.37	0.84	-
Late	Front	**1.26**	0.79	1.08
N = 1,666	Central	0.66	**1.29**	0.72
	Back	1.49	0.56	**1.67**

Target characteristics. CV target frequency in words attempted differed by session with 1,157 attempts (M = 144.63, SD = 114.73) in early sessions versus 2,721 (M = 176.38, SD = 166.45) in later sessions. Overall, non-predicted sequences were more prevalent in early (58%) and later (56%) sessions. Early sessions contained a plethora of labial-central (30%) and labial-back (20%) targets. Later sessions contained more varied CV patterns, including labial-central (24%), coronal-back (19%), and coronal-front (19%) pairings. Dorsal-vowel sequences constituted 5-6% of all CV syllable attempts in either early or later sessions. Observed to expected ratios are shown in Table 21.

Table 21

Ratio of Observed to Expected Occurrences of CV Targets by Time

		Consonants		
Child	Vowels	Coronal	Labial	Dorsal
CI1-Early	Front	**1.43**	-	-
N = 48	Central	1.00	**0.95**	-
	Back	0.86	1.26	-
CI2-Early	Front	**1.06**	0.86	1.94
N = 119	Central	1.21	**1.00**	-
	Back	0.61	1.21	-
CI3-Early	Front	-	-	-

N = 94	Central	-	**1.52**	-
	Back	1.48	0.66	-
CI4-Early	Front	**4.15**	-	6.08
N = 359	Central	-	**1.24**	-
	Back	0.68	1.12	-
NH1-Early	Front	**0.87**	1.17	-
N = 300	Central	0.79	**1.07**	1.55
	Back	1.96	0.36	**1.92**
NH2-Early	Front	-	-	-
N = 50	Central	0.49	**1.47**	-
	Back	1.81	-	-
NH3-Early	Front	-	-	-
N = 65	Central	0.35	-	2.95
	Back	1.35	0.90	-
NH4-Early	Front	**1.61**	-	-
N = 142	Central	0.76	**1.35**	
	Back	0.76	1.29	-
	Back	-	-	-
CI1-Late	Front	**0.74**	1.11	-
N = 152	Central	0.87	**1.05**	-
	Back	2.58	-	-
CI2-Late	Front	**1.76**	0.48	1.79
N = 389	Central	0.21	**1.54**	-
	Back	0.64	1.24	-
CI3-Late	Front	**0.91**	1.00	-
N = 294	Central	0.25	**2.66**	2.00
	Back	1.43	-	-
CI4-Late	Front	**1.43**	0.55	1.10
N = 389	Central	0.80	1.25	0.58
	Back	0.80	1.14	1.60
NH1-Late	Front	**0.93**	1.01	1.44
N = 226	Central	0.57	**1.35**	1.25
	Back	1.72	0.45	-

NH2-Late	Front	**1.46**	0.39	1.37
N = 698	Central	0.36	**1.91**	0.34
	Back	1.03	0.82	**1.39**
NH3-Late	Front	-	-	-
N = 219	Central	0.76	**2.42**	-
	Back	1.15	-	-
NH4-Late	Front	**0.67**	1.21	-
N = 334	Central	1.29	**0.81**	-
	Back	1.22	0.87	-

Accuracy. Correct (48%) and partially correct (29%) CV sequences constituted the majority of words analyzed across participants. Participants in both groups improved their ability to match CV target characteristics over time (χ^2 =3.78, p<.05), improving on average from 39% to 52%. The most correct CV patterns in early sessions were labial-central (60%) and dorsal-front (59%). Later sessions marked the appearance of coronal-front (65%) sequences. Observed to expected ratios are shown in Table 22. Early sessions in both groups show above-chance levels for predicted sequences (4/4) and fewer for non-predicted (4/10). Later sessions show similar results, with 4/5 predicted CV associations and 4/10 non-predicted patterns accurate at levels above chance.

Table 22

Ratio of Observed to Expected Occurrences of Accurate CV Productions by Time

		Consonants		
Child	Vowels	Coronal	Labial	Dorsal
CI-Early	Front	**2.28**	-	4.15
N = 4	Central	0.38	**1.38**	-
	Back	1.39	0.90	-
NH-Early	Front	**1.26**	0.84	1.63
N = 2	Central	0.72	**1.20**	-
	Back	1.29	0.77	-
CI-Late	Front	**1.19**	0.79	1.63
N = 2	Central	0.44	**1.58**	-
	Back	1.64	0.38	-

NH-Late	Front	**1.14**	0.76	1.69
N = 4	Central	0.46	**1.67**	0.48
	Back	1.65	0.32	**0.52**

Although both groups increased accuracy for intrasyllabic CV sequences, they diverged in the patterns produced most accurately. The CI group's CV accuracy improved over time (36/42%). Dorsal-front targets (63%) were matched most frequently in early sessions followed by coronal-front (53%) and labial-central (51%). Labial-front patterns emerged in later sessions (53%). CV accuracy of the NH group also progressed over time (43/61%). Labial-central were produced with greatest accuracy overall (70% in both early and later sessions). Coronal-central (58%) and coronal-front (79%) accuracy also exceeded 50% in early and later sessions, respectively.

Both correctness and error type category differed based on the relationship between the consonant and vowel across groups. Accuracy of CV pairings with articulatory compatibility exceeded that of incompatible sequences in early and later sessions by an average of 20%. Error patterns for predicted CV co-occurrences were likely to belong to the correct CV category (13% overall) whereas non-predicted CVs tended toward partially correct productions (42% overall), particularly correct consonant-incorrect vowel combinations. These trends persisted across group, session, and word position. As shown in Table 23, little change occurred in the type of error patterns in CV syllables related to predictions. In contrast, sequences involving additional tongue movement showed improved accuracy, decreased partial accuracy, and diminished partial/total omissions from early to later sessions.

Predicted intrasyllabic CV sequences, particularly labial-central co-occurrences, increased in frequency in inventories and accurate productions across time. Proportion of predicted and non-predicted CV associations in target characteristics varied as a function of time. Early sessions were more limited to predicted CV patterns while later sessions showed more diversity in types of CV in word targets attempted.

Table 23

Inventory, Targets, and Accuracy for CV Sequences by Time

				Level of accuracy					
Sess.	CV	Inventory (N)	Targets (N)	Correct	Corr. CV Cat.	Partially correct	Incorrect	Partially omitted	Omitted
Early	LF	67	117	28%	8%	32%	2%	15%	16%
	LC	485	352	59%	19%	9%	1%	7%	6%
	LB	69	264	19%	1%	72%	1%	6%	1%
	CF	115	140	49%	19%	18%	1%	9%	5%
	CC	135	75	49%	4%	20%	4%	17%	5%
	CB	55	180	29%	1%	44%	7%	13%	6%
	DF	17	20	60%	20%	15%	5%	0%	0%
	DC	10	27	7%	0%	19%	0%	63%	11%
	DB	2	9	22%	0%	56%	11%	11%	0%
Late	LF	241	338	60%	7%	24%	1%	6%	2%
	LC	568	641	61%	14%	14%	1%	7%	3%
	LB	81	264	18%	3%	64%	1%	14%	0%
	CF	310	509	65%	8%	9%	1%	10%	7%
	CC	233	277	48%	7%	28%	5%	11%	1%
	CB	174	514	49%	2%	40%	3%	6%	1%
	DF	22	77	49%	3%	39%	1%	3%	5%
	DC	21	37	27%	3%	54%	8%	5%	3%
	DB	16	37	16%	0%	38%	41%	3%	3%

Note. Gp = Group; Corr. CV Cat. = Correct CV Category; LF = Labial-Front; LC = Labial-Central; LB = Labial-Back; CF = Coronal-Front; CC = Coronal-Central; CB = Coronal-Back; DF = Dorsal-Front; DC = Dorsal-Central; and DB = Dorsal-Back.

Intrasyllabic VC Sequences

Inventory. Early sessions contained 36 (M = 4.50, SD = 3.16) and later sessions contained 168 (M = 21.00, SD = 26.46) VC syllables (see Table 27). Most observations in the later sessions came from NH2 (N = 79) and NH4 (N = 42). Predicted VC sequences based on articulatory compatibility outnumbered diverse sequences in early (53%) and later (66%) sessions. The most frequently produced VC co-occurrences were central-labial (28/29%), front-coronal (25/35%), and central-coronal (42/13%). Table 24 displays the ratio of observed to expected ratios in VC co-occurrences produced by the children in early and later sessions. Children across groups produced patterns predicted by the Frame/Content Theory at levels above chance more often than non-predicted patterns.

Chi square for difference in relative frequencies could not be calculated validly due to insufficient observations per cells, particularly in the early sessions.

Table 24

Ratio of Observed to Expected Occurrences of Child VC Productions by Time

		Consonants		
Child	Vowels	Coronal	Labial	Dorsal
Early	Front	**1.63**	-	-
N = 36	Central	0.65	**1.55**	-
	Back	-	-	-
Late	Front	**1.40**	-	1.38
N = 168	Central	0.61	**2.00**	0.58
	Back	1.15	-	-

Target characteristics. The number of intrasyllabic VC targets increased over time from 742 (M = 92.75, SD = 83.02) to 1,054 (M = 131.75, SD = 66.01) in early and later sessions, respectively. Participants attempted diverse VC word targets across sessions (74/65%) with back-coronal (35/35%), central-coronal (18/21%), and front-coronal (15/26%) sequences attempted most often, as shown in Table 27. Table 25 displays observed to expected ratios for individual children in early and later sessions. No significant difference was found between the presence of predicted (Early: 8/10; Late: 10/13) and non-predicted VC co-occurrences (Early: 11/20; Late: 11/23) in word targets (Early: $\chi^2 = .65$, $p > .10$; Late: $\chi^2 = 1.21$, $p > .10$).

Table 25

Ratio of Observed to Expected Occurrences of VC Targets by Time

		Consonants		
Child	Vowels	Coronal	Labial	Dorsal
CI1-Early	Front	**-**	-	-
N = 44	Central	0.80	**1.68**	-
	Back	1.22	-	-
CI2-Early	Front	**0.86**	-	1.74
N = 65	Central	0.91	-	-
	Back	1.15	-	-

CI3-Early $N = 45$	Front	**1.02**	-	-
	Central	-	-	-
	Back	0.98	-	-
CI4-Early $N = 289$	Front	**1.30**	-	0.60
	Central	0.40	**1.08**	2.28
	Back	1.43	1.28	-
NH1-Early $N = 121$	Front	**1.13**	-	-
	Central	1.05	**1.37**	0.46
	Back	0.81	-	**2.11**
NH2-Early $N = 69$	Front	-	-	-
	Central	0.45	**2.38**	-
	Back	1.40	-	-
NH3-Early $N = 52$	Front	-	-	-
	Central	1.05	-	-
	Back	0.95	-	-
NH4-Early $N = 57$	Front	**0.76**	-	1.47
	Central	1.65	-	-
	Back	-	-	-
CI1-Late $N = 60$	Front	**0.93**	-	3.70
	Central	0.61	**7.89**	-
	Back	1.10	-	-
CI2-Late $N = 142$	Front	**1.09**	-	-
	Central	0.96	-	-
	Back	0.82	-	-
CI3-Late $N = 100$	Front	**1.09**	-	-
	Central	0.96	-	-
	Back	0.82	-	-
CI4-Late $N = 221$	Front	**1.03**	1.05	0.66
	Central	0.74	-	3.25
	Back	1.13	-	-
NH1-Late $N = 157$	Front	**1.18**	-	-
	Central	0.52	**2.32**	-

	Back	1.40	-	-
NH2-Late *N* = 187	Front	**1.03**	-	1.40
	Central	0.84	**2.67**	1.00
	Back	1.13	-	**0.64**
NH3-Late *N* = 24	Front	-	-	-
	Central	0.75	**1.35**	-
	Back	-	-	-
NH4-Late *N* = 163	Front	**0.88**	-	1.88
	Central	1.18	-	-
	Back	0.92	1.81	**1.09**

Accuracy. The primary change in accuracy over time involved shifting from singleton vowel (77/65%) to VC syllable (4/15%), though not necessarily the correct VC pattern (Table 27). Later VC syllables were split between correct (9%), partially correct (4%), and incorrect (2%) categories, but the effect of session was not statistically significant ($\chi^2 = 2.30$, $p > .10$). The majority of VC sequences in early sessions were partially omitted; later sessions marked the emergence of central-labial (21%) and central-coronal (18%) patterns. Observed to expected ratios, shown in Table 26, suggest that children across groups are more accurate on predicted VC patterns (2/3 in early and later sessions) and less accurate on non-predicted patterns (3/6 in early and 2/6 in later sessions). Chi square analysis could not be calculated due to insufficient cell values.

Table 26

Ratio of Observed to Expected Occurrences of Accurate VC Productions by Time

		Consonants		
Child	Vowels	Coronal	Labial	Dorsal
Early *N* = 742	Front	**1.03**	-	1.45
	Central	0.70	**1.86**	1.48
	Back	1.26	0.70	0.30
Late *N* = 1,054	Front	**1.03**	0.33	1.57
	Central	0.82	**2.44**	0.99
	Back	1.13	0.34	0.54

Production propensities based on articulatory compatibility guided VC inventories in both early and late sessions. Word targets included diverse VC patterns. The primary change in accuracy involved the transition from partial omissions to VC syllables. Singleton vowels dominated early sessions. The VC pattern emerged in later sessions, although participants did not necessarily match both vowel and consonant targets.

Table 27

Inventory, Targets, and Accuracy for Intrasyllabic VC Sequences by Time

Sess.	VC	Inventory (*N*)	Targets (*N*)	Levels of accuracy					
				Correct	Corr. VC cat.	Partially correct	Incorrect	Partially Omitted	Omitted
Early	FC	9	113	6%	0%	1%	3%	77%	13%
	FL	1	1	100%	0%	0%	0%	0%	0%
	FD	1	47	0%	0%	4%	17%	79%	0%
	CC	15	135	4%	1%	1%	4%	73%	16%
	CL	10	63	10%	0%	0%	54%	37%	0%
	CD	0	84	0%	0%	0%	2%	98%	0%
	BC	0	256	0%	0%	2%	2%	83%	14%
	BL	0	25	0%	0%	8%	4%	88%	0%
	BD	0	18	0%	0%	6%	11%	83%	0%
Late	FC	58	272	18%	1%	2%	7%	51%	21%
	FL	0	11	0%	0%	9%	9%	73%	9%
	FD	9	40	0%	0%	20%	3%	70%	8%
	CC	21	223	3%	0%	1%	2%	84%	11%
	CL	48	84	21%	2%	1%	30%	45%	0%
	CD	5	26	8%	4%	12%	4%	69%	4%
	BC	17	367	5%	0%	4%	10%	71%	10%
	BL	5	14	7%	0%	14%	14%	64%	0%
	BD	5	17	6%	0%	29%	12%	53%	0%

Note. Sess. = Session; Corr. VC Cat. = Correct VC Category; FC = Front-Central; FL = Front-Labial; FD = Front-Dorsal; CC = Central-Coronal; CL = Central-Labial; CD = Central-Dorsal; BC = Back-Central; BL = Back-Labial; and BD = Back-Dorsal.

Intersyllabic Vowel Relationships in CVCV Contexts: Front-Back Dimension

Inventory. Intersyllabic vowel sequences totaled 78 in early sessions (M = 9.75, SD = 10.66) and 425 in later sessions (M = 53.13, SD = 58.94) (see Table 28). Nearly all sequences produced in early and later sessions were reduplicated (73/79%). Central vowel reduplication (64/24%) was most common in early sessions and front reduplication (53%) occurred most frequently in later sessions.

Target characteristics. Early sessions contained fewer V1-V2 patterns (N = 101, M = 6.44, SD = 19.23) than later sessions (N = 466, M = 40.22, SD = 92.63), as shown in Table 28. Vowel sequences with front-back reduplication were attempted more frequently (88/82%) than variegated sequences. Front-front and central-central were the most frequent vowel patterns in word targets over time, although the relative proportions changed from early to later sessions. Central vowel reduplication (51/21%) dominated early sessions while front vowel reduplication (36/61%) dominated later sessions.

Accuracy. Correct productions increased (57/78%) and partial omissions decreased (23/9%) from early to later sessions, as displayed in Table 28. Participants across groups tended to produce correct V2 over V1 and were more likely to omit V2 than V1 in later versus early sessions (odds ratio = 26.3, $\chi^2 = 159.73$, $p < .0001$). Even though differences existed between early and later sessions, the effect of time on V1-V2 accuracy did not reach statistical significance ($\chi^2 = .66$, $p > .10$).

Time marginally affected intersyllabic vowel accuracy but the effect depended on group ($\chi^2 = 3.13$, $p<.10$). NH children were 7 times more likely to show improved accuracy from early to later sessions (odds ratio = 6.9, $\chi^2 = 7.70$, $p < .001$). NH scores improved from 43% to 83%, mostly due to decrease in partial omissions (32/6%). In contrast, the CI group declined from 78% to 69%.

Overall accuracy was greater for front-back reduplication (60/82%) than variegation (42/57%) over time, as shown in Figure 10. Error patterns were consistent across time. Participants tended toward partially correct (12/8%) or partially omitted (25/10%) productions of reduplicated sequences compared to partially correct (33/20%) or incorrect productions (17/20%) of variegated sequences.

Figure 10

Accuracy of Reduplicated vs. Variegated Vowel Front-back Sequences by Time

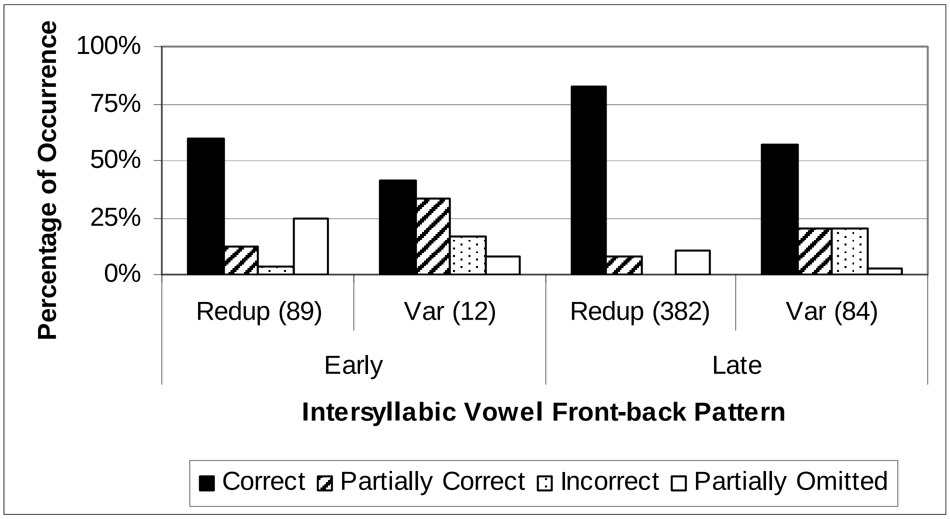


Table 28

Inventory, Targets, and Accuracy for Intersyllabic Vowel Front-Back Sequences by Time

Sess.	VV type	Inventory (N)	Targets (N)	Levels of Accuracy: Correct	Partially Correct	Incorrect	Partially Omitted
Early	FF	7	36	19%	28%	6%	47%
	FC	4	0				
	FB	2	3	0%	33%	67%	0%
	CF	10	9	56%	33%	0%	11%
	CC	50	52	88%	2%	0%	10%
	CB	5	0				
	BF	0	0				
	BC	0	0				
	BB	0	1	0%	0%	100%	0%
Late	FF	226	282	78%	9%	0%	13%
	FC	7	0				
	FB	1	5	0%	60%	40%	0%
	CF	68	58	78%	9%	10%	3%
	CC	100	97	93%	4%	0%	3%
	CB	5	0				
	BF	5	21	14%	43%	43%	0%
	BC	5	0				
	BB	8	3	100%	0%	0%	0%

Note. Sess. = Session; F = Front; C = Central; and B = Back.

Table 28 displays differences in patterns by early and late session. Central vowel reduplication was the most frequently produced, attempted, and accurate pattern in early sessions. Although production and target characteristic patterns were limited to front-front, central-central, and central-front sequences, later sessions illustrated greater diversity in correct productions of both vowels in the intersyllabic sequence. Accuracy exceeded 75% for all reduplicated patterns as well as the central-front variegated pattern. Overall, participants diversified their inventories and word targets from early to later sessions and improved accuracy of intersyllabic vowel sequences over time.

Intersyllabic Vowel Relationships in CVCV Contexts: Height Dimension

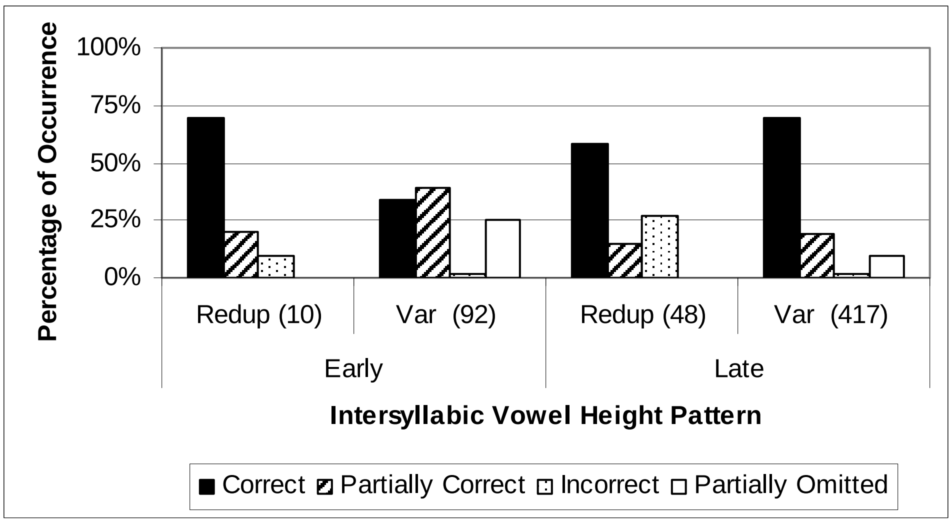
Inventory. There were 79 (*M* = 9.88, *SD* = 10.83) intersyllabic vowel sequences in early sessions and 424 (*M* = 53.00, *SD* = 58.96) in later sessions. Early session productions were balanced between reduplicated and variegated patterns (51% and 49%, respectively). As shown in Table 29, mid and low reduplication and low-mid variegation occurred most frequently in earlier sessions. Later sessions contained 3 times as many variegated as reduplicated sequences. Variegations moving from a lower to higher vowel (low-mid, low-high, mid-high) accounted for 75% of all productions.

Target characteristics. Early sessions contained 102 (*M* = 12.75, *SD* = 16.51) intersyllabic vowel sequences. Later sessions included 465 (*M* = 58.13, *SD* = 65.11) vowel-vowel patterns. The majority of vowel sequences came from CI4 (*N* = 25) and NH1 (*N* = 49) in early sessions and NH4 (*N* = 207) in later sessions. However, characteristic patterns of the children's lexicons did not differ considerably from each other. As shown in Table 29, sequences with variegated height comprised the majority (90/90%) of intersyllabic vowel sequences in targets, in contrast to the predominance of front-back reduplication. Ninety percent of target variegations involved a change from low to high (i.e., low-mid, low-high, mid-high) in both early and later sessions.

Accuracy. Participants in both groups better matched vowel height of reduplicated than variegated sequences in early sessions (70% versus 34%) (see Table 29). Later sessions revealed a different pattern, with greater height accuracy of variegated than reduplicated sequences (69% versus 58%). Partially correct realizations chiefly occurred with variegated sequences (95/92%) and showed no systematic pattern of V1 or V2 correctness. Partial omissions generally involved V2 deletion and only occurred in variegated patterns, particularly those moving from a lower to higher vowel. Figure 11 shows the effect of reduplication and variegation on levels of accuracy over time.

Figure 11

Accuracy of Reduplicated vs. Variegated Vowel Height Sequences by Time



Overall accuracy increased (38/68%) with a concurrent reduction in partially correct productions (38/18%) and partial omissions (23/9%) from early to later sessions. Although the effect of session was not statistically significant ($\chi^2 = 0.56$, $p > .10$), a marginal interaction effect for group x session emerged ($\chi^2 = 3.46$, $p < .10$). V1-V2 accuracy of the NH group improved over time (32/71%) ($\chi^2 = 9.86$, $p < .01$). CI children outperformed their hearing contemporaries in the early sessions ($\chi^2 = 6.08$, $p < .05$).

Participants tended to attempt intersyllabic vowel sequences in CVCV contexts with front-back reduplication and height variegation. Participants matched vowel characteristics of both V1 and V2 in intersyllabic contexts, particularly in reduplicated sequences. Productions more often contained an accurate second vowel in partially correct errors and deletion of the second vowel in partial omissions.

Table 29

Inventory, Targets, and Accuracy for Intersyllabic Vowel Height Sequences by Time

Sess.	VV type	Inventory (N)	Targets (N)	Levels of Accuracy: Correct	Partially Correct	Incorrect	Partially Omitted
Early	HH	0	2	0%	50%	50%	0%
	HM	0	0				
	HL	0	0				
	MH	1	34	21%	32%	0%	47%
	MM	6	3	100%	0%	0%	0%
	ML	2	0				
	LH	4	9	44%	22%	11%	22%
	LM	11	49	41%	47%	2%	10%
	LL	7	5	80%	20%	0%	0%
Late	HH	6	25	40%	20%	40%	0%
	HM	4	0				
	HL	0	0				
	MH	21	148	61%	19%	5%	15%
	MM	6	11	73%	0%	27%	0%
	ML	0	0				
	LH	18	189	82%	10%	0%	8%
	LM	7	80	54%	40%	3%	4%
	LL	2	12	83%	17%	0%	0%

Note. Sess. = Session; H = High; M = Mid; and L = Low.

Intersyllabic Consonant Relationships in CVC and CVCV Contexts: Place

Inventory. Early sessions contained 97 (*M* =112.13, *SD* = 11.19) and later sessions contained 336 (*M* =42.00, *SD* = 47.26) for a total of 433 intersyllabic consonant sequences produced by the children across groups. Reduplicated sequences accounted for the bulk of productions (91/88%) throughout the study, as shown in Table 30. The most frequently produced patterns were labial-labial (72/49%) and coronal-coronal (49/36%).

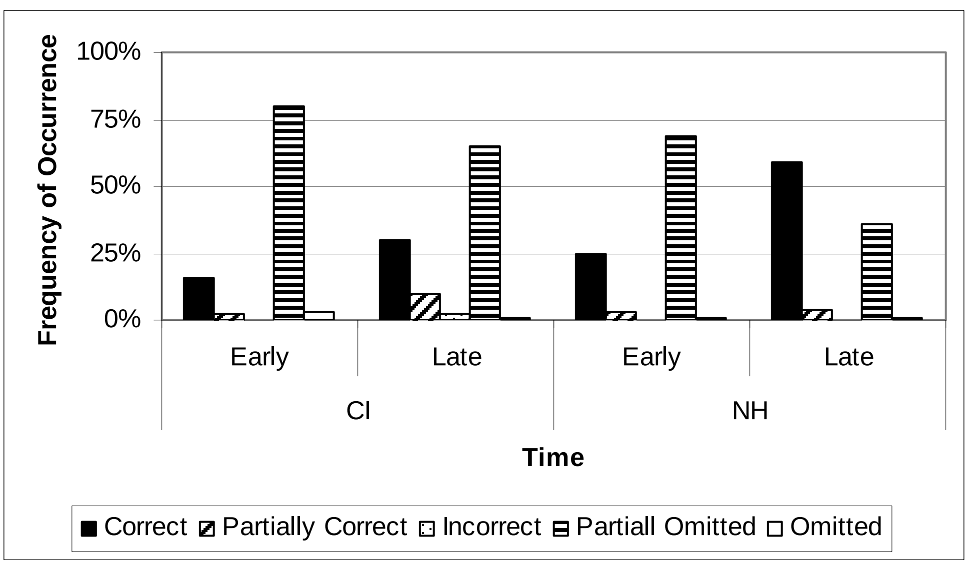
Target characteristics. One-third of word attempts occurred in early sessions (*N* = 451, *M* = 56.38, *SD* = 53.86) and two-thirds occurred in later sessions (*N* = 857, *M* =107.13, *SD* = 83.58). Early sessions included more CVC than CVCV word targets (348 and 103, respectively). Later sessions had a more even balance between the two word shapes with 440 CVC and 417 CVCV targets.

Variegated sequences accounted for 54% of word attempts in early sessions but only 38% in later sessions. Reduplication-variegation patterns differed by word shape. Participants were more likely to attempt diverse CVC targets (65/70%), particularly labial-coronal sequences (58%/36%). Reduplicated CVCV occurred most frequently with labial-labial in early and later sessions (88/43%) and coronal-coronal in later sessions (26%). Table 30 describes intersyllabic consonant patterns in early and later sessions.

Accuracy. Intersyllabic place accuracy significantly increased (19/49%) from early to later sessions, primarily due to a decline in partial omissions ($\chi^2 = 4.38$, $p<.05$) (Table 30). The effect of session was mutually dependent on group ($\chi^2 = 5.12$, $p<.05$) (Figure 12). Both groups improved accuracy and committed fewer partial omission errors in later sessions. However, the effect was only significant for the NH children, who advanced from 25% to 59% accuracy with a 35% decrease in partial omissions (odds ratio = 7.3, $\chi^2 = 36.1$, $p < .0001$). The NH group was also 4 times more likely to outperform their CI counterparts in later sessions (odds ratio = 4.1, $\chi^2 = 14.5$, $p < .0001$).

Figure 12

Group by Session Interaction Effect in Intersyllabic Consonant Place Accuracy



Participants favored targets with coronal and labial reduplication or variegation patterns involving labial and coronal consonants. Intersyllabic place accuracy improved over time for both groups. Even though more CVC targets were attempted, the children achieved greater accuracy on CVCV forms. This apparent dichotomy relates to the prevalence of final consonant deletion in CVC word forms.

Table 30

Inventory, Targets, and Accuracy for Intersyllabic Consonant Place Sequences by Time

				Levels of Accuracy				
Sess.	CC Type	Inventory (N)	Targets (N)	Correct	Partially Correct	Incorrect	Partially Omitted	Omitted
Early	LL	70	146	47%	2%	0%	49%	1%
	LC	7	204	1%	0%	0%	98%	1%
	LD	0	10	0%	20%	0%	80%	0%
	CL	2	2	0%	50%	0%	50%	0%
	CC	18	60	27%	0%	0%	68%	5%
	CD	0	8	0%	25%	0%	75%	0%
	DL	0	0					
	DC	0	20	0%	10%	0%	45%	45%
	DD	0	1	0%	0%	0%	100%	0%
Late	LL	166	289	66%	3%	2%	27%	0%
	LC	14	188	15%	5%	0%	78%	1%
	LD	2	21	33%	19%	0%	48%	0%
	CL	18	72	26%	4%	0%	67%	3%
	CC	121	222	64%	1%	0%	34%	1%
	CD	1	14	50%	21%	0%	29%	0%
	DL	2	11	18%	9%	9%	64%	0%
	DC	2	22	5%	9%	0%	86%	0%
	DD	10	18	100%	0%	0%	0%	0%

Note. Sess. = Session; L = Labial; C = Coronal; and D = Dorsal.

Intersyllabic Consonant Relationships in CVC and CVCV Contexts: Manner

Inventory. Participants across groups produced 101 intersyllabic consonant sequences in early sessions (*M* =12.63, *SD* = 12.48) and 386 in later sessions (*M* =48.25, *SD* = 72.72). Reduplicated sequences were most common (96/86%), particularly stop (50/24%) and nasal reduplication (45/61%). Detailed results are displayed in Table 31.

Target characteristics. There were 175 consonant patterns (*M* =21.88, *SD* = 24.25) in early sessions and 536 (*M* =167.00, *SD* = 80.79) in later sessions, totaling 711. Most word targets were CVCV (72%) rather than CVC and reduplicated patterns were preferred (74/82%). Table 31 details frequency of intersyllabic patterns by session.

Accuracy. Higher C1-C2 accuracy (53/72%) and fewer partial omissions (39/18%) were found in later sessions. Session alone did not significantly impact intersyllabic consonant accuracy (χ^2 = .17, p > .10), but it did interact with group (χ^2 = 5.57, p < .05). The CI group did not show much change from over time. The NH group was 3 times more likely to improve (odds ratio = 2.26, χ^2 = 3.3, p < .10). Correct C1-C2 manner increased (50/72%) and partial omissions decreased (47/17%) from early to later sessions in the NH cohort. Participants matched C1 and C2 manner more often in reduplicated (67/79%) than variegated patterns (11/36%) (Table 31). Partial omissions accounted for a greater portion of variegated attempts (66/53%), principally C2 deletion.

Overall results for intersyllabic consonant manner relationships strongly support a preference for reduplicated sequences in inventories, targets, and accurate productions in both early and later sessions. The most pervasive change in accuracy involved the transition from partial omissions to correct productions from early to later sessions.

Table 31

Inventory, Targets, and Accuracy for Intersyllabic Consonant Manner Sequences by Time

				Level of accuracy				
Sess.	CC type	Inventory	Targets	Correct	Partially correct	Incorrect	Partially omitted	Omitted
Early	NN	50	55	89%	0%	0%	11%	0%
	NF	0	0					
	NS	0	0					
	FN	2	2	100%	0%	0%	0%	0%
	FF	1	2	50%	0%	0%	50%	0%
	FS	0	30	0%	27%	0%	70%	3%
	SN	3	13	23%	8%	0%	69%	0%
	SF	0	0					
	SS	45	73	51%	0%	0%	48%	1%
Late	NN	94	123	81%	3%	0%	15%	0%
	NF	6	9	0%	0%	0%	100%	0%
	NS	29	32	81%	9%	0%	9%	0%
	FN	2	0					
	FF	0	13	0%	69%	0%	31%	0%
	FS	4	31	10%	6%	0%	74%	10%
	SN	5	17	24%	12%	0%	65%	0%
	SF	10	5	20%	0%	0%	80%	0%
	SS	236	306	82%	3%	0%	15%	1%

Note. Sess. = Session; S = Stop; N = Nasal; and F = Fricative.

Summary

Segments and sequences produced most frequently were also most accurate across groups and sessions. Lexical targets were not selected based on child production patterns but reflected more diverse phonetic patterns.

Results revealed little difference between the CI and NH children. The only significant effect for group occurred in consonants, where the NH group omitted fewer final consonants. Word position affected accuracy for both groups with more correct productions in initial position for consonants and VC sequences, and in medial position for vowels. Most omissions occurred in final position for both segments and serial patterns, particularly in CVC words.

Both groups increased accuracy over time, but changes in the levels of accuracy varied by outcome measure. Consonants improved most dramatically, shifting from omissions, the most severe error, to correct productions. Vowels and CV patterns transitioned from partially correct to correct productions in later sessions. Partial omissions (i.e., vowel singletons) toward production of progressed toward production of the correct number of segments within and across syllables. Overall, accuracy of segments and serial patterns in early words improved from early to later sessions for both groups, but the two groups did not differ significantly from each other.

Chapter 4
Discussion

Speech intelligibility is a major factor in acquiring communication competence (Connolly, 1986; Kent et al., 1989). The ability to accurately match segments and sequences in early words is an important initial component of acquiring intelligible speech. Underlying the development of accuracy in young children are production system and auditory perceptual capacities that support the emergence of vocal forms. The goal of this study was to evaluate the acquisition of speech accuracy in early words for two populations differing in auditory history. This comparison can help to elucidate the relative impact of the production and perception systems in initial steps toward lexical accuracy.

Similarities between the groups

Similarities between the NH and CI groups considerably outnumbered differences. Consonant accuracy was the only area in which they diverged significantly. In both groups, the most accurate segments and sequences were strongly related to the most frequent patterns in their phonetic inventories (e.g. labial and stop consonants; intrasyllabic CV pairings with articulatory compatibility). Error patterns were also largely similar. Both groups favored substitution over omission errors. The word targets attempted by these children formed a third dimension of similarity; both groups of children attempted word targets containing sequences and segments that were more diverse than their own production inventories.

The two groups performed similarly overall with respect to inventories, targets, and accuracy in this earliest lexical period with the exception of consonant analyses. These results indicate the resilience of other outcome measures (i.e., vowel segments, intrasyllabic and intersyllabic sequences) in response to perturbations in the auditory system. That is, once the young CI recipients acquired enough audition to instantiate syllable-based speech, the function of the production system is more responsible for early lexical accuracy patterns than the auditory perceptual system.

Results generally agreed with previous research, although some important differences were found in vowel accuracy and word target characteristics. One study (Paschall, 1983) reported conflicting results on the relationship between inventory and accuracy. Contrary to the predominance of mid and low vowels in inventories and accurate productions shown by these children, Paschall (1983) found that 18-month-olds with normal hearing produced equal frequencies of high and mid vowels (36% and 43%, respectively) but matched high and low vowels in spontaneous speech more frequently (73% and 65%, respectively). Greater accuracy of high vowels may reflect greater articulatory control as a function of age. Relative to these children, Paschall's participants were chronologically older (chronological age, CA) than the NH group (18 months vs. 11-17 months) and had longer auditory experience (hearing age, HA) than the CI group (18 months vs. 6-10 months).

Overall similarities in the ability to match segments and sequences in word targets arose despite differences in auditory history and chronological age. The close relationship between inventory and accuracy was comparable across the two groups. This similarity also supports a strong influence of the production system. The children used available resources to achieve accurate productions of their earliest word forms. This finding implies that accuracy patterns are founded on common components in the systems of the CI and NH groups. These common components include an intact production system as well as functioning support from the visual and kinesthetic systems.

Research on visual acuity has shown periods of rapid growth from birth through 6 months and relatively slower development thereafter through age 3 (Adams, Mercer, & Courage, 2004; van Hof-van Duin & Mohn, 1986). Because the chronological ages of the children in this study fall within the period of slower growth, it is unlikely that visual development level greatly differed between the groups. No studies have reported speech-related kinesthetic ability under age 3 years, although sensitivity does not change considerably between 3 and 5 years and undergoes only subtle refinement through adulthood (Chang, Ohde, & Conture, 2002; Geitz, 1998). Previous investigators have found little developmental change in the visual or kinesthetic domains for the chronological ages assessed; therefore, similarities in early speech accuracy most likely point toward a robust effect of the production system.

Lexical target characteristics, although alike in both groups, did not always correspond to the children's phonetic inventories. Consonant repertoires and word targets were both dominated by labial, coronal, and stop consonants, as noted in previous research (Ferguson & Farwell, 1975; Ferguson et al., 1973; French, 1989; Vihman et al., 1994). In contrast, CV and VC sequences within syllables were more diverse in the children's lexical targets than in their phonetic inventories (Davis et al., 2003; Warner-Czyz et al., 2005b, 2005c). The apparent dichotomy in these findings on target characteristics centers on methodological variations. The studies focused on consonants were of phones found primarily in word initial position (Ferguson & Farwell, 1975; Ferguson et al., 1973; French, 1989; Vihman et al., 1994). In contrast, the studies of intrasyllabic sequences analyzed patterns in phonetic contexts and across word positions (Davis et al., 2003; Warner-Czyz et al., 2005b, 2005c). Because lexical targets were not limited by preferences within the children's behavioral repertoire, they indicate influence from factors other than the production system.

Lexical acquisition requires the child to pay attention to sounds and sequences of the ambient language in addition to linking those patterns to semantic concepts. Stoel-Gammon (1998) has pointed out the importance of the auditory feedback loop in lexical development. She asserts that access to the speech of others is crucial to the acquisition of adult language forms. These children attempted more diverse word targets that more closely reflected characteristics of the ambient language than their own restricted production inventory. This type of results suggests both groups of children were sensitive to salient sound patterns in the communicative environment, indirectly implicating input through auditory pathways as the source of diverse word targets the children attempted.

Although the CI children had a dramatically different auditory history in the first year of life, they were able to quickly begin the process of attuning to the links between salient word meanings and their phonetic manifestations. With the exception of consonants, they were also able to achieve accuracy similar to their NH peers from the onset of meaningful word use.

Differences between the groups

Aside from the numerous common findings between the two groups, a significant difference in consonant accuracy arose. This finding is not surprising based on auditory and production system components of consonant phonemes. Constriction differences between consonants and vowels create characteristic perceptual disparities (Pickett, 1999). The open vocal tract of vowels leads to strong, voice-pulsed sounds with longer duration and steady state parameters than consonants. In contrast, consonant constrictions result in lower intensity (i.e., voiced stops, glides, nasals), aperiodic sound (i.e., fricatives), or absence of sound (i.e., voiceless stops). The reduced perceptual salience of consonants relative to vowels may explain why vowel accuracy surpassed consonant accuracy for this study and in other studies of young children with normal hearing (Stoel-Gammon & Herrington, 1990; Templin, 1957) and with CI (Blamey, Barry, Bow, et al., 2001; Ertmer, 2001; Ertmer & Mellon, 2001).

The production system might also be responsible for differences in consonant accuracy. Fricatives, affricates, and liquids are late-developing consonants compared to the prevalence of stops, nasals, and glides in the early repertoires of infants and toddlers. (Gildersleeve-Neumann, Davis, & MacNeilage, 2000). Their infrequent presence in babbling behaviors and accuracy suggest the potential of motor constraints on their production (Gildersleeve-Neumann et al., 2000; Sander, 1972). Fricatives require a narrow constriction with a small range of error relative to size. Affricate production entails a complete occlusion (i.e., stop) followed by formation of a small aperture (i.e., fricative). Liquids require a relatively unusual tongue configuration. Stricter articulatory configurations, a production system effect, may preclude the presence of fricatives, affricates, and liquids in child inventories and accurate productions.

The main difference relative to accuracy between groups involved more frequent omission of word-final consonants by the CI children. Elimination of the final consonant could reflect production system or auditory perceptual influences. In hearing children, syllables with consonant initiation and vowel termination are common in both babbling and first words in English and across languages (Davis & MacNeilage, 1995; Davis et al., 2002, Boysson-Bardies & Vihman, 1991). However, preference for open CV syllables was found in the CI children as well, rendering differences in production system capacities an unlikely explanation for the relative differences between the two groups.

Decreased auditory perceptibility may result from lower overall intensity (e.g., non-sibilant fricatives) or longer vowel duration followed by shorter consonant duration (e.g., voiced consonants) (Balise & Diehl, 1994; Pickett, 1999). Both possibilities may lead to forward masking due to energy of the preceding vowel. This auditory-based explanation appears as one viable perspective on the relatively more frequently observed pattern of final consonant omissions. The CI children were more likely to omit word-final consonants as they are generally less intense and of shorter duration than vowels; thus less apparent in the input signal.

Accuracy levels for both groups may relate to changes in the complexity of word targets from early to later sessions. Reduplications were the most common intersyllabic vowel sequence type for both child productions and word targets attempted across the two groups for the whole period of the study. However, the CI group attempted 10% *more* variegated sequences in later sessions and the NH group attempted 15% *fewer* variegated sequences. The increase in reduplicated word targets by the NH group appears related to their preference for vowel reduplication across syllables, thereby leading to higher accuracy. However, the attempt at more variegated and complex vowel targets by the CI group suggests internalization of sequences for semantic targets present in the ambient language. The attempts at more complex word target types in the CI versus NH children may reflect their differences in chronological age as well as an accelerated rate of speech and language acquisition often found in children implanted before age 2 years (Gillis et al., 2002; Govaerts et al., 2002; Hammes et al., 2002; Moore & Bass-Ringdahl, 2000; Novak et al., 2000).

Early speech accuracy can be studied based on the individual components of production and perception, to gauge the impact of each on early vocal development.

However, viewing the two as separate entities detracts from the considerations that the two subsystems may interact in the emergence of intelligible speech. The interdependence of contributing components as well as potential developmental nonlinearities can be considered from a systems-based approach. The dynamic systems (DS) perspective proposes that complex behaviors emerge from a confluence of multiple heterogeneous inputs (i.e. perceptual, neural, motor, and social) based on use (e.g., Clark, 1997; Gibson & Pick, 2000; Smith & Katz, 1996; Smith & Thelen, 1993; Thelen & Smith, 1994; van Gelder & Port, 1995). In this view, factors contributing to behavioral output may change at different rates resulting in gradual or abrupt change over time in behavioral complexity.

DS theory labels these diverse system inputs as *control parameters* that constrain the output measure. For example, Thelen and Ulrich (1991) have pointed out that independent walking requires coordinated alternating stepping patterns, separate flexion of the hip and knee, postural control, and leg strength. Likewise, control parameters affecting early lexical accuracy may include the production (e.g., jaw oscillations, independent articulator control), perceptual (e.g., vision, audition, kinesthetic), and conceptual (e.g., knowledge of ideas) systems. When the control parameters do not change, the system achieves a state of equilibrium, known in dynamic terminology as a *stable state*. A change in control parameter leads to system reorganization, characterized by a *phase shift*, or period of instability (Bremner, 1997; Norton, 1995; Thelen, 1992; Thelen & Smith, 1994).

The NH group in this study functioned in a stable state because they did not undergo any perturbations of production or perceptual parameters during the early word period. Prior to implantation, the CI group possessed an intact production system but compromised auditory function. Access to consistent auditory input via the CI device led to a phase shift in vocal development patterns. Inventories typified by visible labial consonants, neutral vowel qualities, and visible CV patterns (i.e., labial-back) (von Hapsburg, Davis, & MacNeilage, submitted) gave way to diversified inventories and syllable based speech patterning. Once these children integrated audition into the system, vocal development unfolded similarly to the NH group in early words. By the time the CI children reached the early word period investigated in this work, they had largely overcome sensory differences to produce lexicons with equal diversity and accuracy as hearing children at the same vocal development level.

A cornerstone of DS theory involves not only the incorporation of diverse factors, but also how the balance between these inputs changes as a function of time. Continuous changes occur as the system integrates contributions from multiple subsystems via self-organization. The original intent of this study was to investigate developmental change over time to determine potentially rate-limiting factors in early speech accuracy, similar to Thelen & Ulrich (1991). However, initial analysis of the data showed no evidence of monthly changes for any measure of accuracy analyzed. The analysis was amended by collapsing sessions into *early* and *late* categories. Results showed evidence of general improvement, but collapsing the data into two main data points precluded comparison of linear and nonlinear development over time.

The data on the two groups indicates, however, that the rate of development did not always follow the same trajectory across measures or groups. CV syllable accuracy improved by a factor of 2.0 but VC syllable accuracy only improved by a factor of 1.4. Both sets of children increased consonant accuracy, but the NH participants were 3.2 times more accurate at the study's conclusion. The CI participants were only 1.3 times more accurate at the end of the study.

In addition to differences in the rate of acquisition, changes from early to later sessions were not always positive. The regression to a lower proportion of correct productions of intersyllabic vowel sequences by the CI group may underscore the importance of viewing development as a nonlinear process. Prather et al. (1975) analyzed the articulation skills of 147 children between the ages of 2 and 4 years. Results showed that some vowels were produced correctly by 75% of children at an earlier age but not maintained at older ages. Such reversals may represent sampling variations, but the occurrence of regressions is part of the inherent accelerations and decelerations in development (Thelen & Smith, 1994). Prolonged evaluation across a longer period during acquisition of phonetic accuracy may describe more comprehensively the developmental trajectory of young CI recipients in overcoming regressions to become more accurate.

Although developmental nonlinearities could not be assessed in this study, the effect of the time variable was evident. Vocal development in these very young CI recipients did not show a maturational delay by unfolding in the same timeline as the hearing children (Eggermont et al., 1997; Ponton, Don, Eggermont, Waring, Kwong, & Masuda, 1996; Ponton et al., 1999). Rather, the two groups entered the early word period at different hearing and chronological ages. The NH group required 11 to 17 months HA and CA before onset of first words. For the CI group, word onset began at 6 to10 months HA and 18 to 32 months CA. This accelerated rate into first phases of speech and language development confirms other studies of early-implanted children with device activation prior to age 2 years (Gillis et al., 2002; Govaerts et al., 2002; Hammes et al., 2002; Moore & Bass-Ringdahl, 2000; Novak et al., 2000).

Steeper developmental trajectories in this early-implanted population may result from access to sound when central auditory nervous system and auditory cortex function are minimally degenerate and/or highly plastic (Mellon, 2000; Ryugo, Limb, & Redd, 2000; Sharma, Dorman, & Spahr, 2002; Sharma, Dorman, Spahr, & Todd, 2002). Earlier provision of acoustic input can then initiate more spontaneous rather than "therapized" development (Yoshinaga-Itano, 2002). That is, early-implanted children may be better able to take advantage of production and perception system inputs in more typical fashion rather than having to re-learn articulatory movements. Maladaptive strategies such as ingressive productions (Higgins et al., 1996) and non-native phonemic contrasts (Chin, 2002) have been documented in *older* CI users, but these non-standard vocalization patterns were not present in this early-implanted group.

The younger implantation age for participants in this study may account for some of the differences between these results and previous studies of pediatric CI users. The most apparent differences involved acquisition of vowel accuracy. These CI children best matched front and central vowel qualities. Tobey et al. (1994) found the highest accuracy for back vowels in older children using an imitation paradigm. In addition to differences in accurate vowel productions, vowel error patterns diverged from previous research with older children. The CI group in this study was 4 times more likely to substitute than omit a vowel, consistent with Paschall's (1983) study of 18-month-old hearing infants, who were 6 times more likely to use vowel substitutions than omissions. Tye-Murray and Kirk (1993) found that children implanted after 3 years showed vowel omission errors through 18 months post-implant before shifting to substitution errors at 2 and 3 years post-implant. The disparity in results for these younger CI recipients suggests that early-implanted children may more closely resemble their chronological-age peers than later-implanted children who were also using more primitive CI devices and strategies.

As implantation age has decreased, sophistication of CI devices has improved dramatically. Thus, the proposed differences in age at implantation might be confounded by differences in CI devices and processing strategies. Later-implanted children who participated in earlier studies were more likely to use more primitive CI devices and processing strategies (Tobey et al., 1994; Tye-Murray & Kirk, 1993; Tye-Murray et al., 1995). The children in this study used waveform coding strategies (i.e., Continuous Interleaved Sampling (CIS)) providing more high frequency information and a higher rate of stimulation than the feature extraction strategies (i.e., F0F1F2 and MPEAK) used in the studies by Tobey et al. (1994) and Tye-Murray (Tye-Murray & Kirk, 1993; Tye-Murray et al., 1995). Higher rates of stimulation support a more faithful representation of modulation waveforms to more closely mimic the response of the normal auditory system (Wilson, 1997). Because this work included children implanted younger with more advanced CI systems, differences in accuracy and error types might reflect an amalgamation of implantation age, CI device, and processing strategy.

Future directions

More detailed analysis

Consonant and vowel segments were evaluated by both horizontal (consonant place, vowel front-back) and vertical dimensions (consonant manner, vowel height). Two-segment intersyllabic sequences in this study were limited to reduplication or variegation in terms of one dimension or the other. However, children often produce total reduplication of consonants (“mommy”) or vowels (“tepee”) or the entire syllable (“dada”). By the same token, variegations might include changes in both dimensions. Total reduplication and total variegation of consonants, vowels, and syllables should be evaluated in child productions, targets attempted, and accuracy for a fuller understanding of how intersyllabic accuracy emerges over time.

In addition, accuracy and error patterns were assessed as a function of time. Types of sounds and sequences the children used as substitutions were not evaluated. Previous research has reported that children draw from their phonetic repertoire of segments (French, 1989; Otomo & Stoel-Gammon, 1992) and syllables (Davis et al., 2003). Because the children may not have the ability to produce the segments or sequences in the word target correctly, they revert to a maximum operational level (Cohen, 1988; Hunter & Ames, 1988) by producing the most prevalent elements in their inventories with which they have the most experience. This substitution pattern reflects a “regression” to favored articulatory patterns of canonical babbling at the cost of a correct phonetic production. This type of finding is consistent with Thelen and Ulrich’s (1991) results for gross motor development. They suggest that the child uses available resources to “bootstrap” his way to more complex behaviors. Information on substitutions employed for targets may help to more fully understand the production system components of transition to higher levels of accuracy.

More participants

Very few differences were found between the CI and NH groups. Because the sample size is small, results may need to be interpreted with caution. The similarity in the acquisition of accuracy between the two groups may relate to various demographic factors such as age at implantation, communication mode, and device type.

Age at implantation. CI recipients in this study acquired words at an accelerated rate and achieved similar levels of accuracy relative to their hearing counterparts. These results mirror the faster acquisition of speech and language skills in found in children who receive CI before 2 years (Gillis et al., 2002; Govaerts et al., 2002; Hammes et al., 2002; Novak et al., 2000) and differ from studies of older children suggesting maturational delay via a “thawing period” (Eggermont et al., 1997; Ponton et al., 1999). Behavioral and physiological changes in early- versus later- implanted children may indicate a period of neuroplasticity in which central auditory nervous system and auditory cortex respond best – and more typically - to sound input (Mellon, 2000; Ryugo et al., 2000; Sharma, Dorman, & Spahr, 2002; Sharma, Dorman, Spahr, & Todd, 2002).

Although investigations have suggested that children implanted before age 2 years perform better than those implanted later, differences among this younger group have not been studied frequently (although see Warner-Czyz et al., 2005a). Children implanted at even earlier ages (e.g. before 1 year) may perform comparably to hearing children not only at the reduced hearing ages, but also at similar *chronological* ages (Gillis et al., 2002). Such findings, if consistent, could support different levels of plasticity of the neural system within the first two years of life regarding the ability to integrate multimodal inputs (i.e., production and perception)

CI system. CI device type and processing strategy may also influence how accuracy changes over time. Early-implanted children receive continually more sophisticated devices and processing strategies that aim to imitate the normal auditory system using rapid transmission of waveform transformations. Davis et al. (2004) found that type of CI device does not necessarily change behavioral outcomes in this very young population. However, if electrophysiological studies reveal a difference in central auditory development amongst children implanted before 3.5 years (e.g., differences between children implanted at 1 versus 2 versus 3 years), the implementation of different processing strategies for different ages may be necessary.

Communication Mode. The children in this study all communicated orally. Previous research has shown better vocal development outcomes for children trained in oral-only than total communication programs (TC, i.e., manually coded language plus speech) (e.g., Miyamoto, Kirk, Robbins, Todd, Riley, & Pisoni, 1997; Robbins, Kirk, Osberger, & Ertmer, 1995). How children exposed to TC develop speech accuracy could be revealing. These children may already use conventional signs in intentional communications prior to spoken word onset (Gillis et al., 2002). Thus, they have already been exposed to the basic semantic underpinning of the earliest lexical stage (Bates, 1979; Bloom, 1993; Wetherby, Reichle, & Pierce, 1998). They may be better prepared cognitively to enter the early word period. Children in TC programs may possibly exhibit a more diverse vocabulary based on their lexical "readiness". The transfer of this readiness to their ability to match word target characteristics is unclear.

Because this study included only 4 participants each in the CI and in the NH groups, it is difficult to fully explore the impact of demographic characteristics like implantation age, CI system, and/or communication mode on early lexical accuracy. Results may indicate true group differences, but they may also represent individual differences within each group (Kirk, 2000; Pisoni, Cleary, Geers, & Tobey, 2000). Cognitive factors underlying development (e.g., memory, attention) might also affect the speech perception and production abilities in the CI population (Pisoni, 2000; Pisoni, 2004). A better assessment of the contributions of such demographic characteristics to early lexical accuracy requires investigation of a larger cohort of children with greater variance in demographic and cognitive factors.

Longer data collection period

Investigation of change over time and the potential for nonlinearities in the acquisition of phonetic accuracy in early words was one goal of these analyses. Individual sessions were examined initially for monthly changes based on reports of relatively quick change in early speech output (Prather et al., 1975). No significant effect of individual session was found. When the interval was expanded to 3 months, significant change over time occurred in nearly all analyses. Evaluation of the two time points, early and later sessions, demonstrated the general direction of development (i.e., improvement over time) but not linear versus nonlinear growth over time.

Prolonged data collection may be required to divulge potential nonlinearities in development (Clark, 1997; Davis & MacNeilage, 2002; Thelen & Smith, 1994). DS theory proposes frequent data sampling to map the emergence of complex behaviors in individual participants (Thelen & Smith, 1994). The dynamic process must span a time scale large enough to account for individual variations, as illustrated by the study of treadmill stepping as a step toward independent walking (Thelen & Ulrich, 1991). Pilot data showed rare occurrence of treadmill stepping at 1 month, occasional occurrence at 3 to 4 months, and early elicitation at 7 to 8 months. Thelen and Ulrich tracked the emergence of this behavior from 1 to 8 months to allow identification of how and when the new form of coordination appeared over the entire time studied. Application of this viewpoint to vocal development may necessitate collection of pre-lexical data as well as sessions beyond the single word period to better track the emergence of early speech accuracy over time. Assessment of linear or nonlinear growth patterns requires a longer period of regular, frequent data collection.

Conclusion

Emergence of phonetic accuracy is a first step toward acquiring speech intelligibility. The goal of this study was to explore how early word accuracy unfolds relative to contributions from the production and auditory perceptual systems. These two groups of children experienced dramatically different early auditory histories before the onset of word use. Similarities were found on most accuracy indices observed. These similarities indicate that the children primarily relied on production system capacities evident in their inventories to achieve accuracy on early speech forms. Where differences were apparent, auditory perceptual factors seemed relevant to understanding differences. Lexical targets attempted by the children contained more diverse patterns than their own production repertoires. This disparity highlights the importance of audition in attending to salient sound-meaning patterns in the ambient language. Both groups were able to employ audition for selecting targets despite their differences in early auditory history.

While the production system seemed to be the dominant element in the sound patterns of these two groups, auditory perceptual factors are also present in the expansion of language forms. Nonlinearities in development may be present, but they were not discernable across this short period of development. Overall, these findings produce strong support for the efficacy of early CI. Early implantation with contemporary device technology can help children with profound hearing impairment to achieve speech and language milestones without significant disruption in the process of acquiring accuracy.

Appendices

Appendix A

Consonant inventory categories by place and manner

Manner (vertical dimension)	Place (horizontal dimension)			
	Labial	Coronal	Dorsal	Glottal
Stop	/p, b/	/t, d/	/k, g/	/ʔ/
Nasal	/m/	/n/	/ŋ/	
Fricative	/ɸ, β, f, v/	/θ, ð, s, z, ʃ, ʒ/	/x, ɤ/	/h/
Affricate		/ tʃ, dʒ/		
Glide	/w/	/j/		
Liquid		/l, r/		

Note. Where symbols appear in pairs, the one to the right represents a voiced consonant.

Appendix B

Vowel inventory categories by front-back and height

Height (vertical dimension)	Front-back (horizontal dimension)		
	Front	Central	Back
High	/i, y/ /I/		/ɯ, u/ /ʊ/
Mid	/e/ /ɛ, œ/	/ʌ/ /ə/	/o/ /ɔ/
Low	/æ/	/a/	/ɑ/

Note. Where symbols appear in pairs, the one to the right represents a rounded vowel.

Bibliography

Adams, R.J., Mercer, M.E., & Courage, M.L. (2004). Ontogenetic development of visual acuity over the first three postnatal years. *Ophthalmic Genetics, 25(3),* 199-203.

Balise, R.R., & Diehl, R.L. (1994). Some distributional facts about fricatives and a perceptual explanation. *Phonetica, 51,* 99-110.

Bates, E. (1979). *The emergence of symbols: Cognition and communication in infancy.* New York: Academic Press.

Baumrind, D. (1989). The permanence of change and the impermanence of stability. *Human Development, 32,* 187-195.

Bernhardt, B.H., & Stoel-Gammon, C. (1994). Nonlinear phonology: Introduction and clinical application. *Journal of Speech and Hearing Research, 37,* 123-143.

Biro, P.A., Post, J.R., & Parkinson, E.A. (2003). Density-dependent mortality is mediated by foraging activity for prey fish in whole-lake experiments. *Journal of Animal Ecology, 72(4),* 546.

Blamey, P., Barry, J., Bow, C., Sarant, J., Paatsch, L., & Wales, R. (2001). The development of speech production following cochlear implantation. *Clinical Linguistics & Phonetics, 15 (5)*, 363-382.

Blamey, P.J., Barry, J. G., & Jacq, P. (2001). Phonetic inventory development in young cochlear implant users 6 years post-operation. *Journal of Speech, Language, and Hearing Research, 44 (1)*, 73-79.

Bloom, L. (1993). *The transition from infancy to language.* New York: Cambridge University Press.

Boysson-Bardies, B. de & Vihman, M.M. (1991). Adaptation to language: Evidence from babbling and first words in four languages. *Language, 67,* 297-319.

Boysson-Bardies, B. de (1993). Ontogeny of language-specific syllabic productions. In B. deBoysson-Bardies, S. de Schonen, P. Jusczyk, P. MacNeilage, & J. Morton (Eds.), *Developmental neurocognition: Speech and face processing in the first year of life* (353-363). Dordrecht: Kluwer Academic Publishers.

Boysson-Bardies, B. de, Vihman, M.M., Roug-Hellichius, L., Durand, C., Landberg, I., Arao, F. (1992). Material evidence of infant selection from the target language. In C.A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological Development: Model, research, implications* (pp. 369-392). Timonium, MD: York Press.

Bremner, J.G. (1997). From perception to cognition. In G. Bremner, A. Slater, & G. Butterworth (Eds.), *Infant development: Recent advances* (pp. 55-74). East Sussex, UK: Psychology Press.

Brookhouser, P.E., Beauchain, K.L., & Osberger, M.J. (1999). Management of the child with sensorineural hearing loss: Medical, surgical, hearing aids, cochlear implants. *Pediatric Clinics of North America, 46(1),*121-141.

Bryk, A.S., & Raudenbush, S.W. (1992). *Hierarchical linear models*. Newbury Park: Sage Publications.

Chang, S-E., Ohde, R.N., & Conture, E.G. (2002). Coarticulation and formant transition rate in young children who stutter. *Journal of Speech, Language, and Hearing Research, 45(4),* 676-688.
Cheng, A.K., Grant, G.D., & Niparko, J.K. (1999). Meta-analysis of pediatric cochlear implant literature. *Annals of Otology, Rhinology, and Laryngology, 108,* 124-128.
Chin, S. B. (2002). Aspects of Stop Consonant Production by Pediatric Users of Cochlear Implants. *Language, Speech, & Hearing Services in Schools, 33 (1)*, 38-51.
Chin, S. B., & Pisoni, D. B. (2000). A phonological system at 2 years after cochlear implantation. *Clinical Linguistics & Phonetics, 14 (1)*, 53-73.
Chomsky, N., & Halle, M. (1968). *The sound pattern of English*. New York: Harper and Row.
Clark, A. (1997). *Being there: Putting brain, body and world together again*. Cambridge, MA: MIT Press.
Cohen, L.B. (1988). An information processing approach to infant perception and cognition. In G. Butterworth & F. Simion (Eds.), *Development of sensory, motor, and cognitive capacities in early infancy: From sensation to cognition*. Sussex: Erlbaum (UK) Taylor and Francis.
Cole, M. (1999). Culture in development. In M.H. Bornstein & M.E. Lamb (Eds.), *Developmental Psychology: an advanced textbook, 4th edition* (pp. 73-123). Mahway, New Jersey: Lawrence Erlbaum Associates.
Connolly, J.H. (1986). Intelligibility: A linguistic view. *British Journal of Disorders Communication, 21,* 371-376.
Davis, B.L., & 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. (1995). The articulatory basis of babbling. *Journal of Speech and Hearing Research, 38*, 1199-1212.
Davis, B. L., & MacNeilage, P. F. (2000). An embodiment perspective on the acquisition of speech perception. *Phonetica, 57*(Special Issue), 229-241.
Davis, B.L., & MacNeilage, P.F. (2002) The Internal Structure of the Syllable: An Ontogenetic Perspective on Origins. In T. Givon & B. Malle (Eds.), *The evolution of language out of pre-language* (pp. 133-151). Philadelphia: J. Benjamin.
Davis, B.L., MacNeilage, P.F., & Matyear, C.L. (2001). Variability in first word forms: Phonetic or cognitive basis? Child Phonology conference, April, Boston, Massachusetts.
Davis, B.L., MacNeilage, P.F., & Matyear, C.L. (2002). Acquisition of serial complexity in speech production: A comparison of phonetic and phonological approaches to first word production. *Phonetica, 59,* 75-107.
Davis, B.L., MacNeilage, P.F., & Matyear, C.L. (2003). The relationship of early accuracy patterns to the phonetic substrate in the single word period. 15th International Congress of Phonetic Sciences Conference, August 3-9, Barcelona, Spain.
Davis, B.L., Morrison, H.M., von Hapsburg, D., & Warner-Czyz, A.D. (2005). Early vocal patterns in infants with varied hearing levels. *Volta Review, 105(1),* 7-28.

Davis, B.L., Tobey, E.A., & Moore, J.A. (2004, November). *The effect of auditory experience on early speech production characteristics*. Paper presented at the meeting of the American Speech, Language, and Hearing Association, Philadelphia, PA.

Dawson, P.W., Blamey, S.J., Dettman, S.J., Rowland, L.C., Barker, E.J., Tobey, E.A., et al. (1995). A clinical report on speech production of cochlear implant users. *Ear and Hearing, 16,* 551-561.

Dillon, C.M., Cleary, M., Pisoni, D.B., & Carter, A.K. (2004). Imitation of nonwords by hearing-impaired children with cochlear implants: segmental analyses. *Clinical Linguistics & Phonetics, 18(1),* 39-55.

Dinnsen, D.A. (1992). Variation in developing and fully developed phonologies. In C.A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological Development: Model, research, implications*. Timonium, MD: York Press.

Eggermont, J. J., Ponton, C. W., Don, M., Waring, M. D., & Kwong, B. (1997). Maturational delays in cortical evoked potentials in cochlear implant users. *Acta Otolaryngoligica, 117*, 161-163.

Eilers, R. E., & Oller, D. K. (1994). Infant vocalizations and the early diagnosis of severe hearing impairment. *Journal of Pediatrics, 124*(2), 199-203.

Elbers, L., & Ton, J. (1985). Play pen monologues: The interplay of words and babbles in the first words period. *Journal of Child Language, 12,* 551-565.

Ertmer, D.J. (2001). Emergence of a vowel system in a young cochlear implant recipient. *Journal of Speech, Language, and Hearing Research, 44 (4)*, 802-813.

Ertmer, D.J., Kirk, K.I., Sehgal, S.T., Riley, A.I., & Osberger, M.J. (1997). A comparison of vowel production by children with multichannel cochlear implants or tactile aids: Perceptual evidence. *Ear and Hearing, 18(4),* 307-315.

Ertmer, D.J., & Mellon, J.A. (2001). Beginning to talk at 20 months: Early vocal development in a young cochlear implant recipient. *Journal of Speech, Language, and Hearing Research, 44 (1)*, 192-206.

Fenson, L., Dale, P.S., Reznick, J.S., Bates, E., Thal, D.J., & Pethick, S.J. (1994). Variability in early communicative development. *Monographs of the society for research in child development, serial no. 242, 59(5).*

Ferguson, C.A., & Farwell, C. (1975). Words and sounds in early language acquisition. *Language, 51,* 419-439.

Ferguson, C.A., Peizer, D.B., & Weeks, T.E. (1973). Model-and-replica phonological grammar of a child's first words. *Lingua, 31,* 35-65.

Ford, D.H., & Lerner, R.M. (1992). *Developmental systems theory: An integrative approach*. Newbury Park, California: Sage Publications.

French, A. (1989). The systematic acquisition of word forms by a child during the first-fifty-word stage. *Journal of Child Language, 16,* 69-90.

Fryauf-Bertschy, H., Tyler, R.S., Kelsay, D.M.R., Gantz, B.J., & Woodworth, G.G. (1997). Cochlear implant use by prelingually deafened children: The influences of age at implant and length of device use. *Journal of Speech, Language, and Hearing Research, 40,* 183-199.

Garnica, O., & Edwards, M.L. (1977). Phonological variation in children's speech: The trade-off phenomenon. *Ohio State University Working Papers in Linguistics, 22,* 81-87.

Geitz, B. (1998). *The development of stop consonant place of articulation in preadolescent children*. Unpublished master's thesis, Vanderbilt University, Nashville, TN.

Giani, U., Filosa, A., & Causa, P. (1996). A non-linear model of growth in the first year of life. *Acta Paediatrica, 85,* 7-13.

Gibson, E.J., & Pick, A.D. (2000). *An ecological approach to perceptual learning and development.* New York: Oxford University Press.

Gildersleeve-Neumann, C.E. (2000). Constraints on infant speech acquisition: A cross-language perspective. Unpublished doctoral dissertation. The University of Texas at Austin.

Gildersleeve-Neumann, C.E., Davis, B.L., & MacNeilage, P.F. (1997). Contingencies governing the production of fricatives, affricates, and liquids in babbling. *Applied Psycholinguistics, 21,* 341-363.

Gillis, S., Schauwers, K., & Govaerts, P.J. (2002). Babbling milestones and beyond: Early speech development in CI children. In K. Schauwers, P. Govaerts, & S. Gillis (Eds.), Language Acquisition in young children with a cochlear implant. *Antwerp Papers in Linguistics*, *102,* 23-40.

Golani, I., & Fentress, J.C. (1985). Early ontogeny of face grooming in mice. *Developmental Psychobiology, 18,* 529-544.

Govaerts, P.J., Schauwers, K., & Gillis, S. (2002). Language acquisition in very young children with a cochlear implant: Introduction. In K. Schauwers, P. Govaerts, & S. Gillis (Eds.), Language Acquisition in young children with a cochlear implant. *Antwerp Papers in Linguistics*, *102,* 1-10.

Grossberg, S. (1982). *Studies of mind and brain: Neural principles of learning, perception, development, cognition, and motor control*. Dordrecht, Holland: D. Reidel Publishing Company.

Hare, G. (1983). Development at 2 years. Development at 18 months. In J.V. Irwin & S.P. Wong (Eds.), *Phonological development in children: 18 to 72 months* (pp. 55-88). Carbondale, IL: Southern Illinois University Press.

Hammes, D.M., Novak, M.A., Rotz, L.A., Willis, M., & Edmondson, D.M. (2002). Early identification and cochlear implantation: Critical factors for spoken language development. *Annals of Otology, Rhinology, and Laryngology Supplement, 189*, 74-78.

Hedrick, S.C., Chaney, E.F., Felker, B., Liu, C.-F., Hasenberg, N., Heagerty, P., et al. (2003). Effectiveness of Collaborative Care Depression Treatment in Veterans' Affairs Primary Care. *Journal of General Internal Medicine, 18(1)*, 9.

Hesketh, L. J., Fryauf-Bertschy, H., & Osberger, M. J. (1991). Evaluation of a tactile aid and a cochlear implant in one child. *The American Journal of Otology, 12*(Supplement), 183-187.

Higgins, M.B., Carney, A.E., McCleary, E., & Rogers, S. (1996). Negative intraoral air pressures of deaf children with cochlear implants: Physiology, phonology, and treatment. *Journal of Speech and Hearing Research, 39*, 957-967.
Holmgren, K., Lindblom, B., Aurelius, G., Jalling, B., & Zetterstrom, R. (1986). On the phonetics of infant vocalization. In B. Lindblom & R. Zetterstrom (Eds.), *Precursors of early speech* (pp. 51-63). New York: Stockton Press.
Hopkins, W.G. (2002) A new view of statistics. Retrieved August 29, 2005, from http://www.sportsci.org/resource/stats/effectmag.html.
Howe, M.L., & Rabinowitz, F.M. (1991). Development: Sequences, structure, and chaos. *Annals of Theoretical Psychology, 7,* 65-71.
Howe, M.L., & Rabinowitz, F.M. (1994). Dynamic modeling, chaos, and cognitive development. *Journal of Experimental Child Psychology, 58,* 184-199.
Hox, J.J. (1995). Applied multilevel analysis, 2nd Ed. Amsterdam: TT-Publikaties. Retrieved September 21, 2005, from http://www.fss.uu.nl/ms/jh/publist/amaboek.pdf
Hunter, M.A., & Ames, E.W. (1988). A multifactor model of infant preferences for novel and familiar stimuli. In C. Rovee-Collier & L.P. Lipsitt (Eds.), *Advances in infancy research, Volume 5*. Norwood, New Jersey: Ablex Publishing Corporation.
Ingram, D. (1976). *Phonological disability in children.* London: Edward Arnold.
Jakobson, R. (1968). *Infant language, aphasia, and phonological universals*. The Hague: Mouton.
Jasuta, S.J. (1987). The phonology of the first fifty words: Phonological process and homonomy. Unpublished doctoral dissertation, The University of Texas at Austin.
Kent, R.D. (1992). The biology of phonological development. In C.A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological Development: Model, research, implications*. Timonium, MD: York Press.
Kent, R.D., & Bauer, H.R. (1985). Vocalizations of one-year-olds. *Journal of Child Language, 12,* 491-526.
Kent, R.D., Osberger, M.J., Netsell, R., & Hustedde, C.G. (1987). Phonetic development in identical twins differing in auditory function. *Journal of Speech and Hearing Disorders, 52,* 64-75.
Kent, R.D., Weismer, G., Kent, J.F., & Rosenbeck, J.C., (1989). Toward phonetic intelligibility testing in dysarthria. *Journal of Speech and Hearing Disorders, 54,* 482-499.
Kirk, K.I. (2000). Challenges in the clinical investigation of cochlear implant outcomes. In J.K. Niparko, K.I. Kirk, N.K. Mellon, A.M. Robbins, B.L. Tucci, & B.S. Wilson (Eds.), *Cochlear implants: Principles and practices* (pp. 225-259). Philadelphia: Lippincott, Williams & Wilkins.
Kirk, K.I., & Hill-Brown, C. (1985). Speech and language results in children with a cochlear implant. *Ear and Hearing Supplement, 6,* 36S-47S.
Koopmans van Beinum, F.J., & van der Stelt, J.M. (1986). Early stages in the development of speech movements. In B. Lindblom, & R. Zetterstrom (Eds.), *Precursors of early speech* (pp. 37-49). New York: Stockton Press.

Lamb, M.E., Bornstein, M.H., & Teti, D.M. (2002). *Development in infancy: An introduction, 4th edition.* Mahwah, New Jersey: Lawrence Erlbaum Associates.
Leonard, L.B., Rowan, L.E., Morris, M., & Fey, M.E. (1982). Intra-word phonological variability in young children. *Journal of Child Language, 9*, 55-69.
Liang, K.-Y & Zeger, S.L., (1986). Longitudinal data analysis using Generalized Linear Models. *Biometrika*, 13-22.
Lindblom, B. (1992). Phonological units as adaptive emergent of lexical development. In C.A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological development: Model, research, implications.* Timonium, MD: York 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* (453-475). Hillsdale, N.J.: Lawrence Erlbaum Associates.
MacNeilage, P.F., & Davis, B.L. (1993). Motor explanations of babbling and early speech patterns. In B. deBoysson-Bardies, S. de Schonen, P. Jusczyk, P. MacNeilage, & J. Morton (Eds.), *Developmental neurocognition: Speech and face processing in the first year of life* (341-352). Dordrecht: Kluwer Academic Publishers.
MacNeilage, P.F., & Davis, B.L. (1997). Babbling and first words: Phonetic similarities and differences. *Speech Communication, 22,* 269-277.
MacNeilage, P.F., & Davis, B.L. (1999). Evolution of the form of spoken words. *Evolution of Communication, 3(1),* 3-20.
MacNeilage, P.F., & Davis, B.L. (2000). Deriving speech from nonspeech: A view from ontogeny. *Phonetica, 57,* 284-296.
MacNeilage, P.F., Davis, B.L., & Matyear, C.L. (1997). Babbling and first words: phonetic similarities and differences. *Speech Communication, 22,* 269-277.
McCaffrey, H.A., Davis, B.L., MacNeilage, P.F., and von Hapsburg, D. (1999). Multichannel cochlear implantation and the organization of early speech. *Volta Review, 101(1),* 5-28.
Mellon, N.K. (2000). Language acquisition. In J. Niparko, K. Kirk, N. Mellon, A. Robbins, D. Tucci, & B.S. Wilson (Eds.), *Cochlear implants: Principles and practice* (pp. 291-314). Philadelphia: Lippincott, Williams, & Wilkins.
Menn, L. (1971). Phonotactic rules in beginning speech. *Lingua, 26,* 225-251.
Menn, L. (1979). Transition and variation in child phonology: Modeling a developing system. *Proceedings of the Ninth International Congress of Phonetic Sciences* (Vol. II). Copenhagen: Institute of Phonetics, University of Copenhagen.
Mitchell, P. R., & Kent, R. D. (1990). Phonetic variation in multisyllable babbling. *Journal of Child Language, 17*(2), 247-265.
Miyamoto, R.T., Kirk, K.I., Robbins, A.M., Todd, S., Riley, A., & Pisoni, D.B. (1997). Speech perception and speech intelligibility in children with multichannel cochlear implants. In I. Honjo & H. Takahashi (Eds.), *Cochlear implant and related sciences update.* Advances in Otorhinolaryngology (pp. 198-203). Basel, Switzerland: Karger.

Moore, J.A., & Bass-Ringdahl (2002). Role of infant vocal development in candidacy for and efficacy of cochlear implantation. *Annals of Otology, Rhinology, and Laryngology Supplement, 111(5, Part 2)*, (Supplement 189).

Norton, A. (1995). Dynamics: An introduction. In R.F. Port & T. van Gelder (Eds.), *Mind as motion: Explorations in the dynamics of cognition* (pp. 44-68). Cambridge, Massachusetts: The MIT Press.

Novak, M.A., Firszt, J.B., Rotz, L.A., Hammes, D., Reeder, R., & Willis, M. (2000). Cochlear implants in infants and toddlers. *Annals of Otology, Rhinology, and Laryngology Supplement, 189,* 46-49.

Ohala, J.J. (1983). The origins of sound patterns in vocal tract constraints. In P.F. MacNeilage (Ed.), *The production of speech* (pp. 189-216). New York: Springer.

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. (2000). *The emergence of the speech capacity.* Mawah, NJ: Erlbaum Associates Publishers.

Oller, K., & Delgado, R. (1990). Logical International Phonetic Program. Distributed by Intelligent Hearing Systems.

Oller, D.K., & Eilers, R.E. (1988). The role of audition in infant babbling. *Child Development, 59,* 441-449.

Oller, D.K., & Steffans, M.L. (1993). Syllables and segments in infant vocalizations. In Yavas (Ed.), *First and second language phonology* (pp. 45-62). San Diego: Singular.

Oller, D. K., Wieman, L. A., Doyle, W. J., & Ross, C. (1976). Infant babbling and speech. *Journal of Child Language, 3*, 1-11.

Osberger, M. J., Robbins, A. M., Berry, S. W., Todd, S. A., Hesketh, L. J., & Sedey, A. (1991). Analysis of the spontaneous speech samples of children with cochlear implants or tactile aids. *The American Journal of Otology, 12*(supplement), 151-164.

Osberger, M.J., & McGarr, N.S. (1982). Speech production characteristics of the hearing impaired. In N. Lass (Ed.), *Speech and language: Advances in research and practice, Vol. 8.* New York: Academic Press.

Otomo, K., & Stoel-Gammon, C. (1992). The acquisition of unrounded vowels in English. *Journal of Speech and Hearing Research, 35(3), 604-616.*

Paschall, L. (1983). Development at 18 months. In J.V. Irwin & S.P. Wong (Eds.), Phonological development in children: 18 to 72 months (pp. 27-54). Carbondale, IL: Southern Illinois University Press.

Pater, J. (1997). Minimal violation and phonological development. *Language Acquisition, 6(3),* 201-253.

Perkell, J.S., Guenther, F.H., Lane, H., Matthies, M.L., Perrier, P., Vick, J., Wilhelms-Tricarico, R., & Zandipour, M. (2000). A theory of speech motor control and supporting data from speakers with normal hearing and with profound hearing loss. *Journal of Phonetics, 28,* 233-272.

Pickett, J.M. (1999). *The acoustics of speech communication: Fundamentals, speech perception theory, and technology*. Boston: Allyn and Bacon.

Pisoni, D.B. (2000). Cognitive factors and cochlear implants: Some thoughts on perception, learning, and memory in speech perception. *Ear & Hearing, 21(1),* 70-78.

Pisoni, D.B. (2004). Information-processing skills of deaf children with cochlear implants: some new process measures of performance. *International Congress Series, 1273,* 283-287.

Pisoni, D.B., Cleary, M., Geers, A., & Tobey, E.A. (2000). Individual differences in effectiveness of cochlear implants in children prelingually deaf children: Some new process measures of performance. *The Volta Review, 101(3),* 111-164.

Ponton, C.W., Don, M., Eggermont, J.J., Waring, M.D., Kwong, B., & Masuda, A., (1996). Auditory system plasticity in children after long periods of complete deafness. *Neuroreport, 8,* 61-65.

Ponton, C.W., Don, M., Eggermont, J.J., Waring, M.D., & Masuda, A. (1996). Maturation of human cortical auditory function: differences between normal-hearing children and children with cochlear implants. *Ear and Hearing, 17,* 430-437.

Ponton, C. W., Moore, J. K., & Eggermont, J. J. (1999). Prolonged deafness limits auditory system developmental plasticity: Evidence from an evoked potentials study in children with cochlear implants. *Scandinavian Audiology, 28* (Suppl 51), 13-22.

Port, R.F., & van Gelder, T. (1995). *Mind as motion: Explorations in the dynamics of cognition*. Cambridge, Massachusetts: The MIT Press.

Prather, E.M., Hedrick, D.L., & Kern, C.K. (1975). Articulation development in children aged two to four years. *Journal of Speech and Hearing Disorders, XL 2* , 179-191.

Robb, M.P., Bauer, H.R., & Tyler, A.A. (1994). A quantitative analysis of the single-word stage. *First Language, 14,* 37-48.

Robbins, A.M., Kirk, K.I., Osberger, M.J., & Ertmer, D.J. (1995). Speech intelligibility of implanted children. *Annals of Otology, Rhinology, and Laryngology, 104,* 399-401.

Robinshaw, H. M. (1996). Acquisition of speech, pre- and post-cochlear implantation: longitudinal studies of a congenitally deaf infant. *European Journal of Disorders of Communication, 31*, 121-139.

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, 17,* 19-40.

Ryugo, D.K., Limb, C.J., & Redd, E.E. (2000). Brain plasticity: The impact of the environment on the brain as it relates to hearing and deafness. In J. Niparko, K. Kirk, N. Mellon, A. Robbins, D. Tucci, & B.S. Wilson (Eds.), *Cochlear implants: Principles and practice* (pp. 33-56). Philadelphia: Lippincott, Williams, & Wilkins.

Sander, E.K. (1972). When are speech sounds learned? *Journal of Speech and Hearing Disorders, 27,* 55-63, Santos, R.L.P., Aulchenko, Y.S., Huygen, P.L.M., van der Donk, K.P., de Wijs, I.J., Kemperman, M.H., et al. (2005). Hearing impairment in Dutch patients with connexin 26 (GJB2) and connexin 30 (GJB6) mutations. *International Journal of Pediatric Otorhinolaryngology, 69*, 165-174.

Schumacher, J.G., McNeil, M.R., Vetter, D.K., & Yoder, D.E. (1996). Articulatory consistency and variability in apraxic and non-apraxic children. Paper presented at the Annual Convention of the American Speech-Language-Hearing Association, Detroit, MI, November, 1986.

Sehgal, S.T., Kirk, K.I., Svirsky, M.A., Ertmer, D.J., & Osberger, M.J. (1998). Imitative consonant feature production by children with multichannel sensory aids. *Ear and Hearing, 19,* 72-84.

Serry, T.A., & Blamey, P.J. (1999). A 4-year investigation into phonetic inventory development in young cochlear implant users. *Journal of Speech, Language, and Hearing Research, 42,* 141-154.

Sharma, A., Dorman, M., Spahr, A. (2002). Rapid development of cortical auditory evoked potentials after early cochlear implantation. *Neuroreport, 13,* 1365-1368.

Sharma, A., Dorman, M., Spahr, A., & Todd, N.W. (2002). Early cochlear implantation in children allows normal development of central auditory pathways. *Annals of Otology, Rhinology, and Laryngology Supplement, 189,* 38-41.

Shibamoto, J.S., & Olmsted, D.L. (1978). Lexical and syllabic patterns in phonological acquisition. *Journal of Child Language, 5,* 417-457.

Singer, J.D. (1998). Using SAS PROC MIXED to fit multilevel models, hierarchical models, and individual growth models. *Journal of Educational and Behavioral Statistics, 24 (4)*, 323-355.

Skinner MW, Clark GM, Whitford LA, Seligman PM, Staller SJ, et al. 1994. Evaluation of a new spectral peak (SPEAK) coding strategy for the Nucleus 22 channel cochlear implant system. *American Journal of Otology, 15 (Supp. 2),* 15-27.

Smith, B.L., Brown-Sweeney, S., & Stoel-Gammon, C. (1989). A quantitative analysis of reduplicated and variegated babbling. *First Language, 9*, 175-190.

Smith, L.B., & Katz, D.B. (1996). Activity-dependent processes in perceptual and cognitive development. In R. Gelman & T. Kit-Fong Au (Eds.), *Perceptual and Cognitive Development* (pp. 413-445). New York: Academic Press.

Smith, L.B., & Thelen, E. (1993). *A dynamic system approach to development: Application*. Cambridge: MIT Press.

Stark, R.E. (1980). Stages of speech development in the first year of life. In G. Yeni-Komshian, J. Kavanagh, & C. Ferguson (Eds.), *Child phonology, volume 1: Production* (pp. 73-91). New York: Academic Press.

Stern, D.N. (1998). The process of therapeutic change involving implicit knowledge: Some implications of developmental observations for adult psychotherapy. *Infant Mental Health Journal, 19*, 300-308.

Sternberg, R.J., & Okagaki, L. (1989). Continuity and discontinuity in intellectual development are not a matter of "either-or." *Human Development, 32,* 158-166.

Stevens, K. N., Nickerson, R. S., Boothroyd, A., & Rollins, A. M. (1976). Assessment of nasalization in the speech of deaf children. *Journal of Speech and Hearing Research, 19*(2), 393-416.

Stoel-Gammon, C. (1985). Phonetic inventories, 15-24 months: A longitudinal study. *Journal of Speech and Hearing Research, 28,* 505-512.

Stoel-Gammon, C. (1988). Prelinguistic vocalizations of hearing-impaired and normally hearing subjects: A comparison of consonantal inventories. *Journal of Speech and Hearing Disorders, 53,* 302-15.

Stoel-Gammon, C. (1989). Prespeech and early speech development of two late talkers. *First Language, 9,* 207-224.

Stoel-Gammon, C., & Cooper, J. (1984). Patterns of early lexical and phonological development. *Journal of Infant Language, 11,* 247-271.

Stoel-Gammon, C., & Herrington, P.B. (1990). Vowel systems of normally developing and phonologically disordered children. *Clinical Linguistics and Phonetics, 4(2),* 145-160.

Stoel-Gammon, C., & Otomo, K. (1986). Babbling development of hearing-impaired and normally hearing subjects. *Journal of Speech and Hearing Disorders, 51*, 33-41.

Storkel, H.L. (2001). Learning new words: Phonotactic proability in language development. *Journal of Speech, Language, and Hearing Research, 44,* 1321-1337.

Sweeney, B.W., Czapka, S.J., & Yerkes, T. (2002). Riparian Forest Restoration: Increasing Success by Reducing Plant Competition and Herbivory. *Restoration Ecology, 10 (2),* 392.

Teixeira, E. R., & Davis, B.L. (2000). Early sound patterns in the speech of two Brazilian Portuguese speakers, *Language & Speech, 45(2),* 179-204.

Templin, M.C. (1957). *Certain language skills in children: Their development and interrelationships.* Westport, CT: Greenwood.

Thelen, E. (1986). Development of coordinated movement: Implications for early development. In H. T. A. Whiting and M. G. Wade (Eds.), *Motor Skill Acquisition in Children* (pp. 107-124). Dordecht (Netherlands): Martinue Nijhoff.

Thelen, E. (1992). Development as a dynamic system. *Current Directions in Psychological Science, 1(6),* 189-193.

Thelen, E. (1995). Motor development: A new synthesis. *American Psychologist, 50(2),* 79-95.

Thelen, E. and Smith, L. (1994). *A Dynamic systems approach to the development of cognition and action*. Cambridge, Massachusetts: MIT Press.

Thelen, E., & Ulrich, B.D. (1991). Hidden skills: A dynamic systems analysis of treadmill stepping during the first year. *Monographs of the society for research in child development, 56,* (No. 1, Serial No. 223).

Tobey, E.A., Angelette, S., Murchison, C., Nicosia, J., Sprague, S., Staller, S.J., Brimacombe, J.A., & Beiter, A.L. (1991). Speech production performance in children with multichannel cochlear implants. *American Journal of Otology, 12, S64-S172*.

Tobey, E., Geers, A., & Brenner, C. (1994). Speech production results: Speech feature acquisition. *The Volta Review, 96(5) (monograph)*, 109-129.
Turkewitz, G., & Devenny, D.A. (1993). Timing and the shape of development. In G. Turkewitz & D.A. Devenny (Eds.), *Developmental Time and Timing* (pp. 1-11). Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Tye-Murray, N., & Kirk, K.I. (1993). Vowel and diphthong production by young users of cochlear implants and the relationship between the Phonetic Level Evaluation and spontaneous speech. *Journal of Speech and Hearing Research, 36(3),* 488-502.
Tye-Murray, N., Spencer, L., & Woodworth, G.G. (1995). Acquisition of speech by children who have prolonged cochlear implant experience. *Journal of Speech and Hearing Research, 38(2)*, 327-337.
Vaal, J., van Soest, A.J., & Hopkins, B. (2000). Spontaneous kicking behavior in infants: Age-related effects of unilateral weighting. *Developmental Psychobiology, 36,* 111-122.
Van Gelder, T., & Port, R.F. (1995). It's about time: An overview of the dynamical approach to cognition. In R.F. Port & T. van Gelder (Eds.), *Mind as motion: Explorations in the dynamics of cognition* (pp. 1-44). Cambridge, Massachusetts: The MIT Press.
Van Hof-van Duin, J., & Mohn, G. (1986). The development of visual acuity in normal and preterm infants. *Visual Research, 26,* 909-916.
Vihman, M.M. (1992). Early syllables and the construction of phonology. In C. A. Ferguson, L. Menn, & C. Stoel-Gammon (Eds.), *Phonological development: Models, research, implications* (pp. 393-421). Timonium, Maryland: York Press.
Vihman, M.M. (1993). Variable paths to early word production. *Journal of Phonetics, 21,* 61-82.
Vihman, M.M. (1996). *Phonological development: The origin of language in the child.* Cambridge, MA: Blackwell Publishers.
Vihman, M.M., Ferguson, C.A., & Elbert, M. (1986). Phonological development from babbling to speech: Common tendencies and individual differences. *Applied Psycholingusitics, 7,* 3-41.
Vihman, M.M., Kay, E., Boysson-Bardies, B. de, Durand, C., & Sundberg, U. (1994). External sources of individual differences: A cross-linguistic analysis of the phonetics of mother's speech to 1-year-old children. *Developmental Psychology, 30(5),* 651-662.
Vihman, M.M., Macken, M.A., Miller, R., Simmons, H., & Miller, J. (1985). From babbling to speech: A re-assessment of the continuity issue. *Language, 61(2),* 397-445.
Vihman, M.M., & McCune, L. (1994). When is a word a word? *Journal of Child Language, 21,* 517-542.
Von Hapsburg, D.S. (2003). Auditory constraints on infant speech acquisition: A dynamic systems perspective. Unpublished dissertation, The University of Texas at Austin.
Von Hapsburg, D.S., Davis, B.L., & MacNeilage, P.F. (2005). *Frame Dominance in Infants with Hearing Impairment*. Manuscript submitted for publication.

Waltzman, S.B., & Cohen, N.L. (1998). Cochlear implantation in children younger than 2 years old. *American Journal of Otology, 19,* 158-162.

Warner, L., Macaluso, M., Austin, H.D., Kleinbaum, D.K., Artz, L., & Fleenor, M.E., et al. (2005). Application of the case-crossover design to reduce unmeasured confounding in studies of condom effectiveness. *American Journal of Epidemiology, 161(8),* 765-773.

Warner-Czyz, A.D., Davis, B.L., & Morrison, H.M. (2005a, March). *Lexical accuracy in young CI recipients: Emergence relative to age at implantation.* Paper presented at the 10th Symposium on Cochlear Implants in Children, Dallas, Texas.

Warner-Czyz, A.D., Davis, B.L., & Morrison, H.M. (2005b). Production accuracy in a young cochlear implant recipient. *The Volta Review, 105(2),* 151-173.

Warner-Czyz, A.D., Davis, B.L., & Morrison, H.M. (2005c, March). *Word accuracy in young cochlear implant recipients.* Paper presented at the 17th Annual American Academy of Audiology Convention, Washington, D.C.

Warner-Czyz, A.D., & Moore, J.A. *Production accuracy of consonants in young cochlear implant recipients.* Paper presented at the 2002 American Speech-Language-Hearing Association Annual Convention, November 21-24, Atlanta, Georgia.

Wetherby, A.M., Reichle, J., & Pierce, P.L. (1998). The transition to symbolic communication. In A.M. Wetherby, S.F. Warren, & J. Reichle (Eds.), *Transitions in prelinguistic communication* (pp. 197-230). Baltimore: Paul H. Brookes Publishing.

Wilson, B.S. (1997). The future of cochlear implants. *British Journal of Audiology, 31,* 205-225.

Yoshinaga-Itano, C. (2002). The social-emotional ramifications of universal newborn hearing screening, early identification, and intervention of children who are deaf or hard of hearing. In R.C. Seewald & J.S. Gravel (Eds.), *A sound foundation through early amplification 2001. Proceedings of the second international conference.* UK: Immediate Proceedings Limited.

Yoshinaga-Itano, C., & Apuzzo, M.L. (1998). The development of deaf and hard of hearing children identified early through the high-risk registry. *American Annals of the Deaf, 143(5),* 416-424.

Yoshinaga-Itano, C., Stredler-Brown, A., & Jancosek, E. (1992). From phone to phoneme: What can we learn from babble? *The Volta Review, 94(3),* 283-314.

Zeger, S.L., and Liang, K.-Y. (1986). Longitudinal data analysis for discrete and continuous outcomes. *Biometrics,* 121-130.

Zmarich, C., & Lanni, R.A. (1999). Phonetic and acoustic study of babbling in an Italian infant. *Proceedings of the 5th International Conference on Spoken Language Processing*, Sydney, 1103-1104.

VITA

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Warner-Czyz, A.D. (2000). Clinical Application of Adult Audiologic Rehabilitation Programs. *Seminars in Hearing,*21(3), 235-244.

Warner-Czyz, A.D., Davis, B.L., & Morrison, H.M. (2005). Production accuracy in a young cochlear implant recipient. *The Volta Review, 105(2),* 151-173.

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