The Dissertation Committee for Deborah von Hapsburg Certifies that this is the approved version of the following dissertation:

AUDITORY CONSTRAINTS ON INFANT SPEECH ACQUISITION: A DYNAMIC SYSTEMS PERSPECTIVE

Committee:

Barbara L. Davis, Supervisor

Craig A. Champlin

Randy L. Diehl

Bjorn Lindblom

Helen McCaffrey

Peter F. MacNeilage

AUDITORY CONSTRAINTS ON INFANT SPEECH ACQUISITION: A DYNAMIC SYSTEMS PERSPECTIVE

by

Deborah von Hapsburg, B.S., M.S.

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Supervisor: Barbara L. Davis

This study examined the extent to which auditory sensitivity contributes to the emergence of vocalization patterns observed in the pre-linguistic canonical babbling period. Whereas mechanical characteristics of the speech output system have been suggested as contributing strongly to the emergent patterns of babbling vocalizations, the extent to which these vocalizations depend on auditory sensitivity to be present at the frequencies with which they typically occur is unknown. A dynamic systems perspective was adopted to explore the extent to which the emergence of vocalization patterns typically observed in infants depends on auditory sensitivity. Spontaneous vocalization samples were obtained from 15 infants with auditory sensitivity ranging from normal hearing (PTA 25 dB HL) to profound hearing impairment (PTA > 90 dB HL). Several vocalization inventories were obtained including, (a) vocalization types within utterance strings (e.g., singletons, marginal syllables, and syllables), (b) syllable alternations, (c) syllable shapes (e.g. CV, VC), (d) syllable onset patterns, (e) intra-syllabic CV co-occurrences, (f) inter-syllabic consonant and vowel variegation patterns, and (g) segmental patterns. Results from these analyses suggest that auditory sensitivity may not contribute significantly to the prominence of CV co-occurrence patterns, syllable alternations, and vowel variegation patterns. Syllable shapes, syllable onset, consonant variegation and segmental patterns were dependent on auditory sensitivity.

Results show that auditory sensitivity is a significant control-parameter or variable contributing to the emergent patterns of vocalizations observed during the canonical babbling period, consistent with the dynamic systems perspective proposing that alternate arrangement of system variables (mechanical and perceptual) leads to differing patterns of output organization. The vocalization patterns of hearing infants were consistent with the prominent patterns reported in the literature during the pre-linguistic period. However, different vocalization patterns were observed in the infants with moderate and profound sensorineural hearing loss. Results suggest that the emerging patterns of vocalization organization are due to the contribution of multiple forces (bio-mechanical and auditory perceptual). Auditory sensitivity forces interact with and impinge on speech system propensities, ultimately contributing to the observed patterns of vocalization behaviors.

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Chapter 1: Literature Review

Studies of pre-linguistic speech acquisition in typically developing, hearing infants have suggested that many of the observed vocal patterns are primarily (but not exclusively) due to mechanical (e.g., Davis & MacNeilage, 1995a; MacNeilage, Davis, Kinney, & Matyear, 1999) characteristics of the speech output system. Specifically, studies suggest mandibular oscillations may underlie many of the syllable-based patterns observed during canonical babbling (e.g., Davis & MacNeilage, 1995a). However, the emergent vocalization patterns (output) produced by the speech output system of hearing infants reflect only net effects generated by the cohort of variables (i.e., mechanical, auditory, visual, ands kinesthetic) that make up that system. That is, observed vocalization patterns reflect elements of all contributing system variables. Hence, disentangling the contribution of specific system variables (e.g., mechanical from auditory perceptual) to the emerging patterns of vocalizations is problematic. For instance, from data on hearing infants, it is difficult to infer the role auditory sensitivity plays in determining emerging patterns of vocalization. In order to gain more biologically meaningful knowledge about how the cohort of system variables may organize and how each variable contributes to emergent vocalization patterns, studies must also look at “different” speech output systems. Hence, systems in which the arrangement of variables is known to have changed from that of the typical system should be studied. The interaction of within-system variables, such as auditory perceptual and mechanical variables, during the first year of life has not been widely studied. Consequently, a developmental account of speech acquisition that reduces the explanation for the emerging vocalization patterns to one causal factor is limited. If pre-linguistic vocalization patterns are to be fully understood, the ways in which auditory perception and characteristics of the production mechanism inter-relate must also be understood (Davis & MacNeilage, 2000; Lindblom, 1992; Muchisky, Gershkoff-Stowe, Cole, & Thelen, 1996).

Research into the effects of profound hearing impairment on vocal output in the first year of life has provided some evidence for the role of auditory sensitivity in determining some early vocal patterns. For example, auditory sensitivity affects age of babbling onset, and quantity of syllables produced, as well as the segmental characteristics of vocalization output (Eilers & Oller, 1994; Oller, Eilers, Bull & Carney, 1985; Oller & Eilers, 1988; Wallace, Menn, & Yoshinaga-Itano, 2000). Together, these studies have confirmed that auditory sensitivity plays a key role in instantiating syllable-based vocalizations. However, a more specific role for auditory sensitivity in determining emerging vocalization patterns in hearing infants has not been proposed. Consequently, the ways in which auditory sensitivity interacts with characteristics of the production mechanism to determine early speech-like output patterns has not been studied extensively. In order to understand the nature and process of speech acquisition in the first year of life, the contribution or interaction of auditory sensitivity with characteristics of the production mechanism should be evaluated. In this study, pre-speech vocalizations in 15 infants with varying degrees of hearing impairment will be analyzed. Differences in vocal patterns related to degree of hearing loss will be explored to understand the potential contribution of auditory sensitivity to vocalization patterns in pre-linguistic output.

BASIS OF RESEARCH

A dynamic systems perspective will be adopted as a metaphorical framework for the proposed study (Thelen & Smith, 1994). This perspective proposes explanations for emerging patterns of organization based on all factors (external and internal) affecting the system. The dynamic systems perspective provides a powerful metaphor to characterize potential interactions between auditory sensory input and characteristics of the production mechanism underlying early vocal output patterns. To provide background for this study, a brief overview of dynamic systems will be presented, followed by a summary of critical milestones in auditory perceptual development and production acquisition in normally hearing infants and hearing impaired infants.

DYNAMIC SYSTEMS

Contemporary approaches to the study of sensory and motor systems, and cognitive systems, have adopted a dynamic systems perspective (Smith & Katz, 1996; van Gelder & Port, 1995). One reason for turning to dynamic systems is that it provides a way of understanding emerging patterns of organization without ascribing the patterns to singular causes (i.e., genes, anatomy, environment). In this way, traditional dichotomies used to frame developmental research questions (i.e., learned versus innate, structure versus function, performance versus competence or genes versus environment) are eliminated. Instead, a dynamic systems perspective proposes multiple levels of causality (anatomical, environmental, or social) as necessary to account for the complex behavioral expressions of a system. Emergent patterns are seen as being due to interacting effects among all members contributing to the system (internal and external) output. In this manner, dynamic systems perspectives attempt to account for the context-dependent nature of an organism's behavioral repertoire. That is, dynamic systems account for the fact that the organism is embedded in an environment whose forces (i.e., physical stimuli, social and cultural) impinge on and affect the organism's emergent complex behavioral repertoire. Additionally, the dynamic systems approach emphasizes complex behavior as a self-organizing response to multiple forces and describes it as an ever-changing series of behavioral states with variable degrees of stability and/or instability.

The stability of emerging patterns of behavior is important to understanding dynamic systems. Stability of emerging patterns is probabilistic in that, under certain conditions, a particular behavior will emerge. For example, in the solar system (the sun, planets and satellites), the elliptical path of the planets around the sun is a stable pattern determined by the gravitational forces exerted by each of the planets on each other (van Gelder & Port, 1995). However, the stability of the elliptical pattern is dependent on the relations between the planets. Should conditions change, (i.e., removing a planet), the elliptical path of the planets would also change, reflecting new patterns of stability. When relations among the components of a system change, alternate patterns of stability emerge. Emerging patterns are a result of the interaction of the individual components of the system. When the interaction of the co-operative results in a prominent or stable pattern, it is referred to as an *attractor* (Norton, 1995; van Gelder & Port, 1995) or *stable- state.*

With a dynamic systems approach, questions related to the stability of a behavior as well as when and how behaviors change can be asked. When a stable pattern changes either to a previously existing pattern or to a completely new pattern, it is termed a *phase- shift (*Norton, 1995; van Gelder & Port, 1995). Phase-shifts occur within a system only when a current output pattern loses stability and new relations are formed among the sub-components. For example, in babbling, coronal consonants are preferred over labial consonants; however, during first-word acquisition labial vocalizations are preferred over coronals. This may be considered a phase-shift. Potentially, changes to any of the components of the system (including those within the organism and external to the organism in the environment) can cause a phase-shift. Within a system, some variables may have a stronger influence than other variables; whereas, some variables may not be influential at all. For example, in babbling characteristics of the production mechanism may be more influential than perceptual factors in determining syllable-based output. Components to which a system is sensitive are known as control- parameters (Norton, 1995; van Gelder & Port, 1995). In speech acquisition, characteristics of the production mechanism and auditory sensitivity, among others, are considered important control-parameters affecting the emergent vocalization patterns in early vocalizations.

One important aspect of dynamic systems is non-linearity. That is, the organization of the system may abruptly change as a result of slight changes to one of the system's control-parameters. This sudden or abrupt re-organization is referred to as self-organization (Norton, 1995; van Gelder & Port, 1995). Small changes in the control parameters may result in phase-shifts, and in subsequent re-organization of the system. The way in which auditory sensitivity affects the stability of vocalization output (i.e., the complex emergent behaviors) of the speech output system in hearing infants has not been explored extensively. However, according to a dynamic system perspective, changes in auditory sensitivity could potentially produce a different pattern of stable-states in the output of the speech system.

The power of a dynamic systems perspective for understanding the nature of developmental behaviors is that it allows us to address some basic questions that have been generally difficult to answer. Dynamic systems can be used to study phase-shifts or changes in stability over time. These studies are typically longitudinal and help us understand the course of development for an individual. Dynamic systems can also be used to examine how alternate arrangements of system variables contribute to the emergent output of a system at a particular point in time. Thus, by examining the arrangement of system variables at a particular point in time, knowledge about how variables contribute to system output can be gained. Hence, the question that the present study proposes to examine is: how does auditory sensitivity contribute to the stability of vocalization behaviors observed during the babbling period? It is assumed that the emerging vocalization patterns produced by hearing infants will reflect the net effects of all contributing control-parameters in that system. It is also assumed that infants with hearing impairment (HI) will evidence different patterns of vocalization output, given that the relationship of the system variables is different than that of hearing infants. Thus, when alternate patterns of organization emerge in HI infants, it is suggested that auditory sensitivity is probably an important control-parameter contributing to the emergent vocalization patterns. In this study, it is acknowledged that the organism under study is also constrained developmentally by changes in the nervous system, as well as by peripheral system changes in anatomy and physiology. The relative contributions of the nervous system and characteristics of the production mechanism may be constantly changing in time as the system matures. This study will focus on peripheral characteristics of the production and auditory perceptual sub-systems during the babbling period, while acknowledging the contribution of nervous system organization to the complex output observed.

A review of the early vocalization patterns produced by typically developing infants prior to and during the babbling stage will be provided to establish the typical course of vocalization development during the first year of life. Patterns observed during the babbling period will also be described with more detail than the patterns preceding the babbling period, as these are the patterns that this study will examine across the infants. Although the following discussion provides a description of the development of pre-linguistic vocalizations including those that precede the babbling period, this study will only focus on behaviors that occur during the babbling period.

ACQUISITION OF SPEECH PRODUCTION SKILL

The acquisition of motor skill in developing infants, whether related to locomotion, reaching or vocalization is dominated by multiple factors during the first year of life (Kent, 1984, 1992; Muchinsky et al., 1996; Smith & Thelen, 1993). However, during this early developmental period, the most dominant force determining rate of motor skill acquisition for locomotion, reaching and vocalization has been proposed as being physiological/anatomical (e.g., Kent & Hodge, 1990). The relative contribution of physiologic/anatomical constraints varies as the system matures so that by the end of the first year, the relative contribution of anatomical/physiological constraints may have decreased while the relative contribution of other factors may have increased (Turkewitz & Devenny, 1993). In vocal acquisition, the course of development is determined by many factors. The following discussion of motor-skill acquisition in speech will focus on characteristics of the production mechanism affecting speech acquisition.

Throughout the first year, the anatomical structure of the infant vocal tract differs from adult structures in five ways (Liberman, Crelin, & Klatt, 1972). First, the placement of the larynx is high, resulting in a shorter vocal tract. Second, the pharyngeal cavity is shorter. Third, the size of the tongue is large in relation to the size of the oral cavity. Fourth, a gradual bend of the oropharyngeal cavity exists as opposed to a right-angle bend in adults. Finally, there is a relative closeness of the velopharynx to the epiglottis (Stark & Kent, 1981). These anatomical characteristics limit the types of vocalizations that an infant produces. The range and types of vowel-like phones an infant produces are limited due to the large size of the tongue in the oral cavity. As the infant matures, changes in anatomical and neuro-anatomical function occur, which in turn affect the quality of infants' vocalizations. Changes include a decrease in size of the tongue in proportion to the oral cavity, lowering of the larynx, separation of the oral and nasal cavities, and increased ability to move the tongue (Bosma, 1975; Kent, 1981). Thus, throughout the first year the range of potential vocalizations infants can make is constrained by physiologic factors (Kent, 1992; Locke, 1992). As relationships and physiology of anatomical structures change during the first year, the infant production repertoire also changes. The characteristics of these changes have frequently been captured in a descriptive framework of "stages" (Koopmans-van Beinum & Van der Stelt, 1986; Oller, 1980; Roug, Landberg & Lundberg, 1989; Stark, 1980).

Stages of Speech Motor Skill Acquisition

Conventional descriptions of the course of development typically employ the concept of "stages" to demarcate behavioral changes that emerge throughout development (Gesell, 1933). The stages of vocal development are often described in terms of articulatory, acoustic, and phonatory characteristics. Several descriptions of stages in early vocal development have been proposed (Koopmans-van Beinum & Van der Stelt, 1986; Oller, 1980; Roug et al., 1989; Stark, 1980). Advancement from one stage to another is deemed to be due to maturation of the characteristics of the production mechanism (Kent & Hodge, 1990). A stage description of behavioral milestones is limited because the interplay among all factors affecting development is not considered (factors such as the development of the perceptual systems, and environmental factors such as visual and auditory input are not often considered). However, stage descriptions of “milestones” serve as an important heuristic for describing the course of development, as infants seem to progress through these stages in a largely similar fashion (Buhr, 1980; Kent & Hodge, 1990). These stages are seen as highly stable and resistant to effects of the environment (Locke, 1983; Oller, 2001). Additionally, the milestones may be likened to stable-states from a dynamic systems perspective. According to Muchinsky et al. (1996), interaction of all components of the production system as it develops over time, results in a number of stable states similar to “stages.” Thus, a stage description for developmental behaviors can serve as an important marker of *phase-shifts* and *stable-states* that are species-specific in development. That is, each stage marks a stable or prominent behavior that may or may not remain stable throughout the course of development, but one that describes the general course of development for all members of a species. The purpose of including the following stage description of speech is to emphasize that during the early part of the first year, motor skill acquisition is heavily dependent on characteristics of the production mechanism and to emphasize that prominent vocalization behaviors can be thought of as *stable-states* of production skill. This study will focus on the prominent vocalization patterns observed during the babbling stage.

Reflexive or Phonation Stage

During the first two months of life, oral vocalizations are primarily characterized by reflexive glottal articulations that do not sound speech-like. This class of sounds includes sounds like hiccups, burps, cries and coughs. This stage has been termed the “reflexive” stage (Stark, 1980) or the “phonation stage” (Oller, 1980).

During this stage, infants also produce non-reflexive and non-discomfort sounds. Many oral vocalizations in this stage are categorized as quasi-resonant nuclei (QRN) by Oller (1980). According to Oller (1980), these vocalizations include nuclei that show normal phonation (i.e., non-breathy), but do not involve open/close alternations of the vocal tract. These nuclei are referred to as quasi-resonant because they seem to be produced with the mouth closed or nearly closed. Acoustic analysis reveals that the QRN display low-amplitude acoustic resonances occurring at or below 1200 Hz (Murai, 1963; Oller, Wieman, Doyle, & Ross, 1976). In transcription studies, QRN are often characterized as mid, unrounded, nasalized vowels or syllabic nasals (Oller, 1980). During this period, a small proportion of fully-resonant nuclei (FRN) are also observed. These FRN are often referred to as vowel-like vocalizations or ‘’coos’ (Oller, 1980). However, QRN seem to be the most frequently appearing type of vocalization up to 4 months (Oller, 1980).

Expansion Stage

At approximately 4-5 months of age infant vocalizations tend to change. This stage is marked by increased diversification in supra-glottal constrictions. Gross coordination of phonatory and supra-glottal movements is also made during this period. Reliable velo-pharyngeal valving appears as well. Oral-nasal resonance distinctions emerge as a result. Fully resonant vocalizations (adult-like vowels), and high-pitched squeals and noises like “raspberries” also appear at this stage. Oller (1980) has termed this the “expansion stage. “Marginal babbling” also occurs in this period. Nuclei with consonant-like and vowel-like properties that lack rhythmic or temporal characteristics of canonical babbling are produced.

Babbling Stage

The prominent behaviors or stable behaviors observed during the babbling stage are discussed next. These behaviors are said to be stable in hearing infants, as they are prominent in infants universally. The first appearance of speech-like behaviors begins at the age of 6-10 months when canonical babbling first emerges. Canonical babbling is characterized by the production of repetitive, syllable-like output (i.e., “baba” or “daedae”)**.** Perhaps one of the most striking characteristics of canonical babbling is its seemingly sudden onset and rhythmicity. Oller (1986) defined a canonical syllable as a temporal unit containing a resonant nucleus bounded on either end by a closant or consonant-like sound. Babbling can be reduplicated (same syllable repeated- “baba”) or variegated (segmental changes from one syllable to another within an utterance- “badi”). Reduplication and variegation co-exist in babbling from the onset (Davis & MacNeilage, 1995; Mitchell & Kent, 1990; Smith, Brown-Sweeney & Stoel-Gammon, 1989; Smith & Stoel-Gammon, 1988).

Phonetic Characteristics of Babbling Sequences

Consonants in Babbling Sequences

During the canonical babbling stage, segmental inventories for typically developing infants have been thoroughly detailed (Boysson-Bardies & Vihman, 1991; Davis & MacNeilage, 1995b; Locke, 1983; Roug, Landberg & Lundberg, 1989; Vihman, Ferguson, & Elbert, 1986). The most frequently observed consonant phone qualities during the babbling stage are oral stops (e.g., labial and coronal stops) followed by nasals and glides (Boysson-Bardies & Vihman, 1991; Davis & MacNeilage, 1995b; Locke, 1983; Roug et al., 1989; Vihman, Ferguson, & Elbert, 1986). Labial and coronal stops occur with more frequency than velar stops. Labial and coronal nasals (/m/, /n/) and glides (/w/, /j/) occur with lower frequencies than oral stops. Finally, fricatives, affricates and liquids, occur at very low frequencies.

Vowels in Babbling Sequences

During the babbling period and in the first year, vowel vocalizations tend to concentrate around the lower-left quadrant of the vowel space, showing mostly low-front, mid-front, and neutral/central vowels qualities (Buhr, 1980; Davis & MacNeilage, 1995b; Kent & Bauer, 1985; Kent & Murray, 1982; Lieberman, 1980; MacNeilage & Davis, 1990). Low and mid vowels are probably produced more by a lowering of the jaw than by independent movement of the tongue. High vowels (e.g., /i/ and /u/) are produced infrequently in infant vocalizations during the first year, perhaps because more complex manipulation of the tongue is required (Kent & Bauer, 1985, Davis & MacNeilage, 1995b).

Non-syllabic Output in Babbling Sequences

Several studies have detailed the co-existence of singleton vocalizations with syllable-based vocalizations during the babbling period. Mitchell and Kent (1990), collected vocal samples from eight infants at 0;7, 0;9 and 0;11 months of age. The singleton "vocant," defined as a single vowel-like vocalization, was the most frequently occurring type of vocalization produced by these infants. These singleton vowel vocalizations accounted for approximately 60% of the infants' repertoire. Kent and Bauer's (1985) analysis of 13-month old infants also revealed that vocants dominated each infant's inventory at this age as well. They noted that vocant qualities accounted for 60% of all infant vocalizations. An analysis of the vowel types produced in isolation revealed vocal qualities of /ɛ, æ, a/. Kent and Bauer employed the concept of phonetic entropy to discuss the predominant vocant pattern observed in infants at this production stage. They suggested that phonetic entropy is determined by anatomical and physiological factors and that these factors make some articulations more probable than others. They suggested that the entropic force determining vocant preferences is anchored around an axis in the articulatory space centered on low-front, mid-central, and upper-mid back vocalizations. Thus, production of single vowel-like qualities is a highly stable behavior in infants up to one year of age with the second most stable behavior being the production of rhythmic CV's. No study has reported on the patterns of singleton consonant-like qualities produced by typically developing infants.

Syllable Shapes and Syllable Alternations in Babbling Sequences

Typically, babbling and first word syllable shapes are CV (consonant-vowel) and CVCV (consonant-vowel-consonant-vowel) in English language environments (Davis & MacNeilage, 1995b; Kent & Bauer, 1985). Kent and Bauer (1985) studied five American English-learning infants at 13 months. The most frequent syllable shapes (excluding singleton vowel-like vocalizations which accounted for approximately 60% of syllable shapes) in canonical babbling were CV (19%), VCV (7%), VC (2%) and CVC (2%). In terms of number of syllable alternations, monosyllabic vocalizations (excluding singleton vowel-like vocalizations) accounted for 30% of utterance types. Multi-syllabic vocalizations accounted for only 9% of utterance types. Similarly, Mitchell and Kent (1990) found that monosyllabic CV vocalizations accounted for 19% of the syllable types while multi-syllabic utterances only accounted for 11% of the 4,075 samples collected for analysis.

Sequential Organization of Speech Production in Babbling Sequences

While studies of infant vocalizations have analyzed characteristic components of production, such as consonant and vowel segmental inventories and syllable types, the sequential properties of babbling must also be considered to understand the acquisition of speech production skill. Phonetically based studies of the development of serial organization patterns in speech acquisition in hearing infants have led to the Frame/Content Hypothesis (MacNeilage & Davis, 1990). This hypothesis suggests an explanatory perspective for serial organization of both within-syllable sequencing (intra-syllabic) and syllable-to-syllable (inter-syllabic) sequencing of open and close phases of vocal output. A rhythmic, open-close cycle of mandibular oscillation with concurrent phonation is proposed as providing a frame for syllable production in babbling (Davis & MacNeilage, 1995) and early speech (Davis, MacNeilage, & Matyear, 2000) according to this perspective. Articulators such as the lips, velum, and tongue are not seen as moving independently of the jaw cycle within a syllable or sequence of syllables. Rhythmic open-close cycles of the mandible produce the percept of syllable–like output with consonant and vowel segmental qualities. The open phase of the mandibular cycle produce the percept of vowel sounds while the closing phase gives the percept of consonant sounds, with no requirement of sub-syllabic autonomy of individual segments.

Three types of mechanically driven regularities account for most of the variability observed in intra-syllabic production in babbling and early speech. Mandibular oscillations accompanied by phonation and neutral tongue position give the percept of a syllable containing a labial consonant and a central vowel (i.e., /ba/). Mandibular oscillations with accompanying phonation and a fronted tongue position give the percept of a syllable containing a front consonant (coronal) and front vowel (i.e., /di/). Oscillations produced concurrently with phonation and a backed tongue position creates the percept of a syllable containing a back consonant (dorsals) plus a back vowel (i.e., /gu/).

Most sequences in babbling and early words are reduplicated, where the same qualities are produced throughout the sequence (i.e., /bababa/) (Davis & MacNeilage, 1995). According to the Frame/Content hypothesis (MacNeilage & Davis, 1990), variegated sequences (i.e., /dædi/) with changes in consonant or vowel qualities within an utterance result from amplitude modulation of the mandibular cycle within the sequence. Inter-syllabic sequences of segments observed in babbling and first words are based on amplitude modulation of the mandibular cycle (i.e., degree of mouth opening) accounting for the majority of the variability seen in inter-syllable variegation. Amplitude modulation in the jaw closing movement, results in a preponderance of changes in consonant manner, (i.e., /daejae/ not /daekae/) over place. Vowel variegation produces a preponderance of changes in vowel height resulting from modulation of jaw opening movements as opposed to changes in front/back tongue movement (i.e., /dædi/ not /daedu/).

Vihman (1992) analyzed consonant-vowel associations in four groups of infants from different language backgrounds (Swedish, French, Japanese and English). Consonant-vowel associations were found for labials and central vowels /ba/ across languages, as well as CV associations for dorsal consonants and back vowels in Japanese. An association between coronals with front vowels was not found consistently. Results for the alveolar consonant-front vowel associations may have been confounded by Vihman’s transcription of [æ], as a central vowel; whereas, it is typically transcribed as a front vowel.

Oller and Steffens (1994) examined the consonant-vowel associations in canonical babbling and first words of three infants at 10, 12, 16, 20, and 24 months of age. Consonant vowel co-occurrences were found for dorsal consonants and back vowels and coronal consonants and front vowels. They also found a significant association for labial consonants and front vowels. The labial consonant-central vowel association could not be evaluated, as Oller and Steffens analyzed only front and back vowel associations with labial, coronal, and dorsal consonants.

While vowel, consonant and syllabic vocalizations showing speech-like rhythmicity have been described as being stable and primarily determined by characteristics of the production mechanism, few studies have focused on the role auditory input plays in contributing to the observed stability of these behaviors. Models of speech acquisition need to take into account interactions between auditory sensation and development of oral production skill to fully explore the nature of early speech acquisition. Because syllabic organizational propensities are proposed as being based on characteristics of the production system (i.e., output constraints) rather than perceptual factors related to audition, they should be present if auditory input is sufficient to trigger serially ordered output. However, the degree of hearing loss required to instantiate these aspects of production has not been explored.

The basic properties of syllable-based behaviors observed during the babbling period have been proposed as due primarily to characteristics of the production mechanism (MacNeilage, Davis, Kinney, & Matyear, 1999) and are considered stable states of production behavior in typically developing infants (Muchisky, Gershkoff-Stowe, Cole, & Thelen, 1996; Oller, 2001). Because syllabic organizational propensities are proposed as being stable states of behavior, based on characteristics of the production mechanism rather than perceptual factors related to auditory sensitivity, these aspects of behavior may not be significantly affected by reduced auditory sensitivity. It is suggested that the emergence of syllable-based behaviors should not be affected by disturbances in the auditory realm if it is independent of auditory sensitivity. Thus, in order to understand the general organizing principles operating in the pre-linguistic period, the role of auditory sensitivity, as a system component, must be better understood.

AUDITORY PERCEPTION

The Role of Experience with Language Input

To fully evaluate the contribution of auditory sensitivity to the organization of vocalization patterns, the auditory experience of the infant must be considered. Based on studies of infant auditory response in utero, it has been suggested that a bias for listening to speech (although filtered) develops prior to birth not because of innate mechanisms, but because of exposure or experience to speech in utero (Jusczyk, 1998). The auditory system is one of the first sensory systems to develop and receive stimulation prior to birth (Bradley & Mistretta, 1975). In addition, the course of normal auditory perceptual development and the order in which perceptual systems develop contributes to the way in which the auditory system is organized after birth (Turkewitz & Devenney, 1993). Accordingly, it is important to detail the wealth of perceptual experience that a hearing infant receives prior to and immediately after birth to evaluate how congenital hearing impairment may alter the course of the development of the production system. From a dynamic systems perspective, an alteration in course of development resulting from congenital hearing impairment would be predicted, as the auditory sensory system is considered an important *control-parameter*.

Research on the development of auditory perception shows that hearing infants are attending to the speech signal before birth (Brazelton, 1978; DeCasper, & Fifer, 1980; DeCasper & Spence, 1986; Hammond, 1970). Infants are affected by auditory experience as early as the 28th gestational week (Pujol, Lavigne-Rebillard, & Uziel, 1991), when mature synapses are present. Although human and animal embryonic studies have found that auditory abilities are limited when the cochlea first becomes functional, fetal responses to sound have been recorded using a number of measuring techniques such as heart rate and motor response monitoring. Infants show more sensitivity to their mother's speech than to any other ambient sound. The mother's voice is the most prominent signal and has been measured at a more positive signal- to-noise ratio than many other sounds in utero (Querleu, Renard, Versyp, Paris-Derlue, & Crépin, 1988; Griffiths, Brown, Gerhardt, Abrams, & Morris, 1994). Because the uterus acts as a low-pass filter, the overall speech signal is not available to the infant. The uterine wall, and surrounding fluids filter out sound above 1000 Hz (Querleu et al., 1988), removing much of the high frequency information in the signal but allowing access to prosodic information such as fundamental frequency and stress patterns. Consequently, infants can access prosodic aspects of their mother's speech more readily than any other sounds in utero. Recordings of speech in utero played back to adults showed that some phonemes (up to 30%) are intelligible to adults (Querleu, et al., 1988). Griffiths, et al. (1994) analyzed the transmission of speech in a pregnant ewe. They found that voicing information was better transmitted than information related to place or manner of articulation.

Studies investigating auditory capacities of infants have shown that at birth, infants are attracted to and prefer to listen to global or prosodic aspects of the speech signal. Newborns prefer voicing qualities (Brazelton, 1978; DeCasper & Fifer, 1980; Hammond, 1970). They show a preference for their mother's voice over another female's voice and a preference for female over male voices (DeCasper & Fifer, 1980; Fifer, 1981). DeCasper and Fifer studied 10 neonates' preference for their mother's voice 24 hours after birth. The mothers of the infants recorded a 25-minute sample of a Dr. Seuss story. Using a high amplitude sucking (HAS) paradigm, in which infants' sucking rates manipulated the recording played, they showed that infants preferred their own mother's voice more often than other voices. DeCasper and Prescott (1984), using the same paradigm, also showed that 2-day old infants evidenced no preference for their father's voice over that of another male.

In addition to tuning to voice qualities, infants attend to rhythmicity in speech. In a study of infant auditory perception in utero (DeCasper & Spence, 1986), pregnant women were asked to read target stories to their unborn infants starting 6 weeks prior to birth. The mothers recorded themselves reading the stories. After birth, 16 infants, averaging 55 hours of age, were tested for preferences for the target stories and new stories using a HAS paradigm, in which infants controlled the recording they heard by changing the rate of sucking. Results showed that the pre-exposed infants preferred target stories regardless of whether they were read by the mother or another female, indicating that infants were attending to aspects of the familiar signal. Infants who were not exposed to the target stories in utero did not show a preference for either story, suggesting that infants exposed to story reading before birth attended to the acoustic cues specifying the target story.

Early Phonetic Sensitivity at Birth

In addition to the speech processing abilities present before birth, infant perception studies also point to two main perceptual abilities in hearing infants. First, they can discriminate consonant and vowel phonetic categories. Second, hearing infants can cope with acoustic variability in the signal, showing perceptual constancy. Infants are born with the ability to discriminate consonant contrasts involving voicing (Eilers and Minifie, 1975; Eimas Siqueland, Jusczyk and Vigorito, 1971; Trehub and Rabinovitch, 1972), place (Bertoncini, Bijelac-Babic, Blumstein and Mehler, 1987;

Eimas,1974; Moffit, 1971;Morse, 1972) and manner (Eimas, 1975; Eimas and Miller, 1980) of articulation. Research from infant perception of vowels has also confirmed that infants are able to perceive vowels in an adult-like manner (Kuhl, 1983; Swoboda, Morse & Leavitt, 1976; Trehub, 1973, 1976).

Despite showing substantial experience with auditory stimuli, infants do not possess mature auditory processing capacities at birth (Bundy, Colombo, & Singer, 1982; Clarkson & Clifton, 1985, 1995; Clarkson & Rodgers, 1995; Eisele, Berry, & Shriner, 1975; Irwin, Ball, Stillman & Rosser, 1985; Olsho, Koch, Carter, Halpin, & Spetner, 1988; Schneider, Bull & Trehub, 1988; Trehub, Endman & Thorpe, 1990; Trehub, Schneider & Henderson, 1995; Weir, 1976, 1979; Werner, Marean, Halpin, & Spetner, 1992; Wightman, Allen, Dolan, Kistler, & Jamieson, 1989). Newborns have high absolute thresholds, poor frequency resolution capacities, and poor temporal processing capacities that improve with age. For example, newborn absolute auditory thresholds are 30-70 dB higher than adult thresholds (Weir, 1976, 1979). During the first six months thresholds gradually improve, first in the high frequencies (Maxon & Hochberg, 1982; Olsho, et al., 1988; Weir, 1976, 1979; Werner & Gillenwater, 1990). In terms of intensity discrimination (the ability to discriminate tones of different intensities), infants have significantly poorer intensity discrimination skills than adults (Sinnott & Aslin, 1985). Adults can discriminate about a 1 dB change in intensity of a pure-tone regardless of its intensity (Viemeister, 1988). At six months of age infants require approximately a 6 dB difference in intensity for discrimination (Sinnott & Aslin, 1985). By 4 years of age, infants require only a 3 dB difference for discrimination, reaching adult values by about 6 years of age (Maxon & Hochberg, 1982).

Studies of frequency resolution (the ability to selectively process a single component of a complex sound) in hearing infants show that by 6 months of age, infants have adult-like frequency resolution abilities, suggesting that the auditory filter-width matures early in the post-natal period (Schneider et al., 1988). However, frequency discrimination, the ability to distinguish between sounds of different frequency, is poor at birth and improves with age. Infants are particularly poor at discriminating high frequencies (Olsho, Koch & Halpin, 1987). However, high frequency discrimination abilities improve before low frequency discrimination abilities. At 3 months of age, infants require more than a 3% change in frequency at 500 Hz to discriminate frequencies and require more than a 4% change to discriminate between tones around 4000 Hz. By 6 months, infants have essentially achieved adult-like frequency discrimination abilities for high frequencies.

In terms of temporal processing, hearing infants also show clear developmental trends in some aspects of temporal processing while not in others. Temporal processing involves gap detection, amplitude modulation, duration discrimination, temporal integration and frequency modulation. For example, while adults can detect a brief interruption in the stimulus (gap detection) of 5 ms, infants 3, 6, and 12 months require a gap of 60 ms for detection (Irwin et al., 1985; Trehub et al., 1995; Werner et al., 1992; Wightman et al., 1989). These results suggest poor temporal resolution in neonates. The age at which gap detection thresholds reach maturity is uncertain. However, studies employing differing paradigms have suggested maturity occurs sometime around 5-12 years of age (Irwin et al., 1985; Werner et al., 1992; Wightman et al., 1989).

An apparent paradox exists between infants' absolute auditory abilities as measured psychoacoustically and their ability to process speech during the first year of life. Psychoacoustic data suggest that infants have elevated thresholds, poor temporal resolution, and somewhat immature frequency resolution. In contrast, speech perception data shows that infants are born with quite sophisticated speech processing abilities (i.e., categorical perception of consonants and perceptual constancy). Werner and Gray (1998) propose the following explanations for the apparent paradox. First, the stimuli used for psychoacoustic and speech perception experiments may cause the infant-adult differences noted in psychoacoustic tests. In the investigation of absolute auditory abilities of infants, pure-tones and noise are typically used. It has been suggested that the use of non-conspecific stimuli limits the degree of attention that an infant may place on the stimulus. Speech perception research, on the other hand, makes use of conspecific stimuli-shown to command more attention than noises and tones (Gottlieb, 1985). Therefore, infants may appear more attentive or sensitive when tested with speech stimuli. According to this explanation, the immaturity in detection thresholds or in temporal resolution results from a failure of attention related to the stimuli, rather than immature sensory processing.

A second explanation put forth by Werner and Gray (1998) for the paradox observed between poor infant auditory responses and sophisticated speech processing abilities, is that the poor performance on psycho-acoustic tasks may reflect the actual immaturity of sensory processing evidenced in infants. However, they suggest that the speech perception tasks such as categorical perception evidenced in infants do not tap the limitations or immaturity of the infant auditory system. That is, discrimination studies examine whether a difference between two stimuli can be detected (broad task), they do not examine how well one can discriminate. According to Werner and Gray, although infants have limited auditory capacities, the "fuzzy" representations of speech that they are able to access are sufficient to allow discrimination among many speech sounds. Finally, it is proposed that infants could be using different acoustic cues than adults to discriminate speech sounds and to compensate for auditory system immaturity.

Hearing infants receive a wealth of auditory experience before and after birth. Although the infant's resolving properties do not seem to be mature, they are sufficient to allow for speech processing, at least at the level of categorical perception of speech contrasts. Subsequent to congenital hearing loss, hearing-impaired infants are deprived of the wealth of auditory experience that normally takes place in utero. This disturbance in the sequence of auditory development, from a dynamic systems perspective, might be predicted to cause an alternate pattern of auditory development and consequently affect the general vocal development of the infant.

Integration of Multimodal Sensory Development

While perception and production in speech acquisition have been discussed separately, sensory perception does not operate separately from other sensory or motor processes. A dynamic system's perspective on sensory development suggests that developing sensory and motor systems are interdependent. Because individual sensory systems (vision, hearing, taste, smell, touch) within an organism are contributing to overall development patterns, altering the course of development in one sensory system may result in a different pattern of overall organization among the other sensory and motor systems in contributing to the behavioral outcomes observed in vocalizations. The following discussion reviews multi-sensory integration in development and highlights the importance of activity-dependent interactions for facilitating development of sensory and motor systems in typically developing infants.

One of the central theoretical problems driving psychology, known as the binding problem (Smith & Thelen, 1993) investigates the ways in which separate sensory modalities become integrated or coordinated in development. While senses are separate and distinct, perceptions seem to be coordinated and unitary. The classic approach to the binding problem has been to assume that the merging of the senses occurs in the higher association areas of the cortex, and that the modalities are mapped separately at lower levels. Traditionally, questions about how uni-modal information becomes integrated were pursued from an innate/learned perspective, the question simply being whether the development of inter-sensory mapping is innate or learned. Like other developmentalists of his time, Piaget (1952) located inter-sensory coordination in the higher mental processes assuming that the separate modalities remained separate until reaching the cortex. Recent research has shown that this hypothesis is inaccurate. However, Piaget also proposed a developmental course for mapping inter-sensory information suggesting that infants gradually develop cortical mappings between modalities as a consequence of their own activity. The importance Piaget placed on activity-dependent mappings has much bearing on contemporary views of cognitive development.

Animal studies of intersensory integration have shown that sensory experience in one modality directly affects neural development of other modalities (Lewkowitz & Turkewitz, 1980; Mendelson & Haith, 1976). For example, studies of the co-development of auditory and visual maps in the barn owl found that raising a barn owl with one ear plugged altered the organization of both visual and auditory maps (Knudsen, 1989). Upon removal of the ear-plug, visual and auditory maps re-organized to reflect new patterns of auditory input. The data from this research and subsequent animal and human studies shows that multi-modal processing is a dynamic process, suggesting that system output is dependent on the organization of system related variables.

Results from recent behavioral research on hearing infants suggest that multi-sensory interactions are present in very young infants as well (Bushnell, 1994;

Lewkowitz, 1994; Rose, 1994). For example, activity-dependent processes in the auditory-visual domain have also been studied in newborns. Links between auditory and visual processing are evident in infants early in the post-natal period. Sound elicits increased visual attention and activity in the infant. Properties of the sound, such as intensity, influence the direction of eye movement, with soft sounds eliciting eye movements toward an object and intense sounds eliciting eye movements away from an object (Hammer & Turkewitz, 1975). When presentation of a sound is prolonged, newborns orient their head in the direction of the sound (Clifton, Morrongiello, Kulig & Dowd, 1981). As the sound is moved in the horizontal plane, a newborn's head movement rotates systematically to the location of the sound. Results from infant sound localization studies suggest that the oculo-motor reflex or the variety of other reflexive behaviors that infants possess at birth serve to provide experiences crucial in promoting perceptual learning and development. According to Morrongiello, et al. (1981), head orientation to sound provides the young infant with opportunities in which auditory and visual stimulation coincides in time and space. Such parings of perceptual-motor response patterns serve to promote coding of object location. It has been suggested that infants first use the oculo-motor reflex to learn about location of objects in relation to the self. Furthermore, Morrongiello et al. suggest that through this reflexive action, infants may gain insight into how auditory and visual information in the environment is correlated to motor output information. Early learning experiences provided by reflexes provide teaching about auditory and visual space. Consequently, failure to learn these correspondences may explain why blind infants have difficulties learning how to orient to sound (Schwartz, 1984).

Thelen and colleagues (Thelen, 1985, 1989, 1991; Thelen Corbetta, & Kamm, 1993) provide a multimodal, dynamic systems perspective on human motor development. This body of research has focused on understanding development of basic motor skills, such as reaching for an object and locomotion. Thelen and colleagues (Thelen, Corbetta, & Kamm, 1993) have explored the ways in which engaging in coordinated movements promotes development of movement coordination. They recorded reaching behavior as well as non-reaching behavior in four infants from three weeks until 12 months of age. They proposed that infants developed reaching from “ongoing movement dynamics”; reaching skills evolved from the movement repertoire already available to the infant. Not all infants produced reaching behaviors with the same developmental course. Individual infants showed different spontaneous pre-reaching movements that affected the ways in which they ultimately arrived at a solution to reaching for objects. While each infant had to solve the problem of reaching a toy, the solution to solving the problem came from adjusting pre-reaching limb forces to achieve the task demands in individual ways. Thelen suggested that the solution of adjusting limb forces comes from direct experience with movement. Infants explore what it feels like to deliver different amounts of energy to their limbs. From each activity the infant performs throughout the course of the day (e.g., such as seeing their hand in front of them) they learn to modify muscle contractions for each particular context. Thelen suggests that through repeated spontaneous activity, infants learn the relationship between actions and the world (Edelman, 1987). Thus, Thelen concludes that what infants experience on a moment-to-moment basis through sight, touch and sound, is teaching them about their bodies and about the world. Infants are seen as exploring the range of forces that move their arms to different places and are consequently learning from their exploration. Thus, according to Thelen et al. (1993) and Morrongielo (1994), repetition of active behavior serves as a means to gain and strengthen perceptual knowledge. Learning that takes place as a result of exploration is said to be an embodied type of cognition (e.g., Lakoff, 1987; Johnson, 1987). From an embodied cognition perspective, knowledge structures are a direct result of the interaction of perceiving and acting.

Motor and Auditory Perceptual Relationships in Speech Acquisition

Davis and MacNeilage (2000) proposed that an embodiment perspective (Clark, 1997) might be valuable to understanding the nature of pre-linguistic and early stages speech acquisition. Following Lindblom's (1992) suggestion that perceptual distinctiveness and production ease factors interact to select phonetic units in inventories of languages, Davis and MacNeilage propose that the role of both perception and production needs to be carefully considered if the nature of vocalization patterns observed in the pre-linguistic period is to be understood. They propose that perceptual information generated both extrinsically (from the environment) and intrinsically (from the infant) can play a role in development of production skill. From an embodiment perspective (Clark, 1997), perceptual inputs act as a “supportive scaffolding” for infant production patterns. Both intrinsic and extrinsic perceptual inputs play a significant role in the organization of speech patterning. Making the observation that experimental research on perception rarely attempts to relate perceptual capacities of infants to production capacities, Davis and MacNeilage attempted to relate four production preferences regularly observed in infants during babbling and early speech to production or perception influences. The four commonly observed production patterns examined were (a) consonant manner: degree of obstruction, (b), consonant place (c), use of the vowel space, and (d) oral versus nasal production mode. Little perceptual evidence was found for understanding prominent patterns related to consonant manner, consonant place, and vowel space production preferences observed in infants. Characteristics of the production mechanism were proposed as being more likely to account for production preferences, than auditory perceptual factors. The authors concluded that auditory perception plays a secondary role in determining these production patterns in hearing infants. However, they suggested that perception factors play a primary role in determining the oral mode of production, citing evidence from production patterns of infants with HI, that are highly nasal. In agreement with Thelen's hypothesis (Thelen et al., 1993) Davis and MacNeilage also suggested that both intrinsic and extrinsic perception play a role in establishing perceptual representations. Intrinsic perceptual input provided by the infant's own production explorations act to provide a confirmatory response. Coupling of intrinsic input with extrinsic perceptual confirmation are proposed as contributing to formation of well-developed representations such that when combined these two types of inputs allow for improved representation over those that may be established with either type of input alone.

The dynamic systems perspective suggests that the emerging organization of a complex system is dependent on the interaction of all contributing factors affecting the system (Thelen & Smith, 1994). Developing sensory and motor systems are seen as highly interdependent. Consequently, changing any one factor may lead to a different overall organizational pattern, altering the normal course of development. Research suggests that infant auditory perceptual systems are functional by the third trimester of gestation (e.g., Pujol, et al., 1991) and that infants attend to both prosodic and phonetic aspects of the acoustic signal of speech in the environment (Brazelton, 1978; DeCasper & Fifer, 1980; Hammond, 1970). While characteristics of the production mechanism may be the primary factor determining the overall organization of vocal output in the first year, the relative contribution of auditory sensitivity to vocal production patterns has not been carefully considered. It has been suggested that sensory and motor systems interact early on. Thus, one method for investigating interactive effects of perception and production in early acquisition is to investigate the effects of varying degrees of hearing loss on oral production patterns in infants identified as hearing impaired at birth. Systematic study of the effects of varying degrees of hearing loss on the acquisition of pre-linguistic vocal behaviors may allow new insights regarding the interaction of perception and production in the typical course of acquisition of speech production abilities.

Effects of Hearing Impairment

Background

The incidence of significant hearing impairment in infants is 2-3 per 1000 births (Dalzell, 2000). Prior to the implementation of early hearing detection and intervention (EHDI) programs, the average age of identification for hearing impairment in infants was between 18 months and 2.5 years (Harrison & Roush, 1996; Strong, Clark & Watkins, 1994). Furthermore, prior to EHDI infants with mild and moderate hearing impairments had an average age of identification of 5-6 years of age (Strong et al., 1994) and a later age for amplification (Harrison & Roush, 1996). A goal of universal newborn hearing screening in the United States is to identify hearing loss by 3 months and to begin intervention by 6 months (American Academy of Pediatrics, 1999; Joint Committee on Infant Hearing, 1994; National Institutes of Health, 1993). Given the late age of identification until recent implementation of these new programs, there is a paucity of research on the structure of pre-linguistic babbling vocalizations in infants who receive amplification before the age of 6-8 months.

Reports of recent research on universal newborn screening programs have shown that the median age of identification is now 3-5 months and the median age of implementation of hearing aids is 7.5 months (Dalzell, et al., 2000). Findings from preliminary studies of infants identified at birth show that children who receive intervention (amplification and habilitation) by 6 months derive significant benefits on language skills compared with children identified after 12 months (Yoshinaga-Itano & Apuzzo, 1998). Support for early identification/ intervention has been provided by a variety of studies showing that identification and intervention prior to 6 months of age positively affects both expressive and receptive language levels (Mayne, Yoshinaga-Itano, Sedey, & Carey, 2000). Results from recent research suggest that children identified before the age of 6 months can reach similar language levels following intervention regardless of degree or severity of hearing loss when no other severe motor or cognitive disabilities accompany the hearing loss (Downs & Yoshinaga-Itano, 1999; Yoshinaga-Itano & Apuzzo, 2000). Thus, advances in early use of auditory diagnostic technology coupled with early intervention makes it possible to study the effects of hearing impairment on the acquisition of production skills at a very early age.

Prior to universal newborn hearing screening, it was virtually impossible to study the acquisition of oral production patterns in hearing-impaired infants younger than 12 to 24 months. This younger population of identified infants allows us to begin to address questions regarding the role that auditory sensitivity plays in determining oral production patterns. The following review will discuss the effects of hearing loss and auditory deprivation on the development of the auditory system, the development of other sensory systems and the production system. Dynamic systems concepts suggesting that a disturbance in the auditory system may alter the development of speech production skill will be integrated in this discussion.

Perception in HI infants in the First Year of Life

The Effect of Auditory Deprivation on Language Input

Hearing impairment is defined as a permanent or temporary loss of hearing sensitivity that affects auditory input from the environment by limiting the amount of acoustic information received (Tyler & Summerfield, 1996). Hearing impairment may range in severity from mild to profound. Hearing impairment results in auditory deprivation as well as a lack of normal auditory experience. The lack of auditory experience, caused by auditory deprivation has deleterious effects on different aspects of auditory development (Clopton, 1986; Dmitrieva & Gottlieb, 1994; Moore, 1985; Ruben & Rapin, 1980). Auditory deprivation affects morphological and functional aspects of auditory neuronal function (Eggermont, Ponton, Don, Waring, & Kwong, 1997; Gunnarson & Finitzo, 1991; Ponton, Moore, & Eggermont, 1999; Sininger, Doyle, & Moore, 1999). In addition, auditory processing of speech in humans (Brown, 1994; Clarkson, Eimas, & Marean, 1989; Gravel & Wallace, 1992) is also affected by auditory deprivation. Congenital hearing loss present before birth, even if mild, will affect the ability of an infant to tune into the important speech signals available during that period (Lecanuet, 1998; Ruben & Rapin, 1980). This effect has been shown in animal studies (Dmitrieva & Gottlieb, 1994), and is beginning to be considered an important factor in human newborns (Downs & Yoshinaga-Itano, 1999; Sininger et al., 1999). Downs and Yoshinga-Itano (2000) suggest that the prenatal period may play a crucial role in the development of auditory and other cognitive processes related to audition. They suggest that this may explain why hearing-impaired infants who receive amplification and other related interventions prior to 6 months attain similar language skills regardless of severity of hearing impairment. They suggest that prenatal listening experience may be crucial for development of the auditory system and congenital or prenatal hearing loss may “level the playing field” for all hearing impaired infants.

Hearing infants obtain a wealth of experience in the prenatal period. This auditory history affects subsequent auditory development after birth. In utero, the role of auditory experience has been examined in animals more than in humans. This research indicates that auditory deprivation prior to birth negatively affects the neuronal development of the auditory system (Clopton, 1986; Dmitrieva & Gottlieb, 1994; Moore, 1985; Ruben & Rapin, 1980). Dmitrieva and Gottlieb (1994) studied the impact of auditory deprivation on a duckling’s ability to produce and recognize its species-specific call. They reported on the development of the auditory system in twogroups of duck embryos and hatchlings. Approximately one day before hatching, ducklings emit special contact contentment calls in the frequency range of 1500 Hz-2500 Hz (Gottlieb, 1975). The mallard hen responds to this call, and the embryo and hen begin a dialogue, prior to hatching. In their study, Dmitrieva and Gottlieb subjected one group of embryos to auditory deprivation before and after birth while the other group was allowed to develop normally and subjected to enhanced species-specific contentment calls (the ducklings were exposed to repeated species-specific calls via audiotape for 2-4 days). To test the effects of auditory experience on the development of auditory brainstem evoked potentials, auditory deprivation was simulated on one set of 5 Peking duck embryos, de-vocalized (i.e., vocal folds were paralyzed) at 21 days of embryonic development and reared in isolation in sound treated rooms. A different group of ducklings (N = 5) was exposed to enhanced species-specific auditory stimulation with embryonic contact-contentment calls. A control group did not receive auditory deprivation or enhanced calls. The de-vocalized and isolated embryos were tested with Brainstem Auditory Evoked Potentials (BAEP), an electrophysiologic measure of auditory function at 24 days of embryonic development (approximately the time when contentment-calls begin), at hatching, and at 2 days post-hatching. Brainstem Auditory Evoked Potential thresholds (the softest level at which a brainstem response is obtained) and the latency of P1 component were measured. BAEP in the control ducklings showed their most rapid improvement in thresholds in the mid-frequency range (coinciding with contentment-calls) during the embryonic vocalization period. Ducklings exposed to enhanced signals showed a marked improvement in BAEP thresholds and latencies of P1 at all test frequencies with the most marked influence on low (below 1.5 KHz) and high (above 2.5 KHz) frequencies in comparison to the control group. The auditory deprived and de-vocalized ducklings showed an arrest in development of the BAEP in the high frequency range, corresponding with the frequency range of the mallard hen's calls. In addition, they also exhibited a decline in rate of development in the low and mid-frequency ranges, coinciding with the range of the contact contentment calls, compared to the control group. Prolonged latencies of P1 were also evidenced in comparison with the control group and with the group receiving enhanced signals. According to the authors, de-vocalization and auditory isolation of embryos prevented the ducklings from experiencing or hearing their own calls as well as those of their siblings and their mallard hen. The authors note that the "virtual arrest of auditory development in the mute ducklings in the present study indicates the importance of normally occurring auditory experience for the development of auditory periphery" (pg. 26). Results from similar studies in mammals (Smith, Gray & Rubel, 1983) also suggest that auditory experience early in development plays an important role in development of the auditory system. Lack of experience delays development and enhanced experience may potentially increase the rate of development.

Additionally, results from this study suggest a link between vocalization experience and auditory development.

Although lack of auditory experience (auditory deprivation) affects development of the auditory system and perceptual capacities negatively, it has been established that these effects may be reversed to some extent if auditory stimulation is resumed (Eggermont et al., 1997; Ponton, Don, Eggermont, Waring, Kwong, & Masuda, 1996; Ponton et al., 1999). Eggermont et al. (1997) studied the effects of prolonged auditory deprivation in children with restored auditory stimulation via cochlear implant. They performed auditory electrophysiologic measures, specifically the late cortical potential (P1). In typically developing hearing children, the development of the central auditory system is not complete until approximately age 15 years. Electrophysiologically, there is a gradual evolution of evoked potential features, with the P1 latency becoming adult-like at about 15 years of age. Eggermont et al. (1997) studied the maturational P1 latency changes in a group of normal hearing children and adolescents (N = 31) and in six adults and 12 children who were congenitally or early deafened and received cochlear implants. The children's deafness was acquired sometime between birth and 5 years of age. Duration of deafness ranged between 5 months and 9 years. Cortical evoked potentials using clicks for stimuli were presented and recorded at 30 standard electrode locations on the scalp. The rate of maturation of the P1 latency component in hearing children and in implanted children occurred at about the same rate. Results for the normal-hearing group showed that the latency of the P1 decreased with age, in an exponential fashion. For children who had short duration deafness (approximately 1 year of deprivation), the P1 latencies were near the upper boundary of the normal range. This result suggests minor maturational delays when duration of deprivation is short. However, for those with long periods of auditory deprivation (up to and exceeding 8 years), latencies of the P1 component were well above the range of normal and above the range for the both the short-deprived and medium-deprived groups. Additionally, maturation time in implanted children was delayed by an amount approximately equal to the duration of their deafness. The authors suggest that auditory deprivation caused by profound deafness “freezes” the physiological development of the auditory pathway in an immature state. This conclusion is similar to the finding by Dmitriev and Gottlieb (1994) suggesting that early auditory deprivation “arrests” development of the evoked potentials. However, Eggermont et al., also propose that resumption of auditory stimulation in this case via a cochlear implant, “thaws” the auditory system out of its “frozen state”. Once the system receives stimulation, they suggest that maturation of the auditory system resumes its normal time course, being delayed only by the duration of deafness.

In a recent study of the development of central auditory system, Ponton, et al. (1999) explored the relation between age of onset of deafness and duration of deafness on auditory system recovery. They reported on a longitudinal study of the maturation of late cortical potentials (P1) in two implanted children. One child, CI-1, was identified at 14 months of age with a Mondini defect, a cochlear malformation that results in profound hearing impairment. She was implanted at six years of age. Her hearing-age (HA or time-in-sound) defined as the chronological age minus the period of deafness at time of implantation was 0 years. Her evoked potentials, specifically P1, were tested longitudinally from age 6.5 to 11.9 years (HA; approximately 0 months to 6 years). CI-1’s waveforms showed that the latency of the P1 component decreased over the entire period of study. P1 amplitude at the last testing session was consistent with the mean P1 amplitude for 5-6 year old hearing children. However P1 latency change observed for CI-1 did not correspond with the changes observed in P1 latencies of hearing children in the 0-6 year age range. Instead, the changes observed in CI-1’s latencies corresponded more with the latency decrease observed in hearing children between 2-6 years of age. Because the child had worn powerful hearing aids bilaterally since approximately 18-24 months of age, the authors suggested that sufficient stimulation was obtained through amplification to allow for some maturation to occur prior to implantation. Consequently, when CI-1’s hearing age was adjusted to 2 years at onset of recording, her data matched that of hearing children. During the last recording sessions at ages 10 and 12 years (HA; 4 and 6 years), the latency of P1 did not change, remaining at 89 ms. The predicted change in P1 latency between 4 and 6 years of age for hearing children is about 22 ms. Thus, for CI-1, evoked potential development seemed to have reached a maturational plateau that leaves the P1 latencies much more prolonged than for normal hearing adults. Incomplete maturation (plateau in development) was reached well before normal P1 values were obtained.

The second child in the Ponton et al. (1999), CI-2, had normal hearing until the age of 3.5 years, when he suffered a profound hearing loss as a result of meningitis. He received a cochlear implant between 6 and 6.5 years (same age of implantation as CI-1). Data were recorded for this child from 10 years to 17 years of age (HA; 4 –11). The rate of P1 latency and amplitude change were similar to those of age matched hearing children in the same time period, 10-17 years of age. For example, between the ages of 10-17 years, CI-2’s P1 latency underwent the same 15-20 ms. change as that observed in hearing children. However, absolute values differed from those of hearing children. From 15 to 17 years of age (HA; 9-11), the absolute P1 latency value for CI-2 remained relatively stable at approximately 80 ms., whereas the value for age matched children is approximately 40 ms. CI-2, like CI-1, also showed a plateau effect for P1 latency before reaching full maturity. The authors concluded that the more prolonged the period of deafness or auditory deprivation, the earlier maturation will be reached at sub-adult levels. For example, CI-1 who had an early period of deafness (congenital) coupled with a more prolonged duration of deafness (2 years) showed a premature plateau in development at age 12 (normal maturational plateau of the late cortical potentials occurs at age 15 (Ponton, 1998)). CI-2 with a later age of onset of hearing impairment (3.5 years) and shorter duration of deafness did not show plateau in function until age 15. The authors suggest the possibility that after age 15, maturational changes may be limited by chronological age. Shorter durations of deafness correspond with a better prognosis for normal auditory cortical maturation.

Ponton, et al. (1999) proposed a model for the maturation of the auditory cortex after prolonged deafness. Cortical maturation at the onset of deafness is arrested or "frozen" in whatever maturational state it is in at the onset of deafness. With subsequent stimulation via cochlear implant, maturation is delayed by about 6 months, referred to as the "thawing" period. Subsequent stimulation allows maturation of the auditory cortical system to proceed at the same rate as in normal hearing individuals. However, cortical maturation may asymptote before adult-like auditory function is achieved. The age at which cortical-maturation (at sub-adult level) is reached may depend on the age at onset of deafness and the duration of deafness or auditory deprivation. The earlier the onset of deafness and the longer the child experiences deafness prior to implantation, the earlier cortical maturation will occur at sub-adult levels. These results provide further support for early detection and intervention of hearing impairment.

Auditory deprivation has deleterious effects on neuronal morphology and function (Eggermont, et al., 1997; Gunnarson & Finitzo, 1991; Ponton, et al., 1999; Sininger et al., 1999), as well as on perceptual processing of speech (Brown, 1994;

Clarkson et al., 1989; Gravel & Wallace, 1992). However, regardless of the severity of hearing impairment, some effects of auditory deprivation may be potentially reversed if stimulation is received early in the developmental process (Eggermont et al., 1997). Studies of auditory deprivation underscore the importance of experience to the development of the auditory system, consistent with the dynamic systems perspective.

Integration of Multimodal Sensory Information in Infants with HI

Studies of the development of sensory systems in hearing infants indicate that sensory systems do not develop independently of each other. Rather, sensory systems seem to be coupled to some extent. Experience in one modality interacts with development of other modalities. For example, the auditory and visual systems seem to be coupled systems early in development in hearing infants. Infants look in the direction of sound after birth (Mendelson & Haith, 1976). Morrongielo (1994) concluded that where infants look is controlled by what they hear. Hearing and seeing interact so strongly in the control of visual attention that disrupting one of the modalities affects or alters the sequence of development in the other modality (Netelenbos, & Savelsbergh, 1991; Neville, Schmidt, & Kutas, 1983; Quittner, Smith, Osberger, Mitchell & Katz, 1994). This hypothesis is consistent with a dynamic systems perspective, suggesting that when the components of a system change, a different pattern of development may emerge (Van Gelder & Port, 1994).

Evidence for the interdependence of sensory systems is provided by several studies that document an alternate course of development in one modality when a different modality is disturbed (Mitchell & Quittner, 1996; Quittner, et al., 1994). Quittner, et al. examined the role of auditory experience on the development of visual attention in deaf children. The purpose of their study was to examine deaf and hearing children’s ability to selectively attend to a visual task that did not involve processing of sound. Their goal was to provide evidence for a specific role of hearing experience in the development of visual attention by studying changes in deaf children’s performance in a visual task after cochlear implantation (CI). Visual attention was studied in two groups: (a) deaf children (N = 13) with CI and (b), deaf children (N = 11) without CI (control group). The mean age for both groups of subjects was 9.6 years at the onset of the study. The children were tested longitudinally, with the CI children being tested at an average age of 9.8 months and 18.1 months post-implantation. The children were assessed on a speeded task requiring selective visual attention. They were instructed to view a computer monitor and press a button when they saw the number nine preceded by the number one appear in the center of the screen. Distractor numbers, used to test distractibility, were simultaneously presented in a different portion of the screen. The children were instructed to ignore those numbers. While both groups of children improved from time 1 to time 2 (number of correct responses increased), the number of false alarms (incorrect responses) was significantly different for each group. That is, the number of false alarms significantly decreased with time for the CI group and increased slightly with time for the control group, suggesting that visual attention skills improved for the CI children. The authors concluded that a history of auditory experience (with the CI) promoted the ability to respond to some visual targets while not responding to others. They also suggest that the performance in visual attention must reflect the importance of a history of auditory experiences in the development of visual attentional processes. Furthermore they note that increasing access to sound via CI does not lead to immediate improvement but improvement may appear after a year or more, consistent with reversal of the negative effects of auditory deprivation and a "thaw" period. In their study, changes in visual attention were seen to result from changes in auditory-visual experience. This study supports the idea that improvements to the auditory modality effected improvements in the visual modality, highlighting the interdependencies between sensory systems. It provides further support for a dynamic systems approach to developing sensory systems whereby altering the development in one modality leads to different developmental outcome in another modality.

Neville et al. (1983) studied the relationship between early auditory experience and the organization of visual processing in the brain. Using stimuli presented peripherally and at the fovea, visual-evoked potentials (EP's) were recorded from the scalp. The refractory periods of EP's over visual and auditory brain regions (frontal, temporal and occipital) in normal hearing (N = 13) and congenitally deaf participants (N = 8) were compared. A difference was found between hearing and deaf subjects in foveal versus peripheral processing as measured by the N150 response. Hearing participants' N150 was larger for foveal stimuli than for peripheral stimuli. This pattern was not apparent in deaf participants, who showed an N150 whose amplitude was 1.5-3 times larger for peripheral signals. Second, over the posterior scalp (parietal and occipital lobes), an area related to visual processing, the P230 visual component was observed to be much larger in deaf participants than in hearing participants for both peripheral and foveal stimuli. Results from this study showed that a re-organization of visual areas occurs in deaf adults who were deafened at birth. Specifically, the authors suggest that the loss of audition early in life allows for increased growth and activity of the visual sensory systems, which in turn results in heightened sensitivity (compared to hearing individuals) to peripheral motion in the visual modality.

Netelenbos and Savelsbergh (1991) have also provided evidence in support of the conclusion that altering the course of development in one modality strongly influences development of other modalities. They studied visual localization of objects within and outside the visual field in nine congenitally deaf children (mean age, 133 months) and nine normal hearing children. Eye movements were monitored via corneal reflection techniques. The participants' task was to look at a fixation lamp directly in front-centering condition and to visually fixate any light that came from the periphery and outside of the periphery. Results showed no difference between localization times of deaf and hearing participants when the target was located inside the visual periphery. However, when the target fell outside the periphery, deaf children took longer (approximately half a second more) than hearing children to localize the lamp, showing evidence for interdependence among developing sensory systems where altering the course of development in one modality leads to a different developmental trajectory in the other.

Acquisition of Speech Production Skill

Speech Production Patterns in Adults and Children with Profound Hearing Impairment

The characteristics of speech production in adults and children with hearing impairment will be discussed prior to production acquisition in infants. One effect of profound auditory deprivation is a lack of appropriate auditory feedback. Consequently, deaf speakers adopt alternative production strategies that negatively affect the intelligibility of speech (McGarr, 1983). Errors in speech production of the profoundly hearing impaired span several aspects of segmental and suprasegmental characteristics of speech production (Dodd, 1976; Hudgins & Numbers, 1942; Levitt, Stromberg, Smith & Gold, 1980; Monsen, 1976, a, & b, 1978; Smith, 1975; Tye-Murray, 1990). The low intelligibility of profoundly hearing impaired speech has been ascribed to inappropriate co-articulation, articulatory timing, and respiratory control. It is apparent that in the context of absent auditory input, alternate patterns of production behaviors are instantiated in deaf speakers. These patterns seem to be stable-state patterns, as they seem to be representative of many deaf speakers, universally. The following is a brief discussion of the findings obtained from production studies in individuals with profound hearing impairment.

Transcription studies of speech of hearing impaired children and adults have documented systematic patterns of production errors (Dodd, 1976; Smith, 1975; Levitt et al., 1980). Segmental errors made by the hearing impaired can be divided into six categories: 1) substitutions, 2) omissions, 3) distortions, 4) unidentified substitutions, 5) vowel diphthongization, and 6) failure to achieve an intended diphthong. Consonant omissions are the most common type of consonant error. Consonants in initial and final position are affected the most; whereas, medial and back consonants tend to be omitted more than front consonants (Smith, 1975). Phonemes produced at the front of the mouth have a tendency to be produced correctly; whereas, phonemes produced farther back tend to be produced incorrectly. The tendency of increased correct production with increasing phoneme visibility (front to back) has been noted for spontaneous speech as well as for elicited speech. Other errors involve confusions of the voiced-voiceless contrast. Voiced-voiceless contrasts are made in the direction of the voiced member. Errors in voicing contrast may be due to an apparent failure to coordinate timing of respiration, phonation and articulation in attempting to produce voicing contrasts (Smith, 1975). Vowel errors are also very common in the speech of hearing impaired persons. The errors are of five types: 1) substitution, 2) neutralization, 3) omission, 4) nasalization, and 5) hiatus of diphthong (Levitt et al., 1980).

Acoustic studies of vowels suggest that the formant frequencies of profoundly hearing impaired children and adults tend toward the neutral vowel / ə, ʌ/. A reduced or restricted vowel space has been demonstrated. Overlap of the first, second, and third formants (Angelocci, Koop, & Holbrook, 1964; Monsen, 1976 a) are characteristics of vowels produced by profoundly impaired individuals. The second formant (F2) tends to remain at around 1800 Hz for all vowels (Monsen, 1978). Boone (1966) reported that F2 tends to be lower for deaf than for hearing children. Since F2 is related to tongue movements in the front/back dimension, these results have been interpreted to mean that hearing impaired speakers do not differentiate tongue movements in the front/back dimension for vowels.

Additionally, lack of co-articulation or abnormal co-articulation is a major contributor to the low intelligibility evidenced by hearing impaired individuals (McGarr & Whitehead, 1992; Tye-Murray, 1991, 1992; Tye-Murray & Folkins, 1990). Acoustic and physiologic data regarding co-articulatory patterns in the speech of profoundly hearing impaired adults support the idea that deaf speech exhibits fewer context-effects (McGarr & Whitehead, 1992). Results from acoustic studies have indicated that deaf speakers use restricted tongue movements to effect vowel differentiation. Instead it has been shown that deaf speakers tend to effect vowel differentiation through jaw movements (Tye-Murray, 1991). Even with amplification, the F2 frequency region remains out of the auditory range of the deaf. As a result, deaf speakers focus on the visible aspect of vowel production, jaw movements, while not producing the non-visible aspects of vowel production, mainly tongue movements in the front/back dimension. The notion that deaf speakers use restricted tongue movement in the front/back dimension has been confirmed by physiological studies using cinefluorographic and electromyographic (Tye-Murray, 1991) methods.

Proper supra-laryngeal co-articulation involves more than adequate timing of lingual movements. Proper control of the velo-pharyngeal port also contributes much to the intelligibility of speech as it affects the quality of the acoustic output (Stevens, Nickerson, Boothroyd, & Rollins, 1976). Control of the velo-pharyngeal port entails opening of the port for nasal consonants and closing of the port for oral consonants. Normal coordination of velo-pharyngeal movements in utterances with nasals in vowel contexts show that the vowels produced between two nasals are usually produced with partial opening of the velo-pharyngeal port. Furthermore it has been shown that velo-pharyngeal port anticipates the nasal consonant by 100 ms or more. There is similar carry-over of nasalization following the nasal consonant. In deaf speakers, control of the velo-pharyngeal port is aberrant, primarily because they cannot discriminate acoustic quality differences that are affected by port manipulation, and secondarily because movements of the velo-pharyngeal port remain out of the visual field for deaf speakers. Stevens et al. (1976) assert that most people are not conscious of velo-pharyngeal movements and learn to make them based on the acoustic consequences effected by such movements.

The perceptual effect of inadequate velo-pharyngeal control on vowel production is vowel nasalization. The acoustic correlates of nasalization are shifted formants or a split first formant (Fujimura, 1969; House & Stevens, 1956), enhanced amplitude of the lowest harmonics (Delatrre, 1955) and reduced F2 frequency (Matyear, MacNeilage & Davis, 1998). Stevens et al. (1976) compared velo-pharyngeal timing in hearing (N=17) and deaf (N=25) children aged 8-15 years. Vowel nasality was measured on groups of nasal and non-nasal words as spoken by each group. For words in non-nasal contexts, improper velo-pharyngeal control as evidenced by abnormally high levels of nasalization was evident in hearing impaired speakers.

In summary, the emergent vocalization patterns produced by hearing-impaired speakers have underlying aberrant physiologic correlates that result in low intelligibility of speech. Inadequate auditory input results in the alternate production patterns observed in speakers with deafness. It has been asserted by many investigators that many of the aberrant patterns adopted by hearing impaired individuals are initially due to the lack of auditory feedback available to this population but are to some extent also learned behaviors as a result of certain training methodologies (Higgins, Carney, McCleary, & Rogers, 1996). From a dynamic systems perspective the alternate production patterns evidenced by speakers with profound hearing loss would be predicted based on the differing inputs into the system from those afforded hearing speakers.

Cochlear Implants and Speech Production in Toddlers

Further evidence that auditory input plays a crucial role in determining preferred speech patterns is provided by research on the effects of cochlear implants on speech production (Hesketh, Fryauff-Berschy, & Osberger, 1991; Osberger, Robbins, Berry, Todd, Hesketh, Sedey, 1991; Robinshaw, 1996). Specifically, prior to implantation and regardless of age or type of device (hearing aid or tactile device), children with profound hearing impairment generally evidence similar production patterns such as segmental inventories that are replete with labial nasals, and neutral vowels (Hesketh et al., 1991; Osberger, et al., 1991; Robinshaw, 1996). Following implantation, production patterns of implanted children change significantly from those of deaf children not receiving cochlear implants. For example, Osberger et al. (1991) analyzed the speech production characteristics of multichannel cochlear implant users (n = 7), tactaid users (n = 12), and inconsistent users of tactaid hearing aids (n = 4). The mean age for the tactaid and Nucleus groups was 5;5 and 5;1, respectively at the beginning of the study. The mean age of the control group was 3;7 years at the beginning of study and 4;7 at the end of the study. A 6-minute spontaneous speech sample was obtained at 6 and 12 months after device fitting for each child in each group. The phonetic inventories of the control group, the tactaid group and the CI group were not significantly different in the pre-device fitting period. All three groups showed a preponderance of labial nasal /m/ vocalizations. Vowels produced by all three groups were mostly central vowels. The same pattern was evidence by two other children, Adam, who was implanted with a multi-channel cochlear implant at the age of 2 (Robinshaw, 1986), and KZ who wore a tactile aid for two years prior to receiving an implant at age 5 (Hesketh, et al, 1991). Post-implantation, a dramatic decrease in nasals was observed and a significant increase in oral stop production as well as a slight increase in liquids, glides, and fricatives was also observed for the CI users in all three studies. In all cases the CI groups showed a significant reduction in labial vocalizations and an increase in dental/coronal vocalizations. Slight increases were noted in palatal and dorsal vocalizations as well. Vowel inventories showed evidence of diversification with an increase in the use of front vowels. Interestingly, the inventories of the control group and the tactaid group in the Osberger et al., study did not change significantly when measured one year later, suggesting that auditory input is essential for vocal development.

It is apparent that without adequate auditory input children's inventories continue to be limited well up to and possibly beyond the age of five years. Phonetic studies of CI children have shown that alternate patterns of vocalization organization emerge when hearing sensitivity is severely reduced. These patterns seem to be stable patterns in the context of a speech output system that is not significantly influenced by the auditory perceptual variable. The access to auditory input afforded by CI clearly is sufficient to change the preferred patterns of production to patterns more like those of haring children. The change noted in pre- and post- implant production patterns provide support for a dynamic systems perspective of motor skill acquisition, that suggests that the emergent patterns of organization are dependent on the configuration of speech output system variables. When auditory sensitivity is introduced into the system, the output patterns change to reflect a new system configuration.

Speech Production in Infants with Hearing Impairment

Effect of Hearing Loss on Babbling Onset

Unequivocal evidence for an influential role of auditory sensitivity on vocalization output during babbling has been provided (Eilers & Oller, 1994; Oller, Eilers, Bull & Carney, 1985; Oller & Eilers, 1988; Wallace, Menn, & Yoshinaga-Itano, 2000). Results from studies on the effect of profound hearing loss on babbling onset have produced the following crucial findings. First, infants with profound hearing loss are delayed in babbling and do not begin babbling until after 11 months of age (Eilers & Oller, 1994; Oller, Eilers, Bull & Carney, 1985; Oller & Eilers, 1988). There is no overlap in the onset distribution of canonical babbling between infants with profound hearing impairment (onset distribution 11-49 months, Eilers & Oller, 1994) and normal hearing infants (6-10 months, Oller & Eilers, 1988). Once they have reached the canonical babbling stage, hearing infants consistently produce canonical syllables (a babbling ratio of .2 or better is consistently observed). The same is not true for deaf infants (Oller & Eilers, 1988). It has been found that the babbling ratio in hearing impaired infants is erratic (Eilers & Oller, 1994). Once canonical babbling appears in infants with hearing impairment, a babbling ratio of .2 or higher is not consistently maintained across time (Oller & Eilers, 1988). Finally, attainment of the canonical babbling stage in infants with profound hearing impairment is moderately correlated (r=.68) with age at amplification (Eilers & Oller, 1994).

Phonetic Characteristics of Babbling Sequences

Phonetic inventories have been described primarily for profoundly hearing impaired infants and children. Little data has been collected on the inventories on infants with mild-to-moderately severe hearing impairments. The size of the consonantal inventory of profoundly impaired infants is reduced. A propensity for labial over coronal consonant use is found (Stoel-Gammon, 1986; Locke, 1983; Stoel-Gammon, 1988; Stoel-Gammon & Otomo, 1986; Yoshinaga-Itano, Stredler-Brown and Jancosek, 1992), a trend that is opposite that of hearing infants (Boysson-Bardies & Vihman, 1991; Davis & MacNeilage, 1995b; Locke, 1983; Roug, Landberg & Lundberg, 1989; Vihman, Ferguson, & Elbert, 1986). A large proportion of nasal consonants are also found in the inventories of profoundly hearing impaired infants. This trend is also opposite that of hearing infants who produce more oral consonants than nasal consonants in the babbling period. This is presumably based on lack of access to information about nasality that is acoustically signaled and not visually apparent (Stevens et al., 1976). Davis, McCaffrey, von Hapsburg, and Warner-Czyz (submitted) analyzed the occurrence of nasal and oral consonants in three infants, 9-20 months of age with varied hearing levels. They showed that the infant with moderate hearing impairment had a high ratio of oral consonants, while the two infants with profound hearing loss produced a high ratio of nasal consonants; however, singletons and syllabic segments were pooled for that analysis.

Transcription studies of vowel production in profoundly hearing impaired infants show a preponderance of neutralized vowels (Yoshinaga-Itano, Stredler-Brown,

& Jancosek, 1992) that may to some degree be an artifact of nasality (Matyear, et al., 1998; Stevens et al., 1976). In a study of the effects of nasalization on vowel context in hearing infants (Matyear, et al.), vowels in nasal contexts had lower second formant values and higher first formant values, contributing to the percept of a neutralized vowel.

Degree of Hearing Impairment and Production Acquisition

A paucity of research exists specifically on early identified infants with milder hearing levels (less than severe-to-profound). A composite analysis of the results obtained on the inventories of hearing impaired infants in the 3-12 month age range shows that only 7 infants had a hearing level less than severe-to-profound (Davis, et al., submitted; Eilers & Oller, 1994; Oller, Eilers, Bull & Carney, 1985; Oller & Eilers, 1988; Stoel-Gammon & Otomo, 1986; Stoel-Gammon, 1988; Wallace, Menn, & Yoshinaga-Itano, 2000; Yoshinaga-Itano, Stredler-Brown, & Jancosek, 1992). Results for infants with milder hearing impairments showed a higher proportion of coronal consonants (/d, t, s/ and /l/) than observed in infants with severe-to-profound hearing impairment. This trend is more similar to patterns reported for hearing infants (Boysson-Bardies & Vihman, 1991; Davis & MacNeilage, 1995b; Locke, 1983; Roug et al., 1989; Vihman et al., 1986). Vowel inventories tended to have a higher proportion of the mid-front vowels /e/ or /eI/ than the infants with severe-to-profound hearing loss. For example, Davis, et al. (submitted) studied the inventories of three infants with hearing impairment, one with moderately severe hearing loss. Over a period that spanned chronological age of 9-20 months, the infant’s vowel repertoire consisted of approximately 45% mid vowels, 35% low vowels, and 16% high vowels. In the front/back dimension 44% were front vowels, 36.2% were central, and 15.4% were back vowels. This infant's inventory showed diversification in comparison to the limited inventory of the two profoundly impaired infants studied for comparison. Vowel diversification was also found in a second infant, Infant B. At the onset of the study (during the first two sessions) infant B's hearing was moderate-severe, similar to Infant A. Hearing loss progressed to profound from session 3-5. Analysis of the infant's vowel inventory in the first two sessions showed that all front/back dimensions were represented. By session 5 infant B's inventory changed drastically, showing 93% central vowels.

Regardless of degree of hearing loss, infants with less severe hearing impairment tend to have higher than normal occurrence of neutral vowels. Yoshinaga-Itano, et al. (1992) showed small differences in the phonetic inventory of hard of hearing compared with profoundly impaired infants and suggested that segmental inventories do not reliably discriminate infants in the hard of hearing group (infants with mild to severe hearing impairments) from infants with severe-to-profound hearing impairment.

Vocalization Types within Utterance Strings

In hearing infants, "vocants" and CV's account for 60% and 19% of the vocalization types produced during babbling, respectively (Davis & MacNeilage, 1995b; Kent & Bauer, 1985; Mitchell & Kent, 1990). Studies investigating vocalization types in hearing impaired infants indicate that the predominant vocalization type dominating the repertoire is, like in hearing infants, the singleton vowel or vocant. However, the onset of repetitive syllable-like (CV) canonical babbling is delayed significantly in hearing-impaired infants and is an unstable behavior once it occurs (Eilers & Oller, 1994). That is, the babbling ratio is not consistent once the canonical babbling stage has been achieved (Oller & Eilers, 1988). This lack of stable CV vocalizations suggests that auditory input may be a control-parameter that significantly affects achievement of stable patterns of syllabic output observed in hearing infants.

Davis, McCaffrey, von Hapsburg, and Warner-Czyz. (submitted) monitored the vocalization types occurring within utterance srtings in the three infants with varying degrees of hearing loss described previously. Infant A and B, had moderate to severe hearing impairment at the beginning of the study (infant B's hearing sensitivity decreased to profound hearing loss between the second and third data collection period). Infant A, with moderate-to-severe hearing loss showed a relatively stable pattern of vocalization types. Throughout the period of study (chronological age 9-20 months), singleton vowels were the most predominant syllable type, averaging 55% (range 38%-80%) while CV syllables accounted for approximately 31% (range 18%-51%, See Table 1). This is consistent with the normal distribution of vocalization types produced by hearing infants. Infant C, who had a profound hearing loss across the period of study (CA; 7-19 months; HA of 4-16 months), consistently produced singleton vowels, averaging (90%) across the 5 sessions (range = 76%-98%). Syllables accounted for 4.6% of the repertoire. Infant C did not produce syllables up until sessions 4 and 5, accounting for 7% and 16%, of the inventory, respectively. Infant B, with progressive hearing loss (moderate-to-severe progressing to profound) also had a predominance of singleton vowels during the first two sessions, averaging 82% when hearing was in the moderate-to-severe range. During the first two session the repertoire also showed 9% CV’s. However, a significant re-organization of syllable types in Infant B's inventory emerged subsequent to deterioration in hearing. That is, when the infant’s hearing loss began increasing, the production repertoire showed a dramatic decrease of singleton vowels (40% down from 82%), and a dramatic increase of singleton consonants, accounting for 50.6% of the vocalization types across sessions 3-5. The change was so dramatic that by session four (chronological age approximately 15 months), 96% of the infant's repertoire consisted of singleton consonants, a trend that is not typically observed in hearing infants. However, at session 5, at chronological age 19 months (hearing age 16 months), the infant's repertoire consisted of 70% singleton vowels and 20% syllable types. This is more consistent with normal distribution of vocalization types in hearing children in the 6-10 month period not the 20-month age range (see Table 1-1).

Table 1-1. Vocalization types produced within utterance strings. The information for infant B(a) coincides with sessions 1-2, the period of moderately-severe hearing impairment. The information for infant B(b) coincides with sessions 3-5, the period of progressive hearing loss.

	Vocalization types		
Infant	Singleton V	Singleton C	Syllables
Infant A (moderate)	55%	0%	31%
Infant B			
a. (moderate-severe)	82%	0%	4.5%
b. (Profound)	40%	50%	5.0%
Infant C (Profound)	90%	1.4%	4.6%

The fact that profoundly hearing impaired infants produced fewer syllables may suggest that auditory input is required to some extent for infants to expand their production repertoire to include not only singleton vowels but also a stable syllabic (CV). From a dynamic systems perspective, for hearing infants, repetitive canonical babbling may be a "*stable state*" or an "*attractor state*" that requires auditory input in order to emerge. Consequently, one explanation for the lack of repetitive CV syllables observed in these profoundly impaired infants is that an insufficient amount of auditory input is available to instantiate syllabic vocalizations in relation to other vocalization types. Data from infant B, who started out with moderately-severe hearing impairment speaks to this issue, as a dramatic change in vocalization types occurred subsequent to a decrease in hearing sensitivity. For a hearing impaired infant lacking normal access to auditory input, the alternative organization of the production system may be one that is replete with singleton vowels, singleton consonants and few syllable vocalizations (Eilers & Oller, 1994). Vihman, et al. (1986) suggest that "if the emergence of canonical babbling, marking the beginning of the period of steady growth in use of true consonants were entirely maturational, the same timetable could be expected to obtain for deaf infants" (pg. 34). This suggests that auditory sensitivity is an important system variable affecting emerging vocalization patterns in hearing infants.

Syllabic Organization of Speech

The Frame/Content perspective proposes an explanatory principle for syllable based production patterns in babbling and first words in hearing infants (Davis & MacNeilage, 1995, Davis, MacNeilage & Matyear, in press). This approach goes beyond the taxonomic description of segmental aspects of infant utterances previously explored and examines the emergence of context-based syllabic organization. McCaffrey, Davis, MacNeilage, and von Hapsburg (2000) analyzed the emergence of syllabic organization in a hearing impaired infant to test predictions of the Frame/Content approach. They explored segmental and syllabic organization in one infant who was profoundly hearing impaired and received a cochlear implant at 24 months. Post-implantation, the infant's auditory capacities changed drastically. The implant artificially stimulated the auditory nerve and provided the infant with auditory thresholds in the mild- to- moderate range (30-40 dB HL) across the audiometric frequencies of 250 Hz to 8000 Hz. Prior to receiving the implant, the infant's vocalizations were recorded and phonetically transcribed. She produced predominantly singleton vowels (mostly central) and singleton consonants (mostly prolonged labial-nasal qualities) indicating use of a nasal production mode. She produced few CV syllables. Consequently, CV co-occurrence patterns confirmed only the labial consonant- central vowel association, with labial nasals. At 6 months post-implantation, the infant's repertoire still included singleton vowels but also showed a significant increase in the number of CV syllables. At that time, analysis of intra-syllabic organization showed that syllabic vocalizations were consistent with CV co-occurrence patterns observed in hearing infants. Intra-syllabic organization was predominantly characterized by oral-labial consonants (/ba/) with central vowels as well as by coronal consonants and front vowels (i.e., /dae/). Thus, with significant improvement in auditory sensitivity provided by the cochlear implant, syllabic vocalizations emerged. The number of disyllabic vocalizations increased following implantation; disyllabic utterances were rare pre-implant. Post-implantation both reduplicated and variegated sequences were present, with reduplication decreasing over the data collection period. Intra-syllabic organization in variegated syllables was consistent with patterns observed in hearing infants for consonants but not vowels. For consonants, manner changes predominated over place changes as in hearing infants. However, for vowels, tongue front/back movements predominated over tongue height movements in variegated syllables. It is not clear from this case study whether normal syllabic organizational patterns are generally present in the population of infants receiving cochlear implants. Although syllabic output was quantitatively small in the pre-implant condition, it is not known whether the organization of such output follows normal production patterns. This case study highlighted the difference in production patterns when the infant's auditory condition changed from thresholds in the profound hearing range to thresholds in the mild-to-moderate range. The results obtained in this infant may have been due to changes in audibility, in which case we may see similar results from infants with milder hearing impairments who are not implanted. An alternative explanation would be that the results are due to the signal-processing device (the cochlear implant processing strategy); thus studies comparing effect of intervention device are also warranted.

Studies of the effects of auditory deprivation on pre-linguistic production behaviors have indicated that profound deafness results in substantially delayed babbling onset (Eilers & Oller, 1994; Oller, Eilers, Bull & Carney, 1985; Oller & Eilers, 1988). However, babbling onset may be related to age of identification as well as age of amplification and needs to be studied further. Studies investigating babbling behaviors of hearing impaired infants have mostly focused on the production behaviors of the profoundly hearing impaired. These studies, while highlighting the limited production capacities of infants with profound HI, do not expand on the context dependent process of sequencing consonants and vowels in serially ordered output or how segmental qualities may reflect the influence of degree of hearing sensitivity. In addition to the limitations posed by narrow focus on segmental taxonomies, a number of methodological problems including late age of identification, late age of amplification, and lack of control for hearing-age, has prevented advancement of knowledge of pre-linguistic vocal behaviors in infants identified at birth. With the recent implementation of universal newborn hearing screening programs, infants are now being identified with hearing impairment at birth, and are receiving amplification devices soon after identification. The goal of the proposed study is to analyze the effect of degree of hearing impairment on several aspects of vocalization patterns including the structure of serially ordered vocal organization as well as on segmental qualities that have been frequently studied in past research.

PURPOSE AND RESEARCH QUESTIONS

The review of the literature has provided evidence that emergent properties (output) of a system are dependent on the interaction of the variables that make up that system (namely perceptual and mechanical characteristics). The prominence of the vocalization patterns observed in hearing infants during the babbling period reflects the influence of the cohort of speech system variables (i.e., perceptual and mechanical). Indeed, data presented from activity-dependent systems and cochlear implant research underscores the co-dependence of interacting sensory and motor systems. In HI infants, when the configuration of variables that makes up the speech output system changes from that observed in hearing infants (the hearing variable is altered) alternate patterns of vocalization become established. From a dynamic systems perspective, a disturbance to any contributing variables may alter the emergent output patterns observed, if they are considered significant control parameters. Whereas, past studies on infants with profound HI have shown alternate patterns of vocalization behavior, they have had a narrow focus on profoundly impaired infants. Additionally, research on aspects of vocalization complexity (i.e., serial organization of syllables) has been limited to case studies (McCaffrey, et al., 2000; Davis et al., submitted). Hence, the influence of auditory input on serial organization of CV’s has not been thoroughly examined relative to auditory sensitivity.

The purpose of the proposed study is to examine the contribution of auditory sensitivity to emergent patterns of speech-like vocalizations in 15 infants with varying degrees of auditory sensitivity, ranging from normal hearing to profound hearing impairment. The extent to which the patterns of observed vocal behaviors are dependent on auditory input may vary. Hence, hearing sensitivity may or may not be an important control-parameter in determining the prominence of some vocalization behaviors. If auditory sensitivity is a significant control-parameter for speech-like vocalizations, then alterations in hearing sensitivity should lead to altered vocalization patterns in the HI infants. If auditory sensitivity is not a significant control-parameter for vocalization behaviors, then similar vocalization patterns should be observed for infants with limited auditory sensitivity compared to those of infants with normal hearing.

General Hypothesis

This study will explore associations between hearing sensitivity as estimated by the pure-tone average (PTA, the average of the thresholds obtained at 500, 1000 and 2000 Hz) and various production patterns observed during the babbling period. Specifically, each inventory type (and its sub-components) will be tested to determine whether it is significantly associated with PTA across the infants. The general hypothesis being tested in this study is whether PTA is an important control-parameter contributing to the emergence of patterns typically observed in hearing infants. When PTA is not associated with the pattern of vocalization behaviors, it is suggested that auditory sensitivity does not contribute to the prominence of those patterns. Aspects of vocalizations that are associated with PTA suggest that the prominence of that behavior is dependent on auditory sensitivity and that significant interactive sensory-motor processes are responsible for those behaviors in hearing infants. This hypothesis will be evaluated for each of the following inventories: (a) vocalization types within utterance strings (i.e., singletons versus syllables), (b), general inventories of syllable shapes, syllable alternations, and consonant onset in syllables (c), intra-syllabic, and (d) inter-syllabic organization patterns.

The results of this study will provide information on the role of auditory sensitivity at the level of each vocalization inventory and generally at the system level (how auditory sensitivity interacts with mechanical characteristics of the system). At the level of each inventory-type, aspects of vocalization behaviors that are or are not significantly associated with auditory sensitivity will be identified. Thus, for each inventory-type, information about how auditory sensitivity might contribute to the prominence of vocalization patterns observed in typically developing infants will be obtained. Finally, results from this study of different systems (hearing and hearing impaired) will be used to make inferences about the potential role of auditory sensitivity at the system level. Thus, an aim of this study is to provide more specific knowledge about the role of auditory sensitivity and how it interacts with other speech output system variables (namely characteristics of the production mechanism) in the development of pre-linguistic speech patterns.

Hypothesis 1: Vocalization Types within Utterance Strings

It is hypothesized that auditory sensitivity contributes to the emergent patterns of vocalizations observed within utterance strings. Specifically, PTA will be associated with types of vocalizations observed in utterance strings. The dependent variables are untranscribable nuclei, singleton consonants, singleton vowels, and syllables. The independent variable is pure-tone average (PTA). It is expected that as PTA increases (hearing sensitivity decreases) singleton output will increase, and syllabic output will decrease.

Hypothesis 2: General Inventory of Syllables

It is hypothesized that auditory sensitivity does not contribute to the patterns of vocalizations related to syllable alternations, syllable shapes and consonant onset patterns, as the mechanisms responsible for determining syllable alternation and syllable shape are due to the mechanical characteristics of the production system. Therefore, it is expected that PTA will not be associated with the distribution of syllable alternation patterns observed and that monosyllabic, disyllabic, and polysyllabic alternations will be similar across the hearing groups. Likewise, it is expected that the distribution of syllable shapes is not dependent on PTA and that the proportion of CV, VC, CVC, and VCV's will be similar across the hearing groups.

Hypothesis 3: Intra and Inter-syllabic Organization:

It is hypothesized that auditory sensitivity does not contribute to patterns of intra and inter-syllabic organization, as these aspects of production are primarily determined by mechanical characteristics of the production system. Therefore, no association is expected between PTA and intra and inter-syllabic organizational patterns.

Hypothesis 4: General Segmental Inventories

It is hypothesized that auditory sensitivity contributes to the emergent patterns of segmental inventories. That is, PTA will be associated with manner of consonant production (more nasals than orals) with increased HI in both singleton and syllable contexts. Furthermore, it is expected that PTA will also be associated with place of consonant production (more labials than coronals). In terms of vowels, it is expected that with increasing PTA, vowels will be restricted to mid and central positions.

Chapter 2: Method

PARTICIPANTS

Fifteen infants with PTAs ranging from 25 dB HL to 120 dB HL participated in this study. For ease of participant description, the infants will be grouped according to hearing loss. Group I (N = 4) had hearing sensitivity within normal limits and was used as a control group for this study. Six infants in Group II (N = 6) included infants with hearing impairment ranging from mild-to-severe sensorineural hearing loss. Infants in Group III (N = 5) included infants with severe-to-profound hearing loss.

Typically Developing Infants (Group I)

Data from four typically developing hearing infants who participated in a larger study of early speech acquisition reported by Davis and MacNeilage (1995) were used to compare across the hearing and hearing impaired groups. Hearing participants are referred to as “C”, “M”, “N”, and “R”. These infants were originally located by referral from the local community. All infants had normal birth histories and were developing typically according to parental case history report and were being raised in monolingual English homes. The Battelle Developmental Screening Test (Giubaldi, Nweborg, Stock, Svinicki, & Wneck, 1984) was also used to establish normal developmental status during the study. There were two females and two males in the Group, and each infant had one sibling. All infants passed a sound field hearing screening at 25 dB HL for the frequencies 500-4000 Hz. Thus, the best PTA for each infant in Group I was assumed to be 25 dB HL. All the infants in this group were in the babbling stage, although two infants in Group I were believed to be entering the first-word stage at the time of this analysis. However, the few tokens believed to be words were omitted from the analysis. For these two infants only babbling behaviors were analyzed. It was expected that the vocalization behaviors of these infants would reflect patterns typically observed in hearing infants in the babbling period. The average age of the participants in this group was approximately 12 months (range = 11-14 months). This age was selected to better match the chronological age of infants in Group II (average chronological age 12 months) and the hearing age of infants in Group III (average chronological age 17 months, hearing age 12 months) used in this study. Table 2-1 shows the Group I hearing participant characteristics.

Table 2-1. Hearing Infant Characteristics.

Infant	Gender	Age at time of Analysis in Months
C	F	12
M	M	14
N	M	11
R	F	12
Total		47
Mean		11.75
SD		1.707

Participants with Hearing Impairment (Group II & III)

Data were collected for 11 (F = 4, M = 7) infants with sensorineural hearing impairment. Infants were referred by professionals in the following communities: (a) Knoxville, Tennessee (b), Fort Worth, Texas and (d) San Antonio, Texas. All participants had hearing parents who used oral communication. All participants except for Infant GW were from monolingual English speaking homes. Infant GW was from a bilingual Spanish/English home. All of the infants had received developmental evaluations as part of the early intervention process. The methods employed for developmental evaluations varied for each infant, according to the preferred method used by the program providing intervention. None of the infants participating in this study were reported as having severe motor or cognitive delays. However, some infants were suspected of having mild motor delays, involving balance. Generally, the infants were developing “typically” in areas outside of auditory and language development. All of the infants were attending aural habilitation sessions at least once a week.

A description of the severity of hearing loss for each infant was obtained from the infants’ case history and medical/audiological records made available by parents or guardians. Tables 2-2 and 2-3 show the individual infant air conduction auditory thresholds for Group II and III infants. Not all infants received the same diagnostic testing, as they were referred from various clinics employing different diagnostic protocols. Thus, the auditory threshold information available for each infant varied as well as the method by which that information was obtained. Behavioral thresholds were obtained for the following frequencies: 250-4000 Hz, either through headphones or sound field. The average of the air conduction thresholds obtained at 500, 1000 and 2000 Hz, known as the pure-tone average (PTA), was obtained for each infant. The average PTA for Group II was 47 dB HL and the average PTA for Group III was 96 dB HL. The average PTA for the hearing group (Group I) was 25 dB HL. Even though bone-conduction thresholds were not available for these infants, all infants in this study were suspected of having sensorineural hearing impairments. Otologic examination and immittance results for each infant suggested no middle-ear involvement.

All participants with hearing loss wore behind-the-ear (BTE) hearing aids, bilaterally. According to parental report all infants wore the hearing aids for as much of the day as possible, taking them off only for naps, car-rides, breast-feeding and baths.

All of the parents also reported that the infants usually pulled the hearing aids off several times throughout the day. All participants wore their hearing aids during data collection sessions. The investigator ensured that the infants wore the amplification devices set at the usual settings recommended for that infant by the audiologist, during the recording sessions. The parents and investigator monitored hearing aid usage during recording sessions.

Table 2-2. Auditory thresholds for infants in Group II. The pure-tone average (the average thresholds at 500-2000 Hz) is also provided. SF indicates thresholds obtained in the sound field.

Auditory thresholds in dB HL (re: ANSI, 1989)							
Infant	**Ear**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**PTA**	**Best PTA**
CR	R	35	25	50	55	37	37
	L	40	35	45	50	40	
JH	R	70	75	60	70	68	40
	L	40	35	45	50	40	
NL	SF	35	40	45	55	40	40
AM	R	60	70	DNT	75	65*	65
	L	60	75	DNT	70	68*	
EC	R	35	55	65	95	52	52
	L	45	55	55	60	52	
AW	R	100	100	95	95	98	50
	L	50	50	50	65	50	
Group PTA**							47

* PTA based on available thresholds at 500 and 1000 Hz only.

** Group PTA based on best PTA for each infant.

Table 2-3. Auditory thresholds for infants in Group III. The pure-tone average (the average thresholds at 500-2000 Hz) is also provided. SF indicates thresholds obtained in the sound field.

Auditory thresholds in dB HL (re: ANSI, 1989)							
Infant	**Ear**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**	**PTA**	**Best PTA**
GW	R	80	95	95	90	90	85
	L	85	75	95	95	85	
SP	SF	85	NR*	NR*	NR*	>85**	>85**
MB	R	95	105	100	90	100	100
	L	95	110	100	NR	102	
BB	R	NR	NR	NR	NR	NR	118
	L	NR	120	115	120	118***	
LB	SF	NR	NR	NR	NR	>90	90
Group PTA****							96

* No response at the limit of the audiometer for that frequency.
** Best PTA approximation based on threshold at 500 Hz.
*** PTA based on available thresholds at 1000, 2000, and 4000 Hz.
**** Group PTA based on best PTA for each infant.

Group II: Infants with Mild-to-Severe HI

Six infants with bilateral, mild-to-severe sensorineural hearing loss participated in this study. Their average PTA was 47 dB HL. All infants in this group were male. The average age at which the infants received their first hearing aids was 4.8 months. The average CA of the infants in the mild-to-severe group was 12 months of age (range = 7-14 months). The average H.A. (time since hearing aid fitting) at the time of study for the mild-to-severe group was 7.1 months of age (range 4.5-10.75 months). Table 2-2 shows each infant's most recent auditory thresholds obtained immediately prior to or after data collection. Thresholds are reported for the 500-4000 Hz frequency range. Ear specific data is reported for most of the infants in this group. Table 2-4 shows each infant's age of amplification, chronological age at the time of study, and the estimated hearing age. The individual infant profiles are presented in Appendix A.

Table 2-4. Characteristics of infants with moderate-to-severe hearing impairment. The following information is provided for each infant: age at time of initial fitting of amplification (AA) in months and weeks, chronological age (CA) and hearing age (HA) in months at the time of study. All ages are provided in number of months.

Infant	**AA**	**CA**	**HA**
CR	5;0	13	8
JH	7;0	15	8
NL	6;2	11	4;2
AM	7;0	14	7
EC	2;2	7	4;2
AW	1;1	12	10;3
Total	29.3	72	42.8
AVG	4.8	12	7.1
SD	2.5	2.8	2.4

Group III: Infants with Profound Hearing Impairment

Five infants with bilateral, severe-to-profound sensorineural hearing impairment (mean PTA = 96 dB HL in the better ear) participated. All infants in this group were female. Table 2-5 shows the age of amplification, chronological age and hearing age for the infants in Group III. The average age of the group of infants with profound hearing impairment was 17.4 months of age (range = 13-24); their average hearing age was 12.8 months (range 11-14). The average age at which the infants received amplification was approximately 8.5 (range = 1; 5-13;0) months of age. Infants in Group III were, on average, five months older than infants in Group II and Group I. Additionally, Group III's hearing age (HA) exceeded that of group II by approximately five months, but approximated that of infants in Group I.

Table 2-5. Characteristics of infants with profound hearing impairment. The following information is provided for each infant: chronological age at time of initial fitting of amplification (AA), chronological age (CA), and hearing age (HA) at time of study. All ages are given in months and weeks.

	Age Type		
Infant	**AA**	**CA**	**HA**
GW	1; 2	16	14
SP	1; 2	13	11
MB	1;2	16	13
BB	4	19	15
LB	13	24	11
Total	17;0	87	64
Mean	8.5	17.4	12.8
SD	6.4	3.8	1.8

DATA COLLECTION PROCEDURES

Data collection procedures used were consistent with the method employed by Davis and MacNeilage (1990, 1995) to study the hearing infants (Group I) used as a control group in this study. All infants except MB, BB and LB wore an Audio Technica ATW-1030 wireless microphone clipped to one shoulder of a bib specially made to hold the wireless receiver. Once the microphone and receiver were placed, the infants were typically not aware of their presence. Data were collected on an ATW-20 digital audio tape recorder (DAT), using TDK-DAR90 digital audio-tapes. The investigator observed the infant and mother interact while monitoring the equipment and interacted with the infant only as needed for equipment adjustments. Infants BB, LB, and MB's vocalizations were audio-taped using a Sony TCM-5000 portable cassette tape or Tascam digital audio recorders with a Telex ProStar FM remote microphone clipped to the infant's shoulder. The FM transmitter was placed in a fanny pack secured around each infant's middle, much the same way as for the other infants in this study.

The data for the hearing impaired infants were collected by the principal investigator, with the exception of three infants (BB, MB, LB) whose data were collected by Dr. Helen McCaffrey from Texas Christian University. Data collection sessions for each infant varied according to parent availability and vocalization volubility. For each infant data collection did not exceed a period of one month. For example, data for infants JH, AM, EC, and GW were collected over two-consecutive days. Data for AW and NL were collected in one day, over a 3-hour period. Data for SP were collected on two days separated by approximately a month. Data for CR were collected over three, one hour-long aural habilitation sessions, spread over three consecutive weeks. Data for BB were collected in one 1-hour long session. Data for MB, and LB were collected over two one-hour long aural habilitation sessions, spread over two consecutive weeks. The data collection period for each infant coincided with a HA that fell between 4 -15 months. All samples (except for CR, BB, LB and MB's) were obtained in the infant's home while he or she engaged in daily routines with family members. A total of 809 (mean = 150) and 671 (mean = 134) minutes of data were collected for infants in Groups II, and III, respectively. The data for Group II and III were compared with a total of 360 (Mean = 90) minutes obtained from Group I. Table 2-6 shows the mean number of sessions and minutes of data collected for each group.

Table 2-6. Mean number of sessions, and minutes of data collected for each infant in each group.

Group		**# Minutes**	**# Sessions**
Group I	Total	360.0	6.0
N=4	Mean	90.0	1.5
	SD	34.6	.6
Group II	Total	809.0	10.0
N=6	Mean	150.0	1.8
	SD	26.7	.8
Group III	Total	771.0	12.0
N=5	Mean	134.0	2.0
	SD	62.1	0

DATA ANALYSIS

Transcription

Data were transcribed using the International Phonetic Alphabet (IPA) system of notation (revised 1993; updated, 1996). The primary investigator transcribed all the tapes collected for infants with hearing impairment, including those collected at Texas Christian University (except for infant BB). The tapes for the typically developing infants were already transcribed as part of the hearing infant project (reported in Davis & MacNeilage, 1995). However, because only syllable-based output was transcribed for the typically developing infants, the primary investigator re-transcribed the audiotapes from that project to analyze non-syllable based output excluded from the original transcriptions so that it was comparable with the two hearing-impaired groups in this study. In re-analyzing the typically developing infant corpus, the investigator did not re-transcribe syllable-based output, only singleton vowels, consonants, and untranscribable nuclei that had not been included in the original transcript reported in Davis and MacNeilage (1995).

Broad transcription methods were used. All syllabic and non-syllabic utterances were transcribed. Syllabic vocalizations were characterized according to the following: A syllable consisted of a sequencing of a closant or consonant–like sound by a vowel-like sound (i.e., VC or CV). Non-syllabic utterances were utterances that had vowel-like or consonant–like qualities, but that did not meet the criteria for the syllable (i.e., singleton vowels (V) or singleton consonants (C)). For this study CV's that were bounded by glottal consonants (i.e., /h, ʔ/) were considered marginal syllables.

For consonant transcription, four places of consonantal articulation were specified, including labial (e.g., /p, b, m, wβ,/), βcoronal (e.g., /t, d, n, z sʒ, ɵ, ð, ʃ, ʧ, ʤ, l, j /), dorsal (e.g., /k, g, ŋ/), and glottal (e.g., /h, ʔ, χ Consonants were also classified in terms of the following manner categories, plosive (e.g., /p, b, t, d, k, g/), nasal (e.g., /n, m, ŋ/), fricative (e.g., /f, v, z, s, ʒ, ɵ, ð, ʃ, tʃ, dʒ/) and approximant (e.g., /l, ɹ/). Similarly, for vowel transcription three front/back dimensions were specified including front (i.e., /I, I, e,ɛ,y, æ/), central (i.e., /ə, ʌ, a/) and back (i.e., u,, ʊ, o , ɔ, ɑ/). Vowels were also classified in terms of the following three height dimensions high, (e.g., /i, I, u, ʊ/), mid (e.g., /e, ɛ, o, ɔ, ə, ʌ/), and low (e.g., /æ, a, ɑ/) categories. Vocalizations separated by approximately 1 second on each side were considered to be different utterance strings.

This criterion was verified through the use of Sound Studio Classic software (Kwok, 2001).

Global symbols as described by Oller (1990), were used to transcribe utterances that were not transcribable. This included untranscribable nuclei, untranscribable consonants, and untranscribable vowels (UN, UC, and UV). Vegetative and reflexive sounds (i.e., cries, goos, grunts, coughs, hiccups) were not transcribed.

Reliability

Group I Infants

Reliability for the infants in Group I was previously reported (Davis & MacNeilage, 1995a). Consonant reliability averaged 76.8%. Vowel agreement averaged 45% for the babbling period. The procedures used to calculate agreement can be found in Davis and MacNeilage, (1995a). Briefly, they used a point-to-point method whereby disagreements between transcribers were either correct or incorrect.

Group II and III infants

The primary investigator transcribed all of the infant data for the hearing impaired groups except for those of two infants from Group III that were collected by Dr. Helen McCaffrey. A description of how agreement was calculated for those two infants will follow the description of the agreement for the remaining HI infants. A secondary transcriber transcribed 10% of the HI infant utterances and was blind to the following: (a) the specific predictions of this study and (b) the hearing sensitivity of the infant. Agreement was calculated for all of the infants in Group II and three infants in Group III using the primary observer’s transcription as the comparison for the secondary transcriber. Transcription agreement was calculated using a multidimensional analysis procedure recommended by Oller and Delgado (1990). Each consonant was matched for manner and place agreement. Similarly each vowel was matched for height and front/back agreement. When two segments did not match in manner or place (or height or front/back), the disagreement was assigned to a category based on the extent of the disagreement. Manner and place disagreements were classified into “small” and “big” disagreements. Similarly for vowels, height disagreements were classified into the following categories: “teeney”, “small”, and “big”. Front/back disagreements were classified under the following categories “small” and “big”. In general, the size of the classification depended on the number of categories that separated the two transcriptions. For example, for vowel front/back, the categories front, central, and back were considered steps. Categories adjacent to each other were separated by one step (e.g., front central) and were classified as “small” disagreements. Categories separated by two steps (e.g., front and back) were classified as “big” disagreements. An index of consonant and vowel agreement was obtained for each infant using equations that incorporate the different types of disagreements via a weighting scheme that gives small disagreements less weight than big disagreements. For consonant and vowel agreement the Equations 2.1 and 2.2 were used to calculate total agreement. Table 2-7 provides the results of the agreement analysis.

(2.1)

Consonant Agreement = ((# consonants - (.2 X Small Manner) –
(.4 X Big Manner) - (.2 X Small Place) - (.3 X BigPlace))/ # consonants).

(2.2)

Vowel Agreemen*t* ((# vowels - (.1 X Teeny Height) - (.2 X Small Height) - (.3 X Big Height)- (.4 X Huge Height) - (.2 X Small Front) - (.3 X Big Front))/ # vowels).

Agreement for consonants was 91% for both Groups II and III. Agreement for vowels was 89% and 88% for Group II and III, respectively. The results of this analysis are shown in Table 2-7.

Table 2-7. Transcription reliability for infants with hearing impairment.

	Reliability		
	Group Average (%)	**Individual range**	
GROUP II		**Highest (%)**	**Lowest (%)**
ALL CONSONANTS	91.2	96.8	82.8
ALL VOWELS	89.4	92.8	85.4
GROUP III			
ALL CONSONANTS	91.2	90.0	92.8
ALL VOWELS	87.5	89.0	85.5

For group II, approximately 62% of consonant disagreements involved manner disagreements; whereas, fewer place disagreements (38 %) were observed. For group III, manner disagreements (52%) slightly exceeded place (48%) disagreements. In terms of vowel disagreements both Groups II and III showed more (56%) disagreement in height than front/back (43%). An analysis of the types of disagreements showed that for consonant manner and place the nature of disagreements fell in the “small” category for both groups, suggesting that when the transcribers’ perceptions were different, they were not generally considered big differences. The extent of disagreements for vowel height and front/back also fell within the “teeny” and “small” ranges. The extent of the disagreement is shown in Table 2-8.

Table 2-8. Disagreement classification for infants with hearing impairment.

	DISAGREEMENT	
DISAGREEMENT TYPE	**GROUP II (%)**	**GROUP III (%)**
CONSONANT MANNER		
SMALL	84.0	72.2
BIG	16.0	27.7
CONSONANT PLACE		
TEENY	7.4	17.6
SMALL	70.4	70.6
BIG	22.2	11.7
VOWEL HEIGHT		
TEENY	51.2	52.8
SMALL	42.7	45.3
BIG	6.1	1.8
VOWEL FRONT/BACK		
SMALL	86.1	87.5
BIG	13.9	12.5

The procedure for the two infants (BB, and MB) with profound HI not included in this analysis was as follows. Two listeners re-transcribed the first 20% of each of the audiotapes. Reliability was calculated as the percentage of first and second transcriptions agreed on as being identical. Reliability of transcription was 82.4%, ranging from 72.6% to 92.3% across data collection sessions. A third transcriber then listened to disagreements with the reliability team until a consensus was established.

Data Analysis

The transcribed data were analyzed using the Logical International Phonetics Programs (LIPP, Oller & Delgado, 1990). LIPP analysis included 1) phonetic inventory of consonants and vowels, 2), inventory of utterance types (untranscribable nuclei (UN, UC, UV), singleton vowels (V) and consonants (C), marginal syllables (MS) and syllables (minimally CV or VC) 3), inventory of syllable shapes (CV, VC, CVC and

VCV) and syllable alternations (mono, di- and poly-syllabic utterances) 4), sequential analyses including: (a) CV co-occurrence patterns (b), CV reduplication patterns and (c), CV consonant and vowel variegation patterns. A description of each of these analyzes follows.

Vocalization Types within Utterance Strings

At the level of the utterance string, two inventories were performed: (a) inventory of vocalization types within utterance strings and (b) inventory of syllabic output within utterance strings. The inventory of vocalization types within utterance strings classified the contents of each utterance string into the following categories: (a) untranscribable nuclei (UN), untranscribable vowels (UV), and untranscribable consonants (UC), (b), transcribable non-syllabic singleton vocalizations such as singleton vowels (SV) and singleton consonants (SC), and marginal syllables (MS) (those bounded by glottal consonants), and (d) syllabic output (CV, VC, CVC, VCV, etc) bounded at the onset or offset by labial, coronal and dorsal consonants. Second, utterance strings were analyzed to determine the percent of utterance strings containing syllabic content.

Syllable Alternations and Syllable Shape

Utterance strings containing syllabic material were further analyzed by number of syllable alternations and syllable shape. For this analysis, only utterance strings that contained syllables bounded by or containing labial, coronal or dorsal consonants (e.g., CV, VC, CVC, and VCV) were examined. The number of consecutive syllable alternations appearing within each utterance string was counted. If a vocalization string consisted of a single syllable, it was classified as monosyllabic (i.e., /ba/). If it contained two consecutive syllables, it was classified as disyllabic (i.e., /ba ba/).

Finally, if an utterance contained more than two syllables, it was classified as polysyllabic (i.e., /ba ba ba/). The syllabic output above was further analyzed in terms of syllable shape (e.g., CV, VC, CVC and VCV).

Sequential Analysis

Sequential analysis involved analysis of (a) intra-syllabic organization (CV co-occurrences); and (b) inter-syllabic organization (reduplication, and consonant and vowel variegation patterns).

Intra-syllabic Organization: For analysis of CV co-occurrence patterns, consonants and vowels within a CV syllable were grouped according to place of articulation. Consonants in each CV were divided into one of three places: labial, coronal or dorsal. Vowels within the CV were divided into one of three groups: front, central, or back. Thus, an inventory of CV syllables with labial, coronal and dorsal consonant onsets was created for analysis.

Inter-syllabic Organization: Variegation analysis involved analysis of how consonants and vowels vary from one CV syllable to the next. Four patterns of consonant and vowel variegation that vary only in one parameter within a CVCV sequence were considered to compare with analyses available for hearing infants (Davis & MacNeilage, 1995). The two consonant variegation patterns of interest involve either a change in manner (manner variegation with place duplication) but not place, or a change in place but not manner (manner duplication with place variegation), each of these combinations appearing in the context of unchanging or reduplicated vowels from CV to CV. Two vowel variegation patterns were also observed to change in only one parameter. That is, vowels in CVCV sequences either change in height but not backness (height variegation with back duplication) or change in backness but not height (height duplication with back variegation) when appearing in the context of reduplicated consonants across CVCV syllables. Inventories of duplication and variegation patterns in which only one parameter varied were created for each infant.

Segmental Inventory Analysis

Consonant inventories appearing in singleton and syllabic contexts were developed for each infant by place and manner using the categories provided earlier. Inventories of vowels were developed according to the same vowel height and front/back dimensions provided earlier.

Statistical Analysis

The dependent variables in this study include number of a) vocalization types, b) segmental types, c) syllable shape and alternation types, consonant onset in syllables d), intrasyllabic CV co-occurrence patterns and e) intersyllabic reduplication/variegation patterns. The independent variable includes auditory sensitivity as measured with the PTA, a continuous variable. Because the dependent variables in this study are all categorical count data (binary outcomes and multinomial outcomes), the data are not normally distributed, and do not have homogeneous variances. Consequently, linear models cannot be used. Instead, generalized linear models must be employed to analyze these data. Generalized linear models (GLM) are a broad class of models that include ANOVA and regression models for continuous response variables as well as models for categorical response variables. GLM's allow random components to have a distribution other than normal. GLM uses logistic regression models for binary data and log-linear models for count data, both of which will be used to analyze associations between PTA and production outcomes. These data will be analyzed with these methods adopting a hierarchical or mixed model approach accounting for nested data (sounds within infants) that is particularly useful in analyzing small sample datasets. The HLM (Raudenbush & Bryk, 2002) software package was used to test associations between PTA and the outcome variables.

Due to the relatively small sample size (N = 15), relationships will be investigated based on one independent variable (PTA) rather than on one grouping variable with three factors (normal, moderate and profound). Limiting the independent variable to one rather than three independent variables increases the number of degrees of freedom used in the model, thereby increasing the statistical power of the model to detect differences related to hearing sensitivity. Therefore, differences between groups will not be tested.

For each inventory (e.g., utterance type, syllable alternation, syllable shape, CV-co-occurrence, variegation, reduplication and segments) the association between PTA (across the infants) and the particular outcome variable being examined will be tested. A t-ratio, degrees of freedom, and p-value will be provided. For this study a probability of .05 or less will be considered significant. Probability values between .05-.1 will be considered marginally significant, given the small sample size and the exploratory nature of the study. A non-significant result suggests that the particular outcome variable under study is independent of PTA; that is, no effect of auditory sensitivity is found on that particular inventory. On the contrary, when PTA is found to be significantly associated with an outcome variable, it suggests that the particular inventory under analysis is dependent on auditory sensitivity to some degree.

This study will report aspects of vocalization inventories that are associated with PTA across the infants. It does not test differences between groups (normal, moderate and profound), because of the small sample size. However, for purposes of simplification, group means will be provided for each vocalization inventory.

Additionally, in order to highlight the different patterns established by infants with normal, moderate and profound HI, group patterns will also be presented graphically.

Chapter 3: Results

UTTERANCE STRINGS

Utterances Containing Syllables

An inventory of utterances was developed for each infant. Group I produced a total of 1,225 (Mean = 306) utterances. Group II produced a total 1,959 utterances (Mean = 326). Group III produced 1,907 (Mean = 381) utterances. The average number of utterances per minute for Group I, II and III was 3.91, 2.24 and 3.56, respectively. Table 3-1 shows the mean number of utterances for each group. All subsequent analyses draw from these utterances.

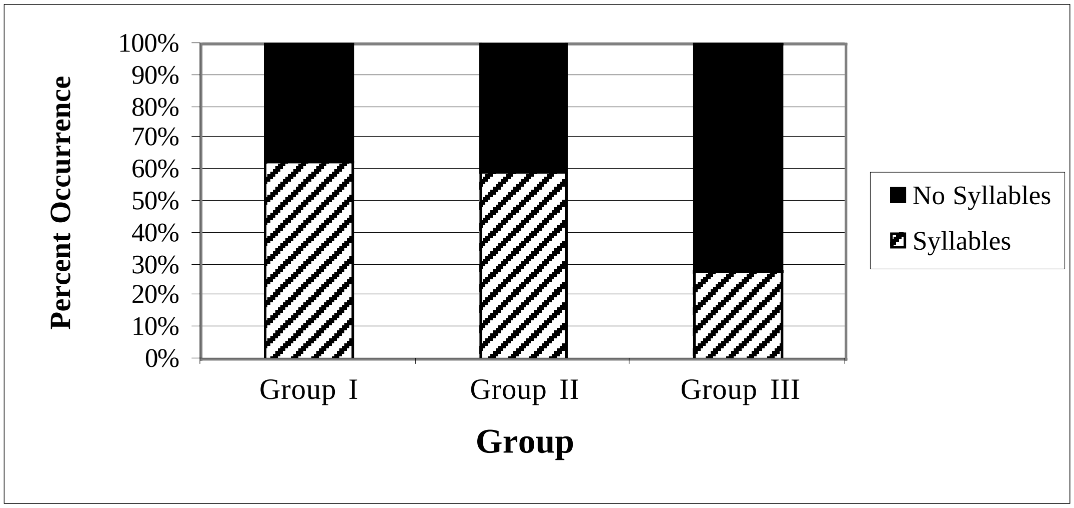
Table 3-1. Mean number of utterances collected for each group.

Group		**# Utterance Strings**
Group I	Mean	306.0
N=4	SD	67.7
Group II	Mean	326.0
N=6	SD	54.7
Group III	Mean	381.4
N=5	SD	147.1

At the level of the utterance string, two inventories were analyzed: (a) inventory of utterance strings containing syllabic content and (b) inventory of vocalization types within utterance strings. First, utterance strings were analyzed to determine the proportion of utterance strings containing syllabic content. Results showed that approximately 60% of the utterance strings produced by infants in Group I (63%) and Group II (59%) contained syllabic content; whereas, only 28% of the utterance strings produced by infants in Group III contained syllabic content. Utterance strings not containing syllables accounted for 37% and 41% of Group I and II inventories, respectively. In contrast, 71% of vocalization strings produced by Group III did not contain syllabic material. Figure 3-1 shows the percent of utterance strings containing syllabic content across the three groups.

HGLM was used to test the association between PTA and the number of utterance strings containing syllables. Results of the analysis showed that PTA is significantly associated with syllable presence in utterance strings (t = -3.210, df = 13, p = .007; without GW t = -3.592, df = 12, p = 0.004). This result suggests that PTA is a significant control-parameter determining syllable presence within utterance strings. As PTA increases (i.e., hearing sensitivity decreases) fewer utterance strings contain syllable content.

Figure 3-1. Percent of utterance strings containing syllables for each group.



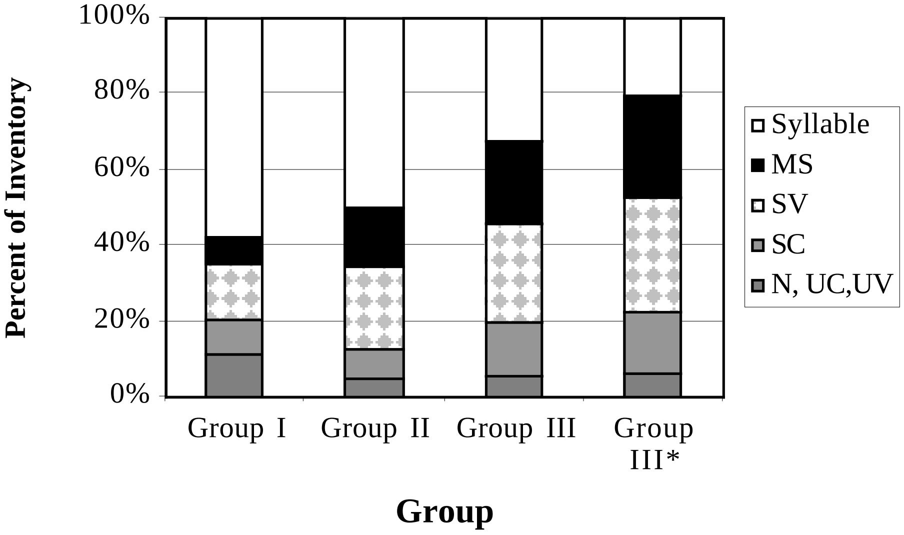
Utterance Types Analysis

Next, an inventory of vocalization types within utterance strings was compiled. This analysis classified the contents of each utterance string into the following categories: (a) untranscribable nuclei (UN), untranscribable vowels (UV), and untranscribable consonants (UC), (b), transcribable non-syllabic vocalizations such as singleton vowels (SV), singleton consonants (SC), and marginal syllables (MS) (those bounded by glottal consonants /h, ʔ/), and (d) syllabic output (CV, VC, CVC, VCV, etc) bounded at the onset or offset by labial, coronal and dorsal consonants. Results of this analysis are shown in Figure 3-2. A total of 3,993 utterance types were analyzed for Group I, 4,838 for Group II, and 4,083 utterance types for Group III. For Group I, approximately 12% of the inventory consisted of untranscribable nuclei, vowels and consonants. Singleton vowels and consonants accounted for approximately 26% of that inventory; whereas, marginal syllables accounted for approximately 10%. Syllables including, CV, VC, CVC, and VCV's accounted for 52% of the utterance types analyzed.

For Group II, 7% of the inventory consisted of untranscribable utterances. Singleton consonants and vowels accounted for approximately 29% of the total inventory. Of these, the SV category accounted for 22% of the inventory, for Group II. Marginal syllables accounted for 15% of the overall inventory. Syllabic output accounted for 50% of the overall inventory.

For Group III, N, UV, and UC nuclei accounted for 3%, 1% and 1% of the overall inventory, respectively, accounting for 6% of the inventory. Singleton consonants (14%) and vowels (26%) accounted for 40% of the total inventory. Approximately 22% of the inventory consisted of marginal CV syllables. Syllable-based utterances such as CV, VC, CVC, and VCV accounted for 32% of the utterance inventory. Infant GW produced a larger proportion of syllables than the other infants in Group III. Therefore, the numbers in the group inventory tended to reflect GW's influence, particularly on syllabic vocalizations. Without GW, syllabic content accounted for 20% of the inventory, with CV's accounting for 13% of that inventory. Because infant GW produced more syllables than the rest of Group III, this analysis and all subsequent analyses were performed with and without her data in order to determine the extent to which she might make a difference to the overall results.

Figure 3-2. Distribution of utterance types for each group. Asterisk denotes Group III mean without Infant GW.



Results for this analysis, using HGLM are all reported using syllabic behaviors as the base comparison. Results showed no significant relationship between untranscribable nuclei and PTA (t = .883, df = 13, p = .393). However, singleton consonants (t = 3.193, df = 13, p = 0.008) and vowels (t = 2.698, df = 13, p = 0.019) are significantly associated with PTA relative to syllables. The relationship between PTA and marginal syllables approached significance (t = 2.04, df = 13, p = .061). When the analysis was performed without GW, the relationship between PTA and marginal syllables achieved significance (*t* = 2.484, *df* = 12, *p* = .029). Auditory sensitivity, as reflected by the PTA, was significantly associated with increased proportions of singletons (consonants and vowels) and marginal syllables, relative to decreasing proportions of syllables in utterance strings across the three groups. Thus, as hearing loss increases the presence of singletons and marginal syllables increases; whereas, syllable use decreases significantly.

In summary, two analyses were performed at the level of the utterance string. The first analysis inventoried the percent of utterance strings containing syllable-based content. This analysis showed that approximately 60% of the utterance strings produced by infants in Group I and Group II contain syllable-based output. Approximately 28% of utterance strings produced by infants in Group III, contained syllable-based material. The second analysis focused on the contents of each utterance string. An inventory of vocalization types was developed and analyzed. Results from this analysis showed a significant relationship between PTA and the proportion of singleton consonants, vowels, marginal syllables relative to syllables present in utterance strings. In particular, as hearing loss increases, the presence of singletons (consonants and vowels) and marginal syllables increases, while, the presence of syllables decreases. The goal of these analyses was to quantify any effect of hearing loss on vocal production behaviors associated with the utterance string. The effect of hearing loss on syllable-based output is explored below.

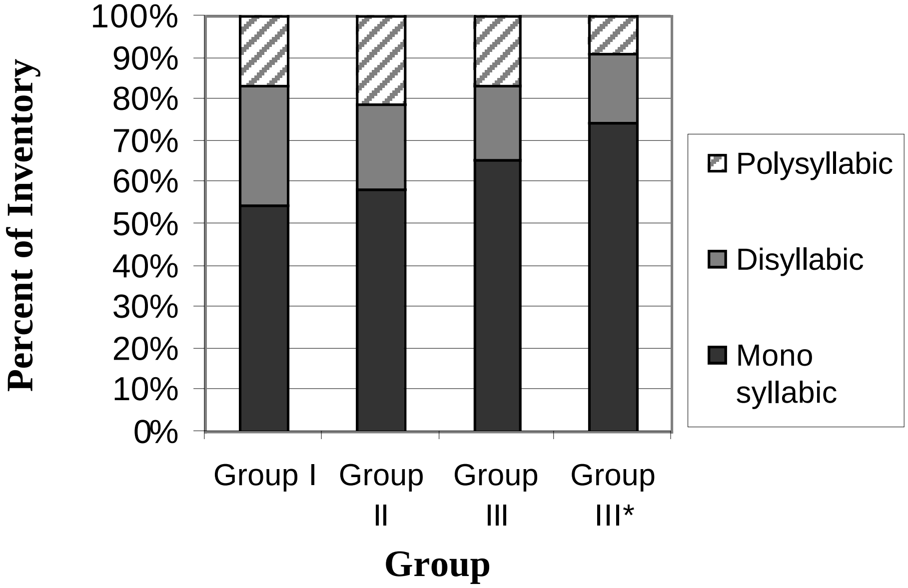
SYLLABLE-BASED ANALYSES

Syllable Alternations

Utterance strings containing syllabic material were further analyzed by number of syllable alternations. For this analysis, only utterance strings that contained syllables bounded by or containing labial, coronal or dorsal consonants (e.g., CV, VC, CVC, and VCV) were examined. The number of consecutive syllable alternations appearing within each utterance string was counted. If a vocalization string consisted of a single CV alternation, it was classified as monosyllabic (i.e., /ba/). If it contained two consecutive CV alternations, it was classified as disyllabic (i.e., /ba ba/). Finally, if an utterance contained more than two CV alternations, it was classified as polysyllabic (i.e., /ba ba ba/).

For this analysis, a total of 765, 1,153, and 548 (224 without GW) utterance strings containing syllable-based output were analyzed for Group I, II, and III, respectively. For all three groups, the analysis revealed that the majority of utterance strings containing syllabic output were monosyllabic, accounting for 54%, 59% and 65% of Group I, II, and III's respective inventories. Utterance strings containing disyllabic alternations accounted for 29%, 20% and 18% of the respective inventories for Group I, II and III. Finally, polysyllabic alternation accounted for 17%, 21% and 17% of groups I, II, and III, respectively. These results are shown on Figure 3-3.

Figure 3-3. Percent occurrence of syllable alternations for each group. Asterisk denotes Group III mean without GW.



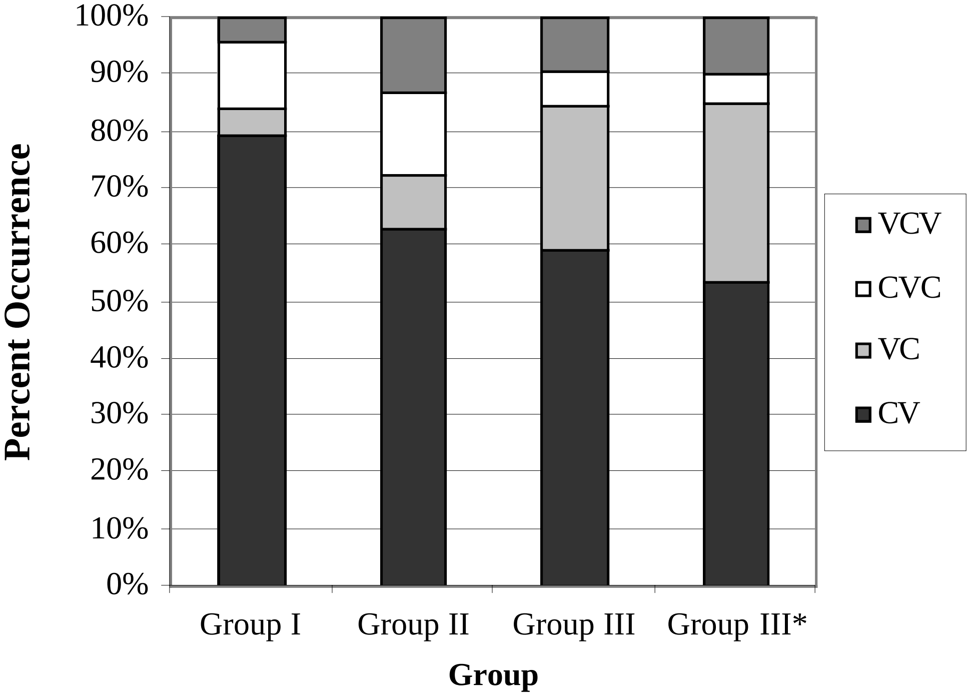
In general the pattern for Group I, typically developing infants, is: monosyllabic > disyllabic > polysyllabic. The pattern for Group II and III HI infants shows a propensity for monosyllabic CV alternations, with approximately equal proportions of di- and poly-syllables. Without GW, the proportion of monosyllabic alternations increases to 74% in Group III. Whereas, the proportion of di-syllabic alternations does not change, the proportion of poly-syllabic alternations decreases to 9% from 17%, when GW is removed from the analysis in Group III.

Results of the analysis with monosyllables as the base comparison, suggests that PTA is not a significant predictor of disyllabic (t = -1.127, df = 13, p = 0.281) and polysyllabic alternations (t = -0.517, df = 13, p = 0.614). This relationship remained non-significant even when GW was removed from the analysis (disyllabic t = 1.4, df = 12, p = .19 and polysyllabic: t = -.918, df = 12, p = 0.38). Thus, while there is a trend toward increasing use of monosyllables as hearing loss increases, this trend is not significant. Auditory input does not appear to be significantly associated with number of syllable alternations within an utterance.

Syllable Shape

Syllabic output was further analyzed in terms of syllable shapes (e.g., CV, VC, CVC and VCV). This analysis was performed for each infant in the three groups. Results of this analysis are reported by group and are shown in Figure 3-4. A total of 1,485, 2,430, and 1,362 (399 without GW) syllable tokens were produced by Groups I, II and III, respectively. The CV shape was the most predominant syllable shape in all three groups, accounting for 79% of syllables in Group I, 63% for Group II, and 59% for Group III (53% without GW in the group). The CVC was the next most prominent syllable shapes for Groups I and II, accounting for 12% and 15% of syllable shapes, respectively. The CVC accounted for only 6% of syllable shape types for Group III. In contrast, for Group III, the second most prominent syllable shape after the CV was the VC, accounting for 25% (31% without GW's data) of syllable shape types in comparison to 4% and 10% for groups I, and II, respectively.

Figure 3-4. Percent occurrence of syllable shapes for each group. Asterisk denotes Group III mean without GW.

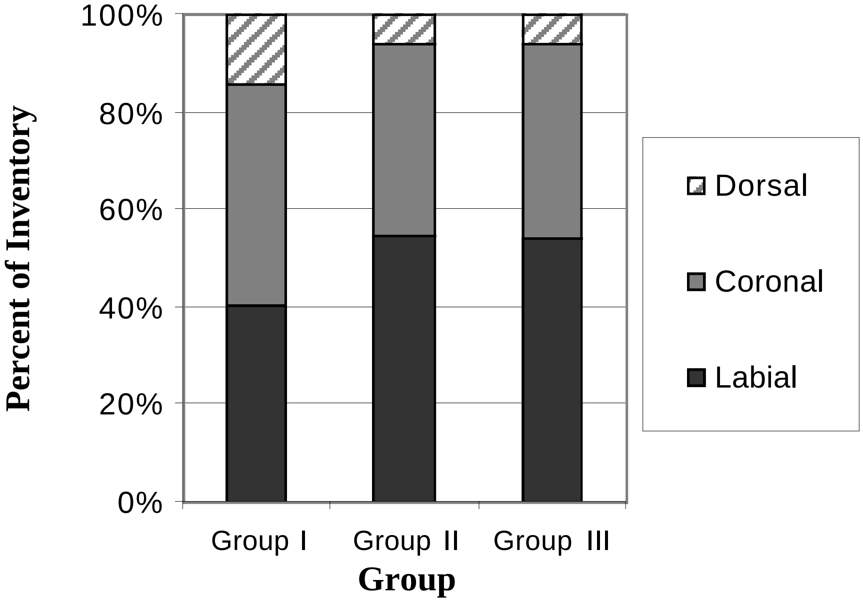


For this analysis all results are in relation to CV syllable shapes. Results of the HGLM analysis showed a non-significant association between PTA and VCV (t = 1.695, df = 13, p = .121), and CVC (t =.140, df =13, p = .891) syllable shapes. However, a significant association was found for VC (t = 2.911, df = 13, p = .013) shapes. The statistical patterns remained when the data were analyzed without participant GW: VCV (t = 1.59, df = 12, p = .138), and CVC (t =.191, df = 12, p = .852) were non-significant and VC (t = 3.467, df = 12, p = .005) remained significant. Thus, as PTA increased the presence of VC shapes in the inventory significantly increased in relation to CV's. Auditory input is significantly associated with the proportions of syllable shapes found in these three groups.

CV Syllable Onset

An inventory of CV syllables classified by consonant onsets was created for each group. A total of 1,274 CV syllables were analyzed for Group I; 2,175 for Group II; and 1,236 for Group III. Infant GW produced 906 of the CV syllables in Group III, whereas Infant BB produced 1 syllable of the CV form. The subsequent data analyses were performed with and without infants GW and BB in the dataset, leaving 330 total CV syllables being produced by the remaining three infants in Group III. Syllables for Group I showed the following patterns of consonant onset: labial onsets 37%, coronal onsets 49%, dorsal onsets 13%. For Group II, 54% of syllables showed labial onset, 39% coronal onset, and 6% dorsal onset. For Group III, syllables were distributed as follows: labial onsets 54% (54% without GW and B), coronal onsets 40% (39% without GW and B) and dorsal onsets 6% (8% without GW and B). Figure 3-5 shows the syllable onset patterns observed for the three groups. As the data is not significantly different when GW is removed from the analysis, Figure 3-5 represents all infants in Group III. Group I produced more syllables with coronal onsets than Groups II and III followed by labial and finally dorsal onsets. Groups II and III produced approximately equal proportions of syllables containing labial, coronal, and dorsal onsets. Syllables containing dorsal onset accounted for less than 15% of syllable inventories, for all groups. Group I onset order preferences were: Coronal > Labial > Dorsal; whereas Group II and III onset order preferences showed the following pattern: Labial> Coronal> Dorsal.

Figure 3-5. Syllable onset patterns for each group.



HGLM analysis was performed with coronal onset syllables as the base comparison. Results showed that PTA was marginally associated with the proportions of dorsal onset syllables relative to coronal onset syllables (*t* = -1.80, *df* = 13, *p* = .09). This association remained significant when the outliers (GW and BB) were removed from the analysis (*t* = -2.67, *df* = 11, *p* = .022). The association between coronal and labial onset syllables was not significant (*t* = .006, *df* = 13, *p* = .99; without GW and BB *t* = 1.2, *df* = 11, *p* = .253). Thus, the proportion of dorsal onset syllables does not seem to be independent of PTA. In this analysis, auditory sensitivity does not show significant association with coronal and labial onsets.

Intra-syllabic Organization: CV Co-occurrences

Syllables with labial, coronal and dorsal onset consonants were also divided according to vowel categories (front, central, and back). Within group consonant-vowel co-occurrence patterns were analyzed using a Chi-Square test to determine whether any consonant patterns preferentially occurred with any vowel patterns. For each cell, the observed to expected ratio for each consonant vowel combination was determined. Values with an observed to expected ratio over 1.00 occur at above chance levels. A 3 x 3 contingency table was created for each infant and for the pooled data for each group and an overall Chi-Square statistic is reported for each group.

Table 3-2 shows the contingency table and observed to expected ratios for the three groups. For Group I results showed four CV co-occurrence patterns occurring above an observed to expected ratio of 1.0: labial-central, coronal-front, dorsal-back and dorsal-front. Of these, the dorsal-front co-occurrence was not predicted by the Frame/Content perspective, but has been observed in typically developing infants as well (see Davis & MacNeilage, 1995). A Chi-Square test showed overall significance (X^2 = 154.4, *df* = 4, *p* = < .001, Cramer's V = .24) for the distribution of CV-co-occurrences for infants in Group I.

Table 3-2. Observed-to -expected ratios for CV co-occurrence for Infants in Group I (N = 4, number of tokens = 1,274), Group II (N = 6, number of tokens = 2,175), and for Group III (N = 5, number of tokens 1,236; without GW (N = 3, number of tokens 330).

Group		**CONSONANTS**		
Group I	**VOWELS**	**Labial**	**Coronal**	**Dorsal**
	Front	0.6	**1.2**	**1.2**
	Central	**1.4**	.9	.5
	Back	.7	.8	**2.1**
Group II	**Front**	.63	**1.2**	**1.2**
	Central	**1.2**	.9	0.9
	Back	**1.2**	1.0	0.8
Group III	**Front**	0.6	**1.2**	.6
	Central	**1.4**	.8	**1.1**
	Back	0.5	**1.1**	**1.1**
Group III*	**Front**	0.5	**2.0**	.7
	Central	**1.2**	0.7	.8
	Back	**1.1**	0.7	**2.8**

Table 3-2 shows the pooled CV co-occurrence patterns observed for infants with moderate hearing impairment. Four patterns occurred above an observed to expected ratio of 1.0. These are labial-central, labial-back, coronal-front and dorsal-front. Of these four patterns, the labial-central and coronal-front patterns are consistent with the Frame/Content perspective. Although the labial-back and dorsal-front patterns are not consistent with the Frame/Content perspective, they have been observed to occur at above chance levels in some typically developing infants. Chi square test showed a significant distribution for Group II ($X^2 = 93.20$, $df = 4$, $p < .001$, Cramer's V = .15).

The observed-to-expected ratios for infants with profound hearing loss showed five cells with observed to expected ratios above 1.0. These were labial-central, coronal-front, coronal-back, dorsal–central, and dorsal-back. The distribution of CV co-occurrences was significant for the four infants in Group III ($X^2 = 73.56$, $df = 4$, $p < .001$, Cramers V = .17). Given that GW produced a majority of the syllables in the dataset her data were removed and a contingency table was created with the data of the three remaining infants (see Table 3-2). Four patterns with an observed-to-expected ratio above 1.0 were observed. These consisted of coronal-front, labial-central, labial-back and dorsal-back. Of the co-occurrence patterns observed, three were consistent with the Frame/Content perspective. Additionally, Group III (without GW) also showed the labial-back patterns observed in Group II.

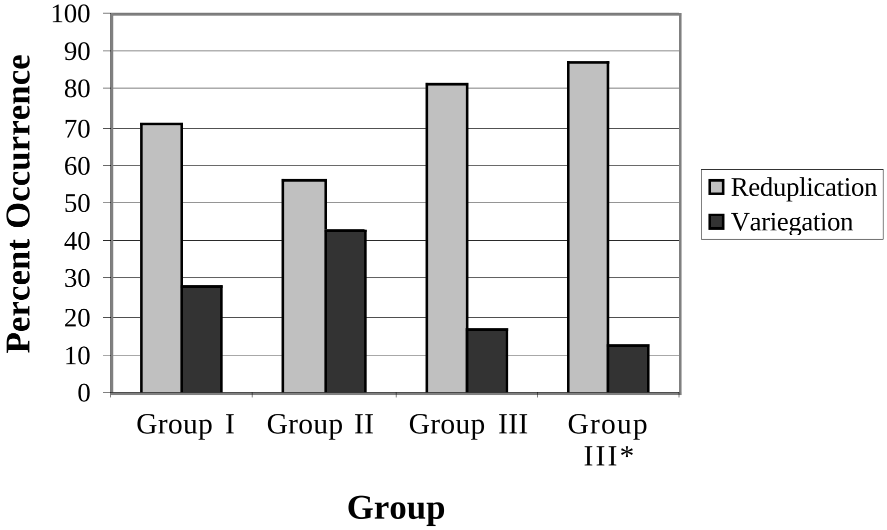
HGLM was used to test the relationship between PTA and CV-Co occurrence patterns observed for all infants. HGLM analysis showed that PTA was significantly associated with the labial-back pattern ($t = -2.177$, $df = 13$, $p = .048$; without GW and B, $t = -1.865$, $df = 11$, $p = .08$), relative to the labial central patterns across the groups. PTA was not significantly associated with any coronal co-occurrence patterns or any one pattern of dorsal co-occurrences (t = -.301, df= 12, p = .765; t = -.031, df = 11, p = .976). This suggests that auditory sensitivity (PTA) is not a significant control-parameter affecting within-syllable organization of coronal and dorsal-onset syllables but is related to labial-back CV co-occurrences.

In summary, the analyses of syllable onset and of CV co-occurrence patterns show some clear patterns across the three groups. First, PTA was found to be significantly associated with the proportion of dorsal onset syllables in relation to labial onset syllables, but was not associated with coronals in relation to labials. Thus, as PTA increases (and hearing sensitivity decreases), production of syllables with dorsal onsets decreases. Second, the overall CV co-occurrence analysis for grouped data, confirms that the labial-central and coronal-front patterns tend to co-occur at higher rates than other within category co-occurrence patterns for Group I and II, and III. Although the overall Chi-square was significant for all groups, the strength of the association between consonants and vowels was considered weak for all groups. The weak association might reflect an effect of sample size, 4 infants in Group I, 6 in Group II, and 4 in Group III. Finally, a statistically significant relationship was observed between PTA and labial-back patterns of CV co-occurrence.

Inter-syllabic Organization: Reduplication and Variegation

Group I produced a total of 329 utterance strings containing multi-syllabic CV sequences, averaging 82 multi-syllabic sequences per infant. Group II produced an average of 335 utterance strings containing multi-syllabic CV sequences, averaging 55 multi-syllabic sequences per infant. Group III produced 390 multi-syllabic utterance strings. Infant GW produced 312 of those sequences. Additionally, infant (BB) did not produce any sequences containing multi-syllabic CV’s. Hence, for Group III, 78 multi-syllabic CV utterances, produced by three infants remained, averaging 26 utterances per infant (without GW and BB). Complete reduplication of consonants and vowels across CVCV sequences occurred in 71%, 57% and 83% (87% without GW) of Group I, II and III, respectively. Variegation accounted for 29%, 43% and 17% (13% without GW) of disyllabic or polysyllabic syllable alternations for Groups I, II and III, respectively. Figure 3-6 displays the proportion of reduplicated and variegated sequences for the three groups.

Figure 3-6. Percent occurrence of reduplicated and variegated sequences for each group. Asterisk denotes Group III without GW.

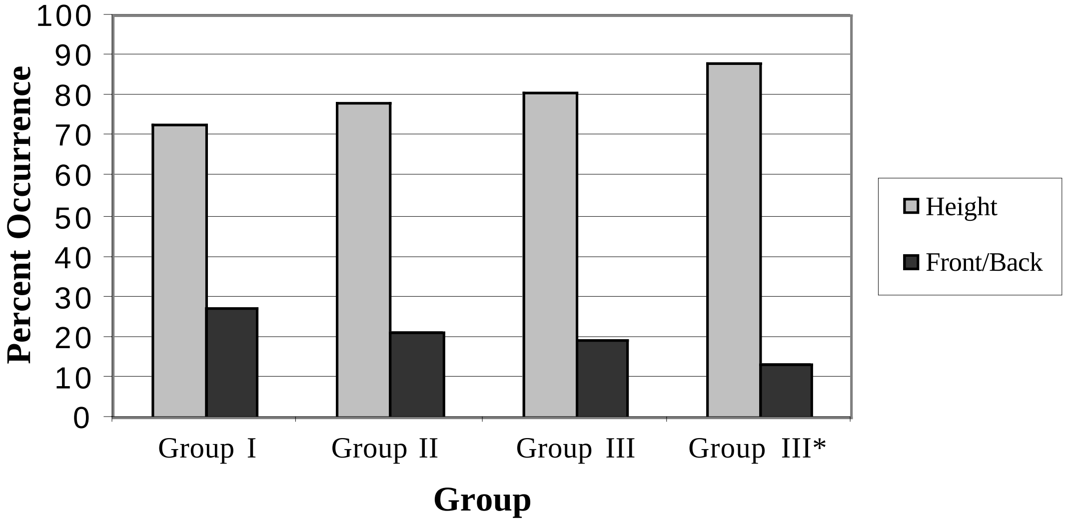


HGLM was used to test whether PTA was associated with the proportion of reduplicated and variegated sequences observed. Reduplication was compared to variegation for this analysis. The analysis was performed with and without GW. Both analyzes were non-significant (t = .741, df = 12, p = .473 and t = -.583, df = 11, p = .571), suggesting that auditory sensitivity as estimated by PTA is not a significant control parameter affecting the proportion of reduplicated/variegated sequences observed in the respective group inventories.

Vowel Variegation

For all three groups height variegation patterns were predominant, accounting for approximately 73%, 78%, and 81% of Groups I, II and III. Variegation in the front/back dimension for Groups I, II, and III accounted for 27%, 21%, and 19% of vowel variegation patterns that change only in one parameter, respectively. Without GW, height variegation accounted for 88% of vowel variegation patterns, and front-back variegation accounted for 13%. For all three groups, these results are consistent with vowel variegation data on hearing infants showing more variegation in vowel height than vowel front/back when the consonants are duplicated across CVCV sequences and the sequence varies only in one parameter. HGLM analysis showed no statistically significant association between the vowel variegation patterns with or without GW in the data set (t = -.430, df = 11, p = .675; t = .036, df = 10, p = .972). While there is a trend toward increasing the use of vowel height variegation (and decreasing the use of vowel front/back variegation) as hearing loss increases, this trend is not significant. Auditory input does not appear to be significantly associated with vowel variegation patterns in which only one parameter is variegated. Figure 3-7 shows the vowel variegation patterns for each group.

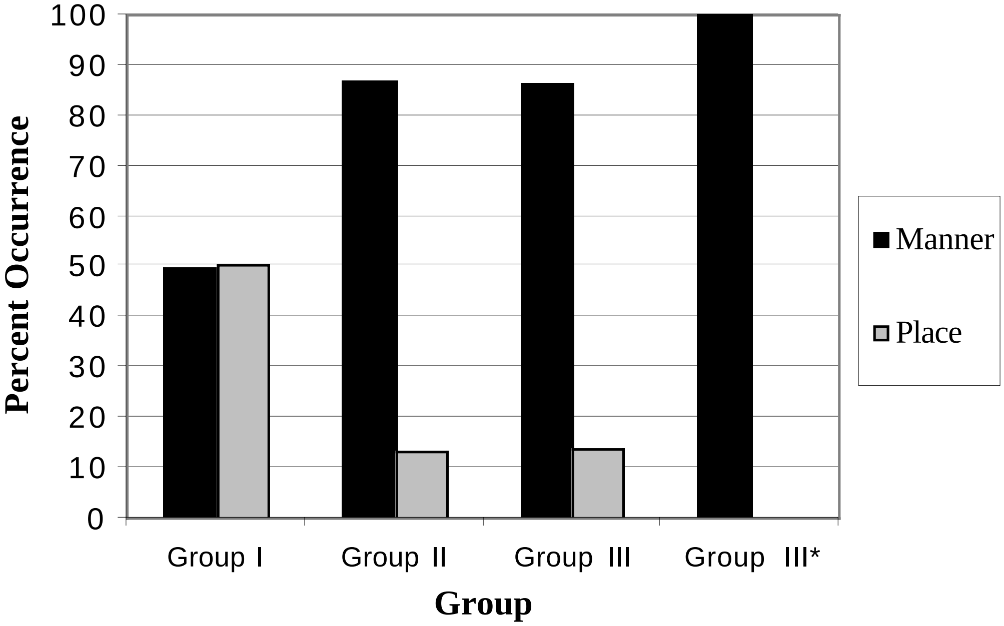
Figure 3-7. Vowel variegation patterns for each group. Asterisk denotes Group III mean without GW.



Consonant Variegation

For Group I, variegation in consonant manner accounted for 50% and variegation in consonant place accounted for 50% of CVCV sequences that varied in one parameter only. This was not consistent with previous patterns reported on infants with normal hearing (Davis & MacNeilage, 1995). Typically, the manner variegation pattern well exceeds the place variegation pattern. For Group II, the manner variegation pattern accounted for 87% of consonant variegation, whereas, place variegation patterns accounted for 13% of the consonant variegation patterns in which only one parameter varied. The pattern of manner exceeding place changes is consistent with previously reported variegation values for hearing infants. Finally, for Group III the manner variegation pattern accounted for 86% of the inventory, with the place variegation pattern accounting for approximately 14%. Infant GW produced all of the sequences in which place varied from one consonant to the next. Without GW, 100% of CVCV sequences changing in one parameter changed in manner. Thus, in general, the three infants with profound hearing impairment did not produce sequences where place varied. Figure 3-8 displays the consonant variegation patterns for all groups.

Figure 3-8. Consonant variegation patterns for each group. Asterisk denotes Group III mean without infant GW.



HGLM was used to determine associations between PTA and consonant variegation patterns. Results from that analysis showed that the relationship between PTA and manner/place variegation patterns did not reach significance (t =1.69, df =11, *p* = .119) when all infants are considered in the dataset. However, when GW was removed from the analysis, the relationship between PTA and variegation patterns involving one parameter change was significant (*t* = 2.975, *df* = 10, *p* = .015), suggesting that auditory sensitivity is a significant control-parameter contributing to consonant variegation patterns.

In summary, complete reduplication of consonants and vowels occurred 71%, 56% and 82% whereas variegation of at least one parameter accounted for 29%, 43% and 17% (12% without GW), of the respective Group I, II and III inventories. Results showed no statistical association between PTA and the proportion of reduplicated/variegated sequences in the respective inventories. However, Group III showed slightly more reduplicated (and less variegated) sequences than the other two groups.

In terms of variegation, consonant and vowel variegation patterns showed that all three groups contained higher proportions of vowel height variegation than front/back variegation. No statistical association was found between PTA and vowel variegation patterns. Thus, patterns for the two groups of HI infants did not seem to differ significantly from the comparison group of hearing infants. Results for consonant variegation patterns showed different patterns for each group. First, Group I place variegation exceeded manner variegation. Group II produced more manner variegation than place variegation (this is consistent with data for hearing infants reported in previous studies). Finally, Group III produced more manner variegation than place variegation when all infants are considered. However, when GW is removed from the data set place variegation is non-existent in the remaining infants' sequences. Thus, both Group II and III produced more manner variegation than place variegation;

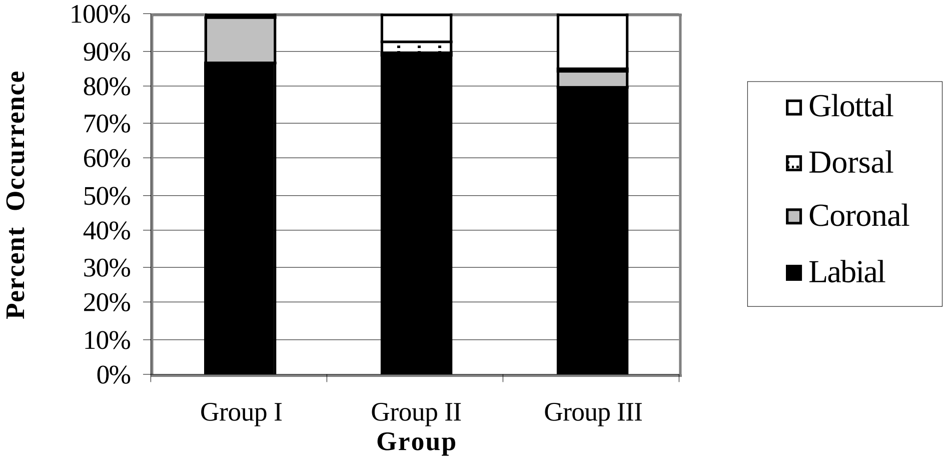
however, Group III produced relatively fewer sequences in which place was variegated. These differences were significant.

GENERAL SEGMENTAL INVENTORIES

Consonant Place in Singleton Contexts

A total of 197, 355 and 1,104 (353) singletons consonants were produced by infants in Groups I, II, and III, respectively. Infant GW was not significantly different from the other infants in her group in singleton vocalizations; however, infant BB, was an outlier, producing 751 instances of /m/. The number in the parenthesis above represents the total number of consonants produced without infant BB. For consonants appearing in singleton context all three groups showed a preference for labial consonants accounting for 80-88% of place preferences. Group I showed the following consonant place of articulation patterns in singleton counts: labial 87%, coronal 12%, dorsal 0% and glottal 1%. Similarly, Group II showed the following place patterns: labial 88%, coronal 1%, dorsal 3% and glottal 7%. Finally, Group III revealed the following patterns: labial 81 %, coronal 4%, dorsal .70%, and glottal, 15%. Figure 3-9 shows segmental inventories of consonants in singleton contexts, for all groups.

Figure 3-9. Consonant place in singleton contexts for each group.

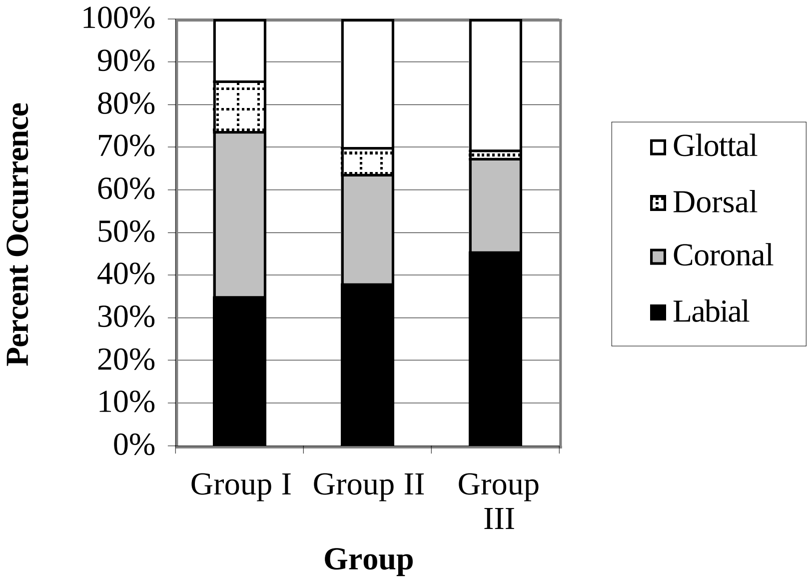


Consonant Place in Syllable Contexts

A total of 1,829, 3,917, and 2,133 (without GW 984) consonants were produced in syllable contexts by Groups I, II and III, respectively. For consonants appearing in syllabic contexts, Group I produced more coronals (39%) than labials (35%), and more glottals (15%) than dorsals (12%). Group II produced more labials (38%) than glottals (30%), coronals (26 %), and dorsals (6%). The pattern for Group III was similar to Group II patterns: more labials (45%) than glottals (31%), coronals (22%), and dorsals (2 %).

Consonant place use comparisons were made relative to use of coronals. Results show no significant association between PTA and consonant place patterns in syllable contexts, suggesting no relationship between consonant place and auditory sensitivity. However, a marginal relationship between PTA and dorsal consonants relative to labials was found (*t* = -1.938 *df* = 13, *p* = .074). This relationship achieved significance when the data were re-analyzed without GW (*t* = -2.301, *df* = 12, *p* = .040). Results suggest that dorsal patterns may not be independent of auditory sensitivity as measured by PTA, with increasing hearing loss, dorsal consonants in syllable context decrease relative to labial consonants. Figure 3-10 shows consonant segmental inventories in syllable contexts.

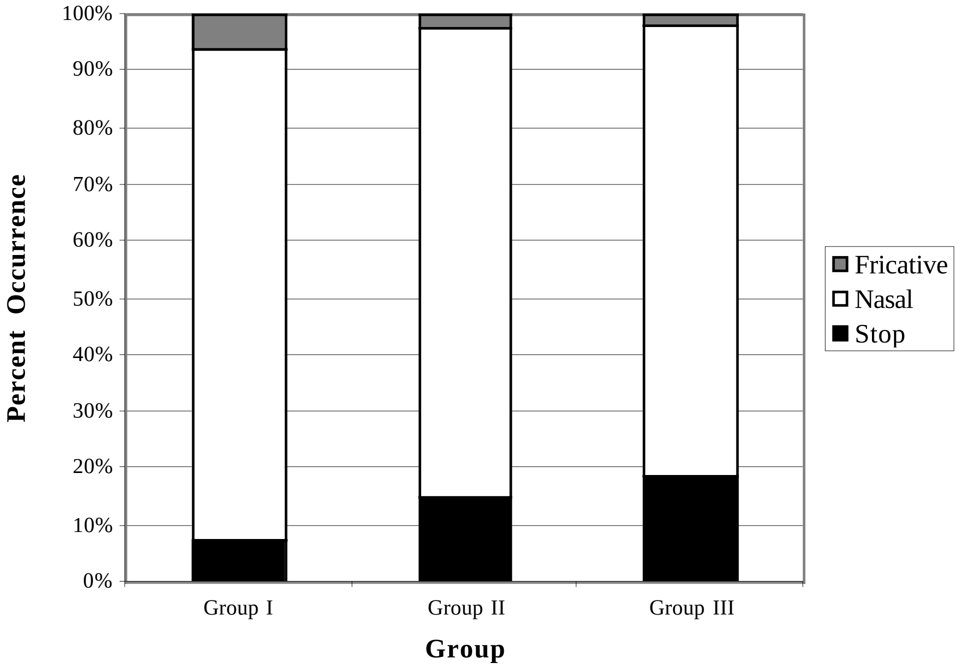
Figure 3-10. Consonant place in syllable contexts for each group.



Consonant Manner in Singleton Contexts

A total of 197, 355 and 1,104 (353) singletons consonants were produced by infants in Groups I, II, and III, respectively. Infant GW was not significantly different from the other infants in her group in singleton vocalizations; however, infant BB was an outlier, producing 751 instances of /m/. The number given in parenthesis above represents the total number of consonants produced without infant BB. For Groups I, II, and III, nasals in singleton contexts were the most predominant consonant manner, accounting for 86%, 82% and 85% of each group's respective singleton inventories. The oral stop consonant manner was the second most frequent manner type observed, accounting for 7%, 15% and 14% of Group I, II, and III's respective consonant inventories. Glides, fricatives and liquids in singleton contexts were produced at very low frequencies for all three groups. No statistical association was found between PTA and consonant manner produced in singleton contexts, suggesting no relationship between auditory sensitivity and manner of articulation for consonants produced as singletons. Figure 3-11 shows the consonant manner of articulation of stops, nasals and fricatives in singleton consonant contexts.

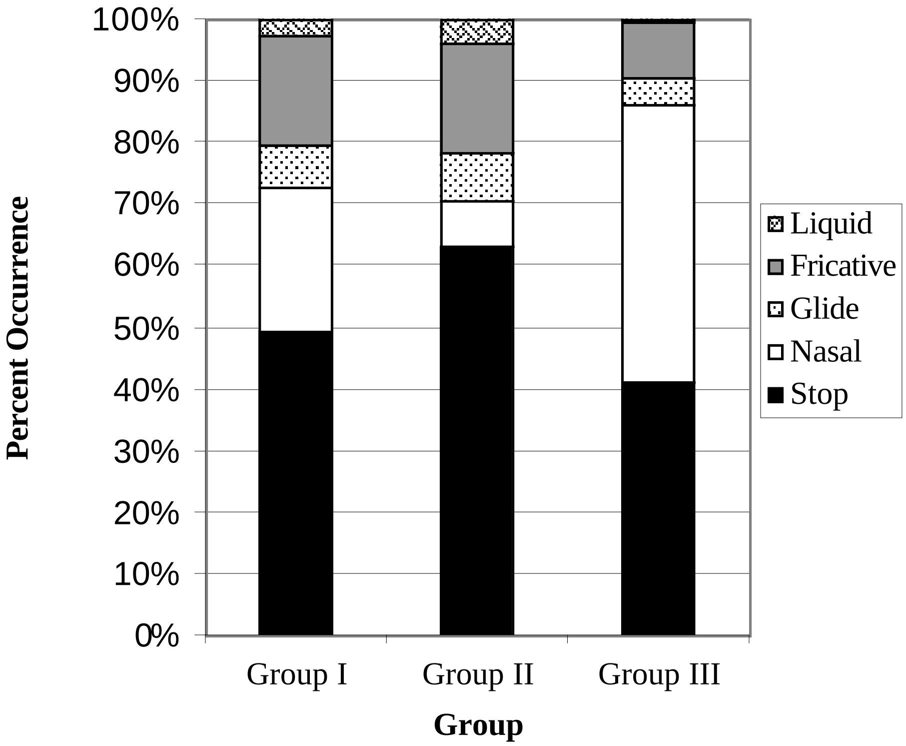
Figure 3-11. Consonant manner in singleton contexts for each group.



Consonant Manner in Syllable Contexts

A total of 1,829, 3,917, and 2,133 (without GW 984) consonants were produced in syllable contexts by Groups I, II and III, respectively. Group I showed the following general patterns for consonant manner: stops 49%, nasals 23%, glides 7%, fricatives 18%, and liquids 3%. Group II revealed the following manner patterns: stops 63%, nasals 8%, glides 7%, fricatives 18% and liquids 4%. Group III manner preferences were as follows: stops 41%, nasals 45%, glides 4%, fricatives, 9% and liquids .4%. Stops are most prominent in the hearing (Group I) and moderate groups (Group II). Nasals are slightly more prominent than stops in the profound group (Group III). Group II produced fewer nasals in syllable contexts than Group I. Fricative production was reduced in Group III. Results of the HGLM analysis showed that PTA is not significantly associated with any consonant manner of production pattern in syllable contexts; as was found for consonant manner in singleton vocalizations. Figure 3-12 shows consonant manner percentages for the three groups in syllable contexts.

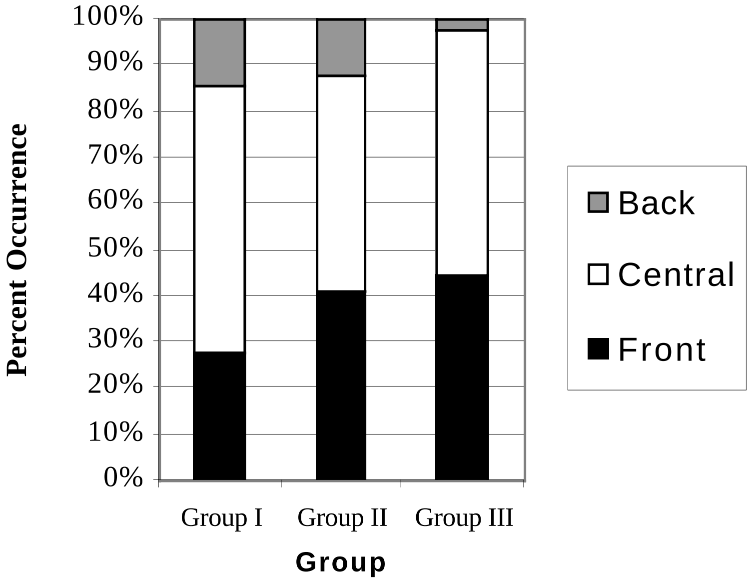
Figure 3-12. Consonant manner in syllable contexts for each group.



Front/Back Patterns in Singleton Context

A total of 326, 939, and 799 vowels were produced in singleton contexts by Groups I, II, and III, respectively. For vowels appearing in singleton contexts, Groups I, II, and III preferred central (58%, 47%, 53%) vowels primarily, followed by front (27%, 41% and 45%,) and back (15%, 12% and 2%). A significant relationship was found between PTA and back vowels relative to central vowels appearing in singleton contexts (*t* = -3.132, *df* = 13, *p* = .008; without GW *t* = -2.811, *df* = 12, *p* = .016). Back vowels are not independent of PTA, indicating an association between auditory sensitivity and the vowel front-back dimension. Thus, as hearing loss increased, the proportion of back vowels decreased relative to central and front vowels. Figure 3-13 shows the percentages of vowel front-back dimension in vowels appearing in singleton contexts.

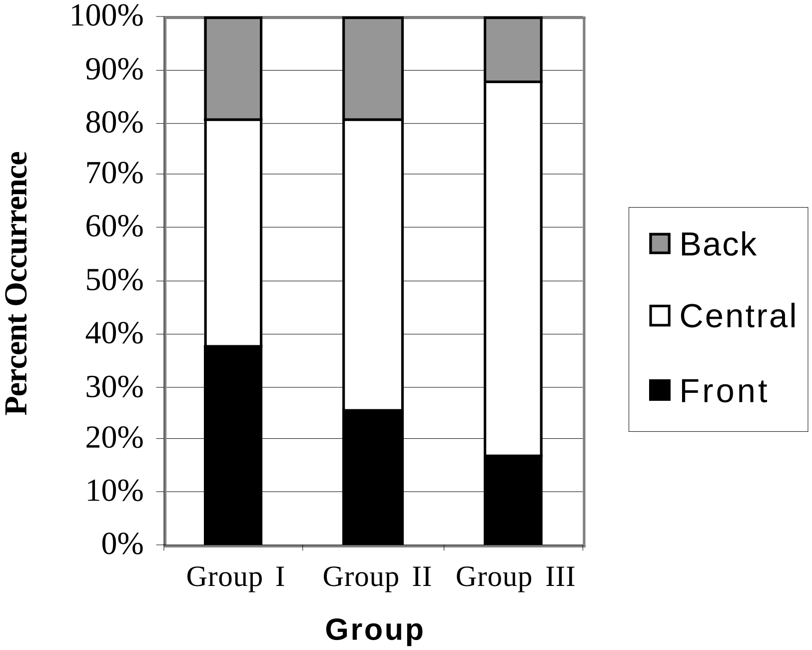
Figure 3-13. Percent occurrence of vowel front/back in singleton contexts for each group.



Vowel Front-Back Patterns in Syllable Contexts

A total of 1,614; 3,585 and 2,156 (1,077 without GW) vowels were produced in syllable contexts by Groups I, II and III, respectively. All three groups show a preponderance of central vowels followed by front then back. Group I vowel front/back patterns were as follows: central 43%, front 38%, and back 19%. Similarly, Group II vowel front/back patterns revealed a preference for central vowels, accounting for 55%, followed by front (26%) and back (19%) vowels. Finally, Group III showed a preference for central vowels (71%), followed by front (17%) and back (12%) vowels. Thus, all groups show a preference for central vowels followed by front and back vowels. HGLM results showed that in relation to central vowels, PTA is significantly associated with back vowels (t = -2.521, df = 13, p = .026; without GW, t = -2.978, df = 12, p = .012). PTA was also marginally associated with the proportion of front vowels relative to central vowels (t = -1.941, df = 13, p = .074; without GW t = -2.02, df = 12, p = .066). The relationship between PTA and front vowels was considered marginally significant when GW was removed from the analysis. Overall, auditory sensitivity was significantly associated with vowel front-back dimension. Figure 3-14 shows the distribution of vowel front-back patterns for segments appearing in syllables.

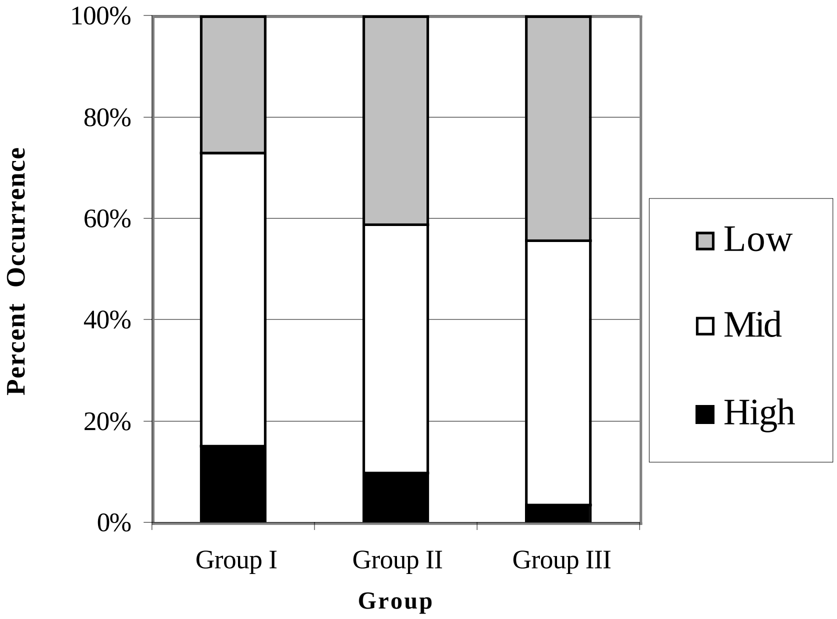
Figure 3-14. Vowel front-back patterns for segments appearing in syllables for each group.



Vowel Height Patterns in Singleton Contexts

A total of 326, 939, and 799 vowels were produced in singleton contexts by Groups I, II, and III, respectively. In singleton contexts, Group I showed the following vowel height pattern: high 15%, mid 58%, and low 27%. Group II showed similar patterns: high 10%, mid 49%, and low 41%. Patterns for Group III also revealed a preference for mid vowels (53%), followed by low (44%) and high (4%) vowels. All groups showed the same general pattern preferences: Mid > Low > High. The pattern remains the same when infant GW is removed (high 4%, mid-53%, and low-44%), showing a general preference for mid and low vowels with little preference for high vowels appearing in singleton contexts. HGLM results show a significant relationship between PTA and high vowels relative to mid vowels in singleton contexts, suggesting that vowel height appearing in singletons is not independent of PTA (t = -3.423, df = 13, p = 0.005; without GW t = -3.199, df = 12, p = .008). Thus, as PTA increases, the relative proportion of singleton high vowels decreases significantly. Figure 3-15 illustrates the distribution of vowel height properties appearing in singleton contexts.

Figure 3-15. Percent occurrence of vowel height in singleton contexts for each group.

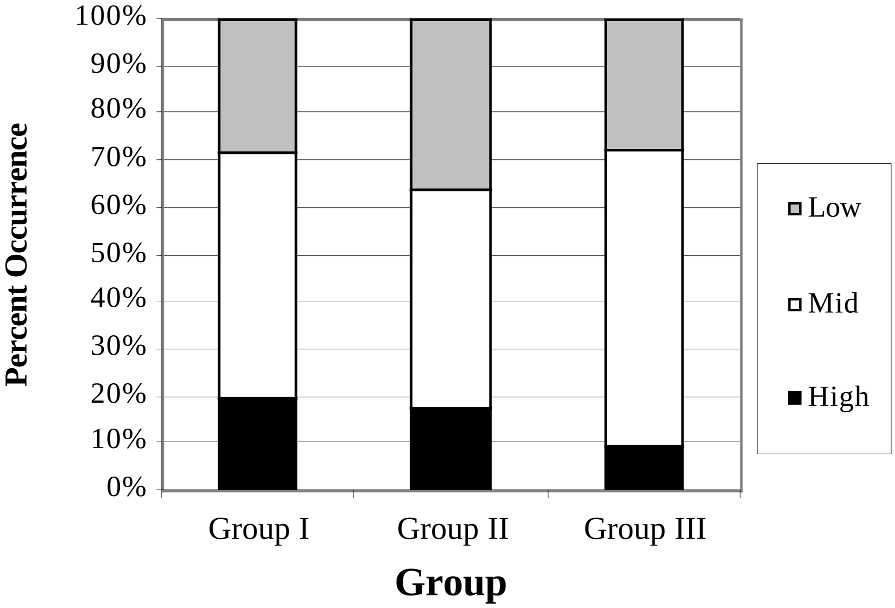


Vowel Height in Syllable Contexts

A total of 1,614; 3,585, and 2,156 (1,077 without GW) vowels were produced in syllable contexts by Groups I, II and III, respectively. In syllable contexts Groups I, II, and III showed a greater propensity for mid vowels (52%, for Group I, 46% for Group II, and 63% for Group III). Low vowels were next in frequency (28% for Group I, 36% for Group II, and 28% for Group III). High vowels appeared less frequently in the three groups (20% for Group I, 18% for Group II, and 10% for Group III).

HGLM results showed a significant relationship between PTA and high vowels relative to mid vowels (t = -2.548, df = 13, p = .025; without GW: t = -2.68, df = 12, p = .020). These results suggest that vowel height is not independent of PTA in syllabic contexts; as hearing loss increases, use of high vowels decreased significantly. Figure 3-16 shows the distribution of vowel height represented in syllabic contexts for the three groups.

Figure 3-16. Vowel height patterns in syllable contexts for each group.



In summary, separate inventories were created for consonant and vowel segments appearing in singleton and syllabic contexts for all three groups. For consonant place, labials accounted for approximately 80-88% of the segments produced in singleton for all infants, regardless degree of hearing loss. Whereas, hearing infants in Group I produced approximately 11% coronals in singletons, infants in Groups II and III produced relatively fewer coronals as singletons. Interestingly, infants in the hearing group (Group I) produced few glottals in singleton positions, whereas infants with hearing impairment (Groups II and III) produced relatively more glottals in singleton contexts. In syllable contexts, the distribution of consonant place was more diverse for all groups. PTA was significantly related to dorsal consonants. Thus, as PTA increased, dorsal consonants appearing in syllabic contexts decreased.

For consonant manner in singleton contexts, nasal consonants were the most prominent across the three groups, accounting for 82-85% of the singleton manner inventory. Nasals were followed by stops and fricatives accounting for about 7-14% and 1-6% of the inventory, respectively. Essentially no liquids or glides were observed in singleton contexts for any group. In syllable contexts, consonant manner distributions change for all groups. That is, unlike for singletons, stops are the most predominant manner used in syllable vocalizations, accounting for approximately 41-63% of manner vocalizations. Nasal vocalizations are the second most frequent manner preference in singleton contexts accounting for about 23-45% of the inventory, a decrease of approximately 40% from what is observed in singleton contexts. PTA was not significantly associated with any observed manner preferences.

For vowels, all groups preferred mid or central vowels, primarily for both singleton and syllable contexts. Associations between PTA and vowels were found for vowel height and vowel front/back dimensions, for both singleton and syllable contexts. For vowel front/back dimensions, there was an association between PTA and back vowels appearing in both contexts. A marginal association was also found for front vowels in syllable contexts. For, vowel height dimension, an association was found between PTA and high vowels of both context types.

SUMMARY OF OVERALL RESULTS

The utterance strings produced by three groups of infants were analyzed. Two inventories at the level of the utterance string were performed. Results showed that as PTA increases, the number of utterance strings containing syllables significantly decreases. Additionally, all utterance strings were analyzed in terms of the vocalization types contained within them. Results showed that as PTA increased, singleton consonants, vowels, and marginal syllables increased while syllables decreased in utterance strings. Table 3-3 shows the results of the utterance string analyses.

Table 3-3. Summary of significant findings for utterance strings: The table provides the inventories that were significantly associated with PTA and the direction of change.

INVENTORY	**CATEGORY**	**DIRECTION OF CHANGE**
Syllables	Syllable Presence	Decreased
Utterance Types	Syllables	Decreased
	Consonant	Increased
	Vowels	Increased
	Marginal Syllables	Increased

A summary of the results for syllable analyses appears in Table 3-4. Syllable analyses showed that PTA was associated with syllable shapes. As PTA increased, CV syllables decreased and VC syllable shapes increased. An analysis of CV syllable onset showed that syllables with dorsal consonant onsets decreased as PTA increased. Intrasyllabic CV Co-occurrence analysis showed that all groups of infants had similar patterns of CV co-occurrences. PTA was significantly associated with only one of the CV co-occurrence patterns; labial-back. Syllable variegation patterns were also evaluated. Vowel variegation patterns were not associated with PTA; however consonant variegation patterns did show an association with PTA. As PTA increased, manner variegation increased and place variegation decreased.

Table 3-4. Summary of significant findings for syllable analyses: The table provides the inventories that were significantly associated with PTA and the direction of change.

INVENTORY	**CATEGORY**	**DIRECTION OF CHANGE**
Syllable Alternations	(mono, di, poly)	No Change
Syllable Shape	CV VC	Decrease Increase
CV syllable Onset	Dorsals Coronals	Decrease Decrease
CV Co-occurrence	Labial -back	No Change
Vowel Variegation		No change
Consonant Variegation	Manner Place	Increase Decrease

Finally, segmental inventories showed an association with dorsal consonants in syllable contexts. No other associations were found for consonant inventories. For vowels, PTA was associated with high vowels as well as back vowels in both context types. Thus, as PTA increased high vowels and back vowels decreased. Front vowels also decreased in syllables. Table 3-5 shows a summary of the significant results related to segmental inventories.

Table 3-5. Summary of significant findings for segmental analyses: The table provides the inventories that were significantly associated with PTA and the direction of change.

INVENTORY	**CATEGORY**	**DIRECTION OF CHANGE**
CONSONANTS		
Place -Singleton		No change
Place- Syllable	Dorsals	Decrease
Manner Singleton		No Change
Manner Syllable		No Change
VOWELS		
F/B Singleton	Back	Decrease
F/B- Syllable	Back	Decrease
F/B-Syllable	Front	Decrease
Height - Singleton	High	Decrease
Height - Syllable	High	Decrease

Chapter 4: Discussion

This study explored the role auditory sensitivity plays in determining the emerging patterns of vocalization observed in the pre-linguistic canonical babbling stage. Vocalization-type inventories were obtained from 15 infants with varying degrees of hearing sensitivity to determine the extent to which auditory sensitivity, as measured by the PTA, contributes to the vocalization patterns observed. Results show that auditory sensitivity contributes significantly to many of the pre-linguistic vocal patterns observed in these infants. Specifically, auditory sensitivity is significantly associated with the types of vocalizations appearing within utterance strings, segmental inventories, syllable shapes, syllable consonant onset patterns, and consonant variegation patterns. Vocalization patterns that are not significantly associated with PTA are syllable alternations, CV co-occurrences, and syllable-based vowel variegation patterns, proposed as being related to mechanical characteristics of the speech system (MacNeilage & Davis, 1990). Results from the organization patterns evidenced by the hearing and hearing impaired groups suggest a role for auditory sensitivity as a force that contributes significantly to the overall emergence of vocal output patterns. By exploring aspects of production behaviors significantly associated with auditory sensitivity, a systems explanation of how co-contributing speech system variables (e.g., mechanical variables and sensory mechanisms) may interact in the formation of pre-linguistic vocalizations is provided.

It has been previously established that the vocalization patterns observed in hearing infants during the babbling period are believed to be canalized, as these patterns are observed in infants universally (e.g., Locke, 1983; Oller, 2001). From a dynamic systems perspective, the emergence of vocalization patterns typically observed in hearing infants is achieved through the contribution of perceptual and mechanical inputs to the system (as well as other variables not measured here). Thus, similar emerging patterns of vocalization should be expected given similar system variable organization. Additionally, it has been suggested that many of the syllable-based vocalization patterns hearing infants produce are strongly influenced by mechanical/articulatory characteristics of the speech output system (MacNeilage & Davis, 1990). In dynamic systems terms, mechanical factors of the speech system are contributing to the emergence of the patterns observed in hearing infants during the babbling period. The extent to which auditory sensitivity factors contribute to the emergence of these vocalization behaviors is unknown. The goal of this study was to explore in more detail how auditory sensitivity contributes to the emergent patterns observed in hearing infants. This study provides information about how auditory sensitivity interacts with other speech system variables to determine the prominent patterns of vocalizations observed in hearing infants during the babbling period. This information is important, as it establishes a more specific role for auditory sensitivity in the speech output system than has been provided previously.

Across the infants, increasing PTA affected vocalization patterns in one of two ways. For some of the analysis types, increasing PTA did not result in any change or *phase-shift* in the emergence of patterns across the infants (i.e., similar patterns emerged despite decreased auditory sensitivity). Non–changing behaviors suggest that auditory sensitivity plays a minimal role in determining the emergence of those behaviors. For other analysis types, increasing PTA resulted in a change in the emergence of patterns across infants, suggesting that auditory sensitivity plays a crucial role in determining the presence of such behaviors. For behaviors exhibiting different patterns, auditory sensitivity can be said to contribute significantly to the emergence of said patterns. In this manner, vocalization patterns whose emergence is dependent on auditory sensitivity were identified. Additionally, by analyzing the ways in which the vocalization behaviors change (increase/decrease) in response to a new system configuration (one with limited auditory sensitivity) a more specific role for auditory sensitivity can be proposed.

The discussion of the results will focus first on the vocalization patterns whose pattern emergence is not dependent on auditory sensitivity, followed by a discussion of the vocalization patterns whose emergence is dependent on auditory sensitivity. Finally, the literature on the role of experience and activity-dependent exploration will be invoked to provide potential explanations for the different patterns observed in infants with HI.

Production Patterns not associated with auditory sensitivity

Syllable Alternation Patterns

Vocalization patterns not significantly associated with auditory sensitivity include syllable alternations, CV co-occurrences, and syllable-based vowel variegation patterns. In this study, PTA is not significantly associated with syllable alternation types. In general, all infants, regardless of degree of hearing loss, show syllable alternation patterns with the propensity for monosyllabic alternations followed by disyllabic and polysyllabic syllables. Although the results are not statistically significant, a trend towards increasing monosyllables and decreasing polysyllables is observed as PTA increases. The results regarding syllable alternation are similar to those reported in other studies of typically developing infants (Davis & MacNeilage, 1995b; Kent & Bauer, 1985; Mitchell and Kent, 1990) and hearing-impaired infants (Davis, et al., submitted; McCaffrey, et al., 2000; Steffens et al., 1994) showing a preference for monosyllables followed by disyllables and polysyllables. Thus, moderate or profound hearing impairment does not prohibit use of serial multi-syllabic sequences (although one infant did not produce any multi-syllabic sequences). Deaf infants of deaf parents have also been noted to produce series of silent jaw wags or mandibular oscillations throughout the babbling period (Meier, McGarvin, Zakia, & Willerman, 1997). These results suggest that the tendency to produce serial mandibular oscillations is related to mechanical aspects of the speech system rather than to auditory sensitivity.

CV Co-Occurrence Patterns

Auditory sensitivity also contributes minimally to the emergence of CV co-occurrences. The Frame/Content perspective suggests that mechanical processes related to mandibular oscillations are the basis for intrasyllabic output patterns in canonical babbling (MacNeilage & Davis, 1990; Davis & MacNeilage, 1995). In babbling, the mandible is seen as the primary articulator contributing to the internal organization of the syllable. Articulators such as the lips, tongue, and velum are not operating independently and therefore the syllabic output is based on close open alternations related to mandibular oscillations. Within this paradigm, the mandibular oscillation is the ‘frame’ onto which ‘content’ is later overlaid as the infant gains facility with independent movements of articulators within vocal sequences. Three frame types have been predicted from this principle. Pure frames are mandibular oscillations with neutral tongue position, resulting in the percept of a labial consonant co-occurring with a central vowel. Fronted frames are mandibular oscillations with front tongue position that result in the percept of a coronal consonant co-occurring with a front vowel. Finally, backed frames are mandibular oscillations coupled with a back tongue position, resulting in the percept of dorsal consonants co-occurring with back vowels. For all three groups studied, including the profound group without infant GW, the pure frames and fronted frames are observed consistently at above chance levels. These results are consistent with previous data obtained for hearing infants (MacNeilage & Davis, 1990; Davis & MacNeilage, 1995). The backed frames are observed for Groups I (hearing) and III (profound) but not Group II (moderate). Auditory sensitivity is not a significant control-parameter determining the intrasyllabic CV co-occurrence patterns with the exception of the labial-back pattern. These results suggest that auditory sensitivity; while having a significant effect on the frequency of syllables produced, does not seem to affect the intra-syllabic organization of those syllables when a sufficient sample of syllables is available for analysis.

Prior to this study, CV co-occurrences had not been evaluated thoroughly in hearing impaired infants. CV co-occurrence data for the infant who received a CI at age 24 months (McCaffrey, et al., 2000) showed the labial-central tendency pre- and post-implant. The coronal-front co-occurrence was only apparent after implantation. Dorsal-back co-occurrences were not evaluated, as the infant did not produce many instances of dorsal onset CV syllables. Additionally the labial-back co-occurrence effect was not reported in that infant.

The relationship between labial-back co-occurrences and PTA needs to be studied more closely. The labial-back pattern observed in the hearing impaired infants might reflect the effect of visual information on the production system when auditory input is limited. That is, labial vocalizations with lip rounding might be more visibly salient than other labial onset syllable vocalizations. Results of this study suggest that the emergence of CV co-occurrences is generally achieved without any significant contribution from auditory sensitivity. Thus, CV co-occurrences are not dependent on auditory sensitivity. Results for the CV co-occurrence data for the profound group is based on a total of four infants. It is suggested that future studies examine these trends in groups with a larger sample size.

Vowel Variegation Patterns

Auditory sensitivity does not seem to contribute to the emergence of vowel-based variegation patterns. Research on inter-syllabic organization has shown that the mechanical properties related to mandibular oscillations also tend to underlie the organization of segments across syllables (Davis & MacNeilage, 1995). In moving from one syllable to another, diversification of consonants tends to occur in manner of articulation rather than place. Similarly, for vowels, changes in vowel from one syllable to the next tend to involve more changes in height than changes in front/back tongue position. Thus, the primary changes observed tend to involve change in the degree of closure/amplitude of the mandibular cycle, for both vowels and consonants. For this study, it was hypothesized that PTA was not an important control-parameter determining inter-syllabic organization patterns. The dominance of mechanical effects for vowels seems apparent across all three groups. Relative to vowel variegation patterns, all three groups produce significantly higher proportions of vowel height variegation than front/back variegation, when only one parameter varied. This result is consistent with the Frame/Content perspective suggesting that the mechanics of mandibular oscillations dominate vowel variegation patterns. Thus, vowel variegation patterns are patterns whose emergence does not depend on auditory sensitivity to a significant degree.

A trend showing increased use of vowel height variegation and decreasing use of vowel front/back variegation patterns was observed with increasing PTA. Although the trend was not significant, it may indicate that production system effects may become exaggerated with decreasing hearing sensitivity, suggesting that auditory sensitivity might contribute to the emergence of the patterns observed in typical infants. Thus, future studies should continue to examine this issue in groups with a larger sample size.

Production patterns associated with auditory sensitivity

Auditory sensitivity is significantly associated with the types of vocalizations appearing within vocalization strings, segmental inventories, syllable shapes, syllable onset patterns, and consonant variegation patterns. Auditory sensitivity, as measured by the PTA, is a significant *control-parameter* in these patterns. In order for these patterns to evidence the stochastic regularities with which they appear in hearing infants, auditory sensitivity must be present. These patterns will be discussed separately. Within this discussion, vocalization patterns for each group will be compared to each other and to previously reported values in the infant acquisition literature on hearing infants and infants with HI. The role of experience, including activity-dependent learning will be invoked in explaining auditory perceptual influences on production patterns in early babbling behaviors.

Utterance Strings

Auditory sensitivity plays an important role in determining the emergence of utterance strings containing syllables. Indeed, one of the most striking outcomes of this study highlights the extent of the contribution of auditory sensitivity to the organization of utterance strings produced in early acquisition. Approximately 60% of the utterance strings in the normal hearing group (Group I) and in the moderate hearing group (Group II) contain syllable-based output. Only 28% of utterance strings in Group III contain syllable-based vocalizations. Despite early-identification, a mean age of amplification of 8 months, and a mean hearing age of 12 months, approximately 70% of the utterance strings produced by infants in Group III did not contain syllable-based content. This pattern is consistent with reports from other studies reporting few syllable-based vocalizations in infants with profound hearing impairment (Kent, Osberger, Netsell, & Hustedde, 1987; Stoel-Gammon & Otomo, 1986). On the contrary, infants with moderate hearing loss (Group II) derived sufficient auditory input with amplification to trigger syllable-based behaviors with a frequency that is comparable to those of the hearing group (Group I). Infants with moderate-to severe hearing impairment (Group II) typically demonstrate aided auditory thresholds in the normal-to-mild range (25-35 dB HL); whereas, infants with profound hearing impairment (Group III) demonstrate aided auditory thresholds in the moderate range, at best. This result suggests that adequate auditory sensitivity is crucial for stimulating the relative frequency of syllable-based output observed in typically developing infants and in infants with moderate hearing impairment, even though both of those groups also produce non-syllable-based vocalizations.

Auditory sensitivity also contributes significantly to the emerging patterns of vocalization types within utterance strings. Results of this analysis are consistent with studies of typically developing infants confirming the co-existence of singleton vocalizations with syllable-based vocalizations during the canonical babbling period (Kent & Bauer, 1985; Mitchell & Kent, 1990). All infants in this study, regardless of severity of hearing impairment, produced singleton vowels, consonants, and marginal syllables as well as syllables. Group I shows utterance string patterns marked by a prominence of syllables and relatively less use of singletons and other utterance types. Group III members (and Group II members to a lesser extent), show alternate patterns marked by strong prominence of singletons and marginal syllables, and relatively less pronounced use of syllable-based vocalizations. In particular, as hearing loss increases, singletons (consonants and vowels) and marginal syllables increase in relation to diminishing frequency of syllables, with Group II showing the same trend as Group III, but to a lesser extent than Group III. The results for the profoundly hearing impaired infants are consistent with previously reported results on infants with profound hearing impairment, showing a propensity for singleton vowels and marginal syllables and use of few syllables (Davis, et al., submitted; Kent, Osberger, Netsell, & Hustedde, 1987; McCaffrey, et al., 2000; Stoel-Gammon & Otomo, 1986). No other study has detailed utterance type analysis on moderately hearing impaired infants. The results of this study suggest that despite the improved benefit received from amplification devices, infants with moderate HI show an increased use of singleton vowels and marginal syllables with a concurrent decrease in syllable use, although their production repertoires resemble more those of the hearing group (Group I) than those of the profoundly hearing impaired group (Group III).

If auditory sensitivity did not play a crucial role in determining the observed pattern of behaviors in the typical system, the relative frequencies of vocalization types within utterance strings would have persisted despite the perturbation in auditory sensitivity shown in Groups II and III. The alternate patterns of vocalization behaviors established in infants with HI (increased singletons/marginal syllables and relatively fewer syllables) may reflect the tendencies of the system when contributions from auditory sensitivity are diminished. Thus, when hearing is limited the observed output reflects the contributions of the remaining system variables (i.e., mechanical, visual, and kinesthetic) that promote singletons and marginal syllables more so than syllable behaviors. By observing the difference in output exhibited by the system with hearing and the system with limited hearing a role for auditory sensitivity can be inferred.

Thus, if the natural tendency of the speech output system (with reduced auditory sensitivity) is to produce a predominance of singletons and relatively fewer syllable behaviors, it could be inferred that auditory sensitivity contributions, interacting with other contributing components, result in a dampening of the net influence of the system variables contributing to the prominence of singleton behaviors and facilitate the emergence of syllable-based behaviors. In order for syllable productions to emerge, contributions from both auditory sensitivity and mechanical aspects of the system are required. Thus, auditory sensitivity contributes significantly to the patterns observed in typically developing infants, by pushing the system into a mode of expression where marginal syllables and singletons are, in a sense, dampened and where syllable-based output seems to be facilitated. It is suggested that auditory sensitivity interacts with other system components ultimately resulting in the emergence of the observed patterns of production.

Syllable Shape

The emergence of syllabic behaviors that are dependent on auditory sensitivity includes: (a) syllable shapes (b), consonant onset patterns and (c), consonant variegation patterns. Regarding syllable shapes, this study revealed two crucial findings. First, all groups, regardless of hearing ability produced a preponderance of CV syllable shapes, suggesting that the onset of syllabic alternations in vocalizations is from a close mouth position rather than an open mouth position. These results are consistent with results obtained in hearing infants (Davis & MacNeilage, 1995b; Kent & Bauer, 1985; Mitchell & Kent, 1990). Second, the syllable shape patterns show an effect of auditory sensitivity for the VC syllable shape in relation to CV's. Thus, as hearing loss increases, the syllable-shape patterns show *decreasing* prominence of CV's and *increasing* prominence of VC's. Together these results suggest that auditory sensitivity is an important control-parameter in determining the emergence of CV and VC syllable shape patterns observed in the babbling period. This study suggests that in the typically developing speech system, the relative syllable-shape patterns observed depend on auditory sensitivity. As hearing sensitivity decreases, the ratio of CV's to VC's in a typical system changes.

The increase in VC's relative to CV's observed in Group III with the most profound hearing loss was an unexpected finding. The increase in VC's may be related to the increased number of singleton vowels produced by hearing impaired infants. One possibility may be that Group III infants produce articulatory closure following some of their singleton vowel vocalizations, resulting in the percept of VC syllable shapes. Thus, it may be that the increased number of VC's are related or linked to increased presence of singleton vowel vocalizations. Because these infants with profound hearing impairment produce a statistically higher proportion of singleton vowels, it is inferred that the increase in observed VC shapes mirrors the increase in instances in which closure occurs following the singleton vowel. Future studies should examine this relationship more closely.

Consonant Onset Patterns

Consonant onset patterns in syllables are also dependent on auditory sensitivity. Syllabic output of the CV form was further analyzed by consonant onset (keeping in mind that Group III infants with profound HI produced far fewer syllables than the other two groups studied). Syllables were analyzed by place of articulation into those beginning with labial, coronal and dorsal consonants. Kent and Bauer (1990) showed that labial and coronal place of articulation were dominant in five 13 month old hearing infants' syllable onset patterns. Their result is consistent with the patterns shown by all three groups in this study. In general, the syllable-onset patterns for the moderate (Group II) and profound (Group III) HI groups show more frequent use of labial than coronal onset syllables; however, the difference is not considered statistically significant when compared to the proportion of labial and coronal onset syllables observed in the hearing group. An unexpected finding was observed for dorsal onset syllables in relation to coronal onset syllables, however. Overall, the results show that as hearing loss increases, dorsal and coronal consonant onsets decrease significantly. Hence, this study suggests that auditory sensitivity might be associated with the production of syllables with dorsal onset. Dorsal onset syllables occur at a low frequency in typically developing infants as well. It has been suggested that these sounds tend to require more complex manipulation of the tongue-dorsum and therefore account for a smaller proportion of infant phonetic repertoires (Gildersleeve-Neuman, Davis, & MacNeilage, 2000). The decrease in dorsals and coronals is apparent for both Group II and III infants, suggesting that even with amplification infants with moderate HI may not be receiving sufficient input to significantly explore the patterns of syllable-onset production. The results of this study suggest that auditory sensitivity contributes significantly to the mechanism that determines consonant onset in CV syllables. By comparing how the prominent patterns change across the groups, a role for auditory sensitivity seems to be one that facilitates the emergence of syllables with coronal and dorsal onsets and dampens the mechanical tendency to produce syllables with labial onsets.

Consonant Variegation Patterns

Consonant variegation patterns are also dependent on auditory sensitivity. This study shows an effect of PTA on consonant manner/place variegation patterns. Results for consonant variegation patterns show a different pattern for each group and should be interpreted cautiously. In this study the consonant variegation patterns of Group I show an equal proportion of manner and place variegation (50%). Previous studies have reported approximately 66-73% manner variegation and 27-34% place variegation for typically developing infants in the babbling and first words stage for these same infants (Davis & MacNeilage, 1995; Gildersleeve-Neumann, 2001). The patterns for moderate (Group II) and profound groups (Group III, with GW) showed approximately 86% manner variegation and 14% place variegation, whereas, Group III without infant GW produced 100% manner changes in variegated sequences. The patterns of infants with hearing impairment (Group II and III with GW) showed on average, up to 36% more manner variegation sequences than infants in Group I, as well as up to 13-20% more manner variegation sequences than reported in other studies. Without GW, infants with profound hearing impairment (Group III) produced 27-34% more manner variegation sequences than that reported for typically developing infants. These patterns will be discussed separately in the following sections.

First, why did the data for Group I not turn out as predicted, consistent with results published elsewhere? The possibility exists that the observed differences between the groups reflect a difference in the amount of data collected. The patterns observed by Davis and MacNeilage (1995b) represent the average patterns obtained for the entire babbling period, approximately spanning a 6-month period for each infant. Davis and MacNeilage collected and analyzed approximately 24 (4 hours/month for 6 months) hours of data for each infant during the 6-month babbling period. In contrast, this study sampled an average of 90 minutes (range 1-2 hours) of data for the hearing infants. It is possible that this reduced amount of data is not sufficient to capture the consonant variegation patterns now already well established in data for hearing infants. With such reduced sampling, individual differences in production preferences occurring within a sampling session have the potential to obscure average patterns. An average of 150 and 134 minutes were collected for infants in the moderate and profound groups.

Consonant variegation data for Group II and III infants was consistent with the general patterns observed in typically developing infants, showing dominance of manner variegation over place variegation. These results confirm the proposal that there is a strong tendency to effect change from one syllable to the next through jaw amplitude modulations with minimal horizontal (front/back) tongue movement in all infants regardless of hearing sensitivity. Additionally, this study showed that the tendency to effect consonant changes through mandibular oscillation (with minimal tongue movement in the front/back dimension) *increases* with increasing hearing-impairment (becomes more prominent). Conversely, as hearing loss increases, infants' exploration of place variegation sequences decreases significantly. Thus, in hearing impaired systems, factors related to mechanical aspects of production become increasingly more important to the way in which variegated sequences are produced. Variegation in consonant place suggests that in moving from one mandibular cycle to the next, some amount of tongue movement or re-positioning must be executed in order to effect consonant variegation patterns (e.g., going from mandibular oscillation with /b/ onset to mandibular oscillation with /d/ onset). This movement pattern may be more complex, as it requires coordination of the mandibular oscillations with concurrent tongue front/back movements.

The different consonant variegation patterns observed in infants with HI may reflect the net contribution of the remaining system variables (mechanical, visual, kinesthetic) showing an increased affinity for manner variegation. Thus, auditory sensitivity may act on the natural tendency of the remaining system variables to explore manner variegation sequences, dampening the system’s preference for manner changes, and introducing sufficient energy to establish increased exploration of place variegation patterns. Regarding the typically developing system, these results suggest that changes in manner tend to be mediated by mechanical characteristics of the speech system; whereas, changes in place may potentially be mediated by auditory sensitivity, as they require movement of the tongue within sequences. The balance between manner variegation and place variegation is mediated by mechanical characteristics coupled with auditory sensitivity. Thus, in the hearing infant, the role of auditory sensitivity may be to reduce manner variegation patterns (by *decreasing* the prominence of that behavior) and to facilitate the production of place variegation patterns (by *increasing* the prominence of that behavior). Together, mechanical and auditory sensitivity variables may mediate the overall patterns of organization observed in inter-syllabic sequences.

To some extent, the data on inter-syllabic organization patterns observed for hearing-impaired infants (specifically profound HI) can be related to general articulatory patterns observed in congenitally deafened adults. It has been shown that lack of co-articulation or abnormal co-articulation is a major contributor to the low intelligibility evidenced by adult individuals with congenital hearing-impairment (McGarr & Whitehead, 1992; Tye-Murray, 1991, 1992; Tye-Murray & Folkins, 1990). Acoustic and physiologic data regarding co-articulatory effects in the speech of profoundly hearing impaired adults supports the proposal that deaf speakers' speech exhibits fewer context effects in production patterns (McGarr & Whitehead, 1992). One of the aberrant co-articulatory patterns adopted by profoundly impaired individuals is diminished tongue front/back movements in effecting mandibular cycles (Tye-Murray, 1991, 1992; Tye-Murray & Folkins, 1990). It has been suggested that lack of experience with the auditory signal contributes to the established aberrant co-articulatory patterns observed in congenitally deaf adult speakers. As a result of insufficient auditory input, deaf speakers focus on the visible aspect of vowel production, jaw movements, while not producing the non-visible aspects of vowel production, mainly those involving tongue movements in the front/back dimension. This strategy may explain the patterns observed in the profoundly hearing impaired infants studied here, who are producing more (increased) manner changes (for vowels and consonants) and relatively fewer place (front/back) changes relative to their hearing counterparts. It may be that the poor co-articulatory patterns observed in congenitally deaf adults are beginning to be established early in the speech acquisition process in these hearing impaired infants. This study provides some evidence for this assertion, in that the profound infants (Group III) did not generally produce many CVCV sequences that varied in place or front back dimensions, suggesting that they are focusing on oscillations that are variegated in amplitude (manner) and reduplicated in place.

Additionally, it has been asserted that many of the aberrant patterns adopted by hearing impaired individuals are initially due to the lack of auditory feedback available to this population, but are to some extent also learned behaviors as a result of certain training methodologies (Higgins, et al., 1996). The results of this study suggest that the alternate production patterns adopted by congenitally deaf speakers may become instantiated early in life, as some evidence for these patterns was already observed in the two groups of early-identified infants who received amplification devices in the first year. No published studies have examined the effect of intervention strategies on early-identified infants during the babbling period. Hence, it remains unclear how early intervention therapy might be affecting the early production patterns observed by these infants.

The patterns evidenced by these infants show that in the context of increasing hearing loss, the aspects of syllable organization related to mandibular oscillations increasingly become more dominant in the infant production repertoire, in both groups. Additionally, this study showed that hearing loss tends to limit the variety of variegation patterns observed in profoundly impaired infants, interfering with the exploration of patterns requiring more complex co-ordination of mandibular oscillation with concurrent tongue front/back movements. This effect seems to be evident in both moderate and profoundly impaired infants, but seems to be more exaggerated in profoundly impaired infants. To that end, this study has shed light on the interactive roles of the auditory and motor components of the speech output system.

Segments

Separate inventories were created for segments appearing in singleton and syllabic contexts. For vowels, all three groups preferred mid, and central vowels, primarily for both context types. Associations between PTA and vowels were found for vowel height and vowel front/back dimensions, for both singleton and syllable contexts. As PTA increased, the tendency was for mid and central vowels to increase with a concurrent tendency for high vowels as well as back vowels to decrease in both singleton and syllabic contexts. For syllable contexts a similar preference was reported for mid and central vowels over front, high, and back vowels in the hearing impaired children studied by Steffens et al., (1994).

During the canonical babbling period, vowel vocalizations have been described as tending to concentrate around the lower-left quadrant of the vowel space, mostly low-front, mid-front, and neutral/central vowels (Buhr, 1980; Davis & MacNeilage, 1995b; Kent & Bauer, 1985; Kent & Murray, 1982; Lieberman, 1980). It has been suggested that low and mid vowels are produced more by lowering the jaw than by independent movement of the tongue and are therefore more dependent on mechanical factors than auditory factors. Additionally, it has been suggested that high vowels are produced infrequently in typically developing infant vocalizations during the first year, perhaps because more complex manipulation of the tongue is required (Davis & MacNeilage, 1995b; Kent & Bauer, 1985). Kent & Bauer, (1985) and Davis and MacNeilage, (1995b) have suggested that high vowels are infrequent in infant vocalizations during the first year, because they may require more complex manipulation of the tongue. Additionally, Buhr (1980) also noted that the "back vowel axis", was poorly represented in a corpus of tokens he studied, suggesting also that the poor representation of the back vowel axis reflected the more complex production mechanism required for these vowels, involving coordinated movement of lips, tongue and jaw. These results suggest that high and back vowels (in both singleton and syllable-based contexts) might be more susceptible to decreases in auditory sensitivity. The patterns evidenced by the infants in this study showed a tendency to favor increasing the "central effect" while decreasing behaviors that are typically known to require more complex manipulation or coordination of articulators. It may be the case that the HI infants studied are using articulatory movements consistent with non-central vowels, but the perceptual outcomes are being masked by the overriding effects of nasality (resulting from poor velo-pharyngeal control) and subsequently result in a percept of central vowels (Fujimura, 1969; House & Stevens, 1956; Matyear, MacNeilage, and Davis, 1997). Without acoustic analysis it is impossible to determine whether the infants in this study were actually effecting articulatory movements consistent with non-central vowels. Regardless, the profoundly impaired infants did produce instances that were perceived as high or as back vowels, (in singleton and syllable contexts), but their numbers were diminished relative to the hearing peers. Results from this study suggest that lack of auditory experience with the signal will result in diminished exploration of these parts of the vowel space.

Separate inventories for consonants showed differences related to context. In singleton contexts for consonant place, labials accounted for approximately 80-88% of the segments produced as in singletons for all infants. Coronals accounted for 11% of the singleton inventory for infants with normal hearing; whereas, infants in Groups II and III produced relatively few coronals as singletons. In syllable contexts, the distribution of consonant place was more diverse for all groups, with all groups producing approximately equal proportions of labials and coronals. PTA was significantly related to dorsal consonants, suggesting that PTA is a significant control-parameter in determining dorsal consonants in syllable contexts. Thus, as PTA *increases*, dorsal consonants appearing in syllabic contexts *decrease* relative to coronals. Group III produced the lowest number of dorsal consonants, Group I the highest. A similar effect is found for syllable analyses, suggesting that segmental inventories in syllable contexts and syllable inventories may be providing redundant information.

For consonant manner in singleton contexts, nasal consonants were the most prominent across the three groups, accounting for 82-85% of the singleton manner inventory. This was followed by stops and fricatives accounting for about 7-14% and 1-6% of the inventory, respectively. In syllable contexts, consonant manner distributions differed from those in singleton context for all three groups. Unlike for singletons, stops are the most predominant manner used in syllable-based vocalizations, accounting for approximately 41-63% of consonant manner vocalizations. Nasal vocalizations are the second most frequent manner preferences in syllable contexts accounting for about 23-45% of the inventory, a decrease of approximately 40% from that observed in singleton contexts. PTA was not significantly associated with any manner preferences across groups, suggesting that PTA is not a significant control-parameter in determining consonant manner. However, there was a non-significant trend for increasing nasals with increasing PTA. Distinctions have traditionally not been made between segments appearing in singleton and syllable contexts. Thus, it is difficult to compare these results with other studies. Steffens et al., (1994) reported similar trends (preference for stops over semi-vowels, nasals and fricatives) in the syllable-based inventories of a group of six toddlers (mean age 32 months) with profound hearing impairment wearing hearing aids and tactile devices.

Segment production patterns for consonants show context-dependency for all groups in this study. The proportional distribution of consonant place and manner in singleton contexts was very different than the proportional distribution of the same consonants appearing in syllable contexts. In singleton contexts, all groups produced nasal labials (e.g., /m/), predominately. In syllable-based contexts, all groups, including the profound group, preferred oral stops over nasals. The majority of studies focusing on hearing impaired infant babbling, have focused on comparing segmental inventories across hearing categories either from pre- to post-implantation, or from hearing-impaired to hearing infants, without distinguishing the context in which these behaviors occurred. Results of these comparisons often suggest that hearing impaired infants (in the pre-implant condition) tend to produce mainly nasal consonants while hearing infants (post-implant) tend to produce oral stops. This difference between pre- and post implantation or between hearing and hearing impaired infants may in fact reflect differences in context comparisons-singletons in hearing impaired (pre-implant conditions) to syllables in improved hearing conditions (post-implant). What is not clear is the extent to which these differences are exaggerated by the act of comparing segments without regard for context in which they appear. What is generally thought to be a difference in segmental organization between pre- and post or between hearing impaired and hearing infants may in fact be reflecting the change in the frequency of occurrence of syllable vocalizations instead of a change in segmental organization. Thus, what might actually be changing from pre- to post implantation is the frequency of occurrence of syllables in response to improved auditory input. It is recommended that studies comparing segmental differences between auditory conditions account for the context-dependency of segmental vocalizations, so that the true effects of auditory input on segmental inventories can be discerned.

The Role of Auditory Sensitivity

Results from this study established that at the system level, the emergence of many of the vocalization patterns observed depends on the co-contribution of auditory sensitivity and characteristics of the production mechanism. Second, within the vocalization level, auditory sensitivity does not significantly contribute to vocalization patterns that have been attributed to mechanical characteristics of the production system. Third, auditory sensitivity seems to contribute significantly to the development of production behaviors that are known to require more complex manipulation of articulators. Finally, results from this study suggest that the role of auditory sensitivity in contributing to typical production organization patterns seems to be in the form of input that pushes the system into alternate forms of organization and expression. It is suggested that auditory sensitivity acts as a force, supplying energy to the typical production system, that subsequently dampens the expression of some behaviors that tend to become established in the absence of auditory sensitivity (e.g., singletons, consonant manner variegation) while simultaneously facilitating the emergence of behaviors that are less prominent in the absence of auditory sensitivity (e.g., syllables, consonant place variegation). The results of this study suggest that the emergent patterns of organization of the pre-linguistic speech system are established through the contribution of multiple forces (mechanical and perceptual). Auditory sensitivity forces may interact with and impinge on other system processes, ultimately contributing to the observed vocalization behaviors. When one of those forces is removed (i.e., auditory sensitivity), alternate patterns of production emerge. The alternate patterns evidenced in a system with limited auditory sensitivity can be attributed to the remaining system variables. Thus, in the case of the speech system found in infants with profound hearing impairment, the alternate patterns of organization are generated by the new arrangement of contributing forces (mechanical, visual, kinesthetic, etc.). The patterns observed in HI infants might reflect the organizational arrangement of influential variables. Thus, for example, the increased prominence of singletons, and or consonant manner variegation might reflect the tendencies of the mechanical properties of the system (if that is the dominant force operating in that system) when free from the constraining influence of auditory sensitivity. Thus, the output of the system without significant constraints provided by potential auditory influences reflects the stochastic tendencies of the limited system. Evidence of this was provided in the consonant manner variegation patterns of Group III that showed almost an exaggerated increase in use of manner variegation patterns.

It is suggested that by introducing auditory sensitivity back into the system, new relations can potentially be formed between system variables (i.e., in the case of cochlear implants or infants with moderate HI receiving amplification). Specifically, for those patterns identified as patterns that require auditory sensitivity to emerge, auditory sensitivity forces seem to dampen (patterns that increase in prominence in the context of limited auditory sensitivity), and amplify (patterns that decrease in the context of limited auditory sensitivity) the alternate patterns created by the remaining system forces. Evidence of this role for auditory sensitivity can be gleaned from research on toddlers with CI. Prior to implantation, the system, lacking significant auditory influences, organizes to produce a prominence of singletons and relatively few syllables. Post-implantation, the system, reflecting new relations among its variables, re-organized to reflect the new properties of the system, showing increased prominence of syllabic behaviors, and eventually reduced prominence of singleton behaviors. It is suggested that increased auditory sensitivity results in new relations among perceptual and mechanical system variables. These new system relations then, result in different patterns of production. Thus, it is suggested that increased auditory sensitivity in implanted infants may act as a force that reduces the tendency of the system to produce singletons, at the same time facilitating the reduced tendency of the pre-implant system to produce syllables. In hearing infants, auditory sensitivity interacts with other system forces to determine the emerging patterns of organization.

The different patterns of organization observed in the production repertoires of these hearing impaired infants are due to the different arrangement of sub-system components that provide different forms of feedback and experience from hearing infants. Work on infant development suggests that the experience obtained through the coordination of movement/perception systems leads to the further development of action skills. Perception-action studies have suggested that repetition of active behavior serves as a means to gain and strengthen perceptual knowledge (Morrongielo 1994; Thelen et al. 1993), known as embodied cognition (e.g., Lakoff, 1987; Johnson, 1987). Dmitrieva and Gottlieb (1994) showed that an intricate cycle of action-perceptual experience promotes the development of motor skill, as well as the development of auditory perceptual neural structures. Thus, experience with signals and actions leads to bi-directional development of action and perceptual systems (Gottlieb, 1998). For example, bi-directional effects of experience were shown in Dmitrieva and Gottlieb's (1994) study of Peking ducklings that showed a relationship between auditory structure and vocal function. An arrest of auditory neuronal system development was noted in ducklings that were not exposed to and could not produce their own species-specific signal.

One unexpected finding from this study that could be explained using principles from activity-dependent exploration relates to vocalizations known to appear at low frequencies of occurrence in typically developing infants. Results from this study showed a systematic effect of auditory sensitivity on less frequent articulations (thought to be more complex), such as back vowels, high vowels, dorsal consonants, dorsal onset syllables, and consonant place variegation sequences. With increasing hearing loss, the proportions of these more 'complex' sequences in the inventory diminished significantly. Thus, one conclusion from this study is that lack of auditory experience with the speech signal may interfere with exploration of more complex patterns of production and that activity-perceptual exploration seems to play a significant role in promoting more complex vocal behaviors, (i.e., those that are typically produced less frequently by hearing infants). Hence, when infants were not able to hear the perceptual consequences of more complex motor coordination, those motor actions were probably less likely to be explored and were subsequently not present in the inventory. Thus, typically developing infants may rely on auditory input as a feedback mechanism to promote exploration of more complex motor forms. Lack of exploration of more complex forms will likely lead to arrested development in the auditory system as well as in the production system. Thus, in order for the bi-directional cycle of activity-dependent exploration to continue, adequate experience with the auditory signal must be obtained.

The results from this study also suggest that experience (producing and perceiving) plays an important part in influencing different patterns of vocal development in the two groups of hearing impaired infants. This study showed that infants with moderate-to-severe hearing impairment (Group II) obtain pre-linguistic speech outcomes generally similar to those of hearing infants when exposed early to the speech signal with amplification devices. Specifically, infants with moderate HI produced significantly more syllables than infants with profound impairment (Group III). However, despite increased production of syllables, the same organization trends noted in Group III (but to a lesser extent) were noted in Group II. Like Group III infants, Group II infants showed fewer dorsal-onset syllables, fewer consonant-place variegations, more VC’s, etc., suggesting that infants with moderate HI do not achieve production outcomes completely similar to hearing infants once they receive amplification devices. Although their aided thresholds are expected to be much better than the profound group (Group III), mostly within the 25-35 dB HL range; that level of auditory sensitivity still may not be sufficient to enable the system output to organize similar to hearing infants. Thus, a different level of auditory sensitivity may be required for effecting frequent production of syllables than for effecting specific patterns of organization of some syllable characteristics. Infants with moderate HI derive sufficient input to the signal to trigger productions of syllables, but may not have sufficient access to the signal to explore some more diverse patterns. Additionally, although these infants received early identification and intervention, it could be that the relative timing of auditory input relative to the development of other perceptual and motor capacities affected the infants' abilities to organize like hearing infants (Turkewitz & Devenny, 1993).

The outcome for Group III infants is unfortunately not the same as for infants with severe-to-profound hearing impairment. Although these infants were being identified and fit with amplification devices relatively early, the nature of profound hearing impairment in the majority of cases is such that despite many advances in technology, they are either not able to access the complete range of the speech signal, and/or the underlying processing mechanisms are not sufficiently intact to process the auditory signal. The net effect for the infant without adequate access to the signal results in lack of experience with the acoustics of incoming speech (exteroceptive) signals as well as to the acoustics of signals produced by the hearing impaired infant (proprioceptive). Without adequate access to the signal the infant is faced with both an inability to perceive the environmental signal, and an inability to monitor his/her own vocalizations. This in turn affects the development/maturation of the auditory/production system (Dmitrieva & Gottlieb, 1994).

Infant GW, the infant with profound hearing impairment, whose vocal patterns were very different from the rest of the infants in Group III, provides an interesting case to highlight effects of experience. Her production repertoire resembled more the vocalizations of the infants in the moderate group (Group II), showing proportionately more syllables than any other infant of her group. Her PTA, from 500-2000 Hz for the right ear was 90 dB HL and 85 dB HL for her left ear. Her PTA was at least 15 dB better than the other infants in her group. With amplification, her aided PTA was approximately 53 dB HL. Hence, she had access to the low-to- mid frequency regions of conversational speech signal. Although GW had a profound hearing impairment, she had sufficient residual hearing to afford her better aided-thresholds than the other infants in Group III. It is suggested that the auditory experience that this infant gained with amplification was sufficient to trigger frequent syllable vocalizations and thus promoted activity-perceptual exploration. GW received a cochlear implant at 24 months. Follow-up conversations with her mother revealed that by the time of implantation, she had not yet developed any consistent use of words. Although her babbling resembled the babbling behaviors of both the moderately impaired infants and to some extent the typically developing infants, the benefit of slightly better hearing did not translate into word use for this infant by the age of 24 months. Thus, what may seem like sufficient auditory experience to trigger syllable production may not be sufficient to link sounds to meanings for lexical acquisition. The relationship between the audibility of the syllable and word acquisition should be investigated further.

Implications, Limitations, and Future Studies

The goal of this study was to explore the role of auditory sensitivity by conditioning on one variable (hearing), assuming other speech system variables to be constant. Whereas this approach is informative, this is nevertheless an incomplete approach, as it fails to provide details about the interplay of factors not under study. These results are but a snapshot of a developmental process, focused on one aspect of the process- hearing (and its relation to the other system factors). Future studies should investigate how other potentially causal factors interact (auditory, vision, kinesthetic, motor, etc) with each other, and how these relationships might change over time, as the ultimate factor of interest lies in how auditory sensitivity affects the acquisition of language and oral speech over the developmental period.

As is the case with many natural experiments involving developmentally delayed populations, large sample sizes are often difficult to find. Additionally, variability across infants is difficult to control. Although the sample size was relatively small and the variability from infant to infant was high, the sample was still sufficiently robust to allow statistical treatment of the outcomes using computational methods that account for small data sets (Raudenbush & Bryk, 2001). Some definite trends were established in this preliminary look at how auditory sensitivity affects production behaviors in moderately and profoundly impaired infants identified in the first six months of life relative to hearing infants in the same developmental period. Because the multi-syllabic behaviors are the least frequent behaviors produced by infants with profound hearing impairment, the inferences made about consonant and vowel variegation patterns need further exploration, preferably in groups with larger sample sizes.

General patterns of vocal production across these groups at a particular point in time were explored. This snapshot approach allowed an initial investigation into how the speech system variables (particularly auditory and bio-mechanical) interrelate. Average patterns were highlighted in order to increase understanding of how the hearing infant’s system becomes organized at a general level. While this initial approach provided insight into overall system organization, it blurred another aspect of system organization, that is, the effect of variability on individual developmental outcomes. Within groups, infants showed the same general tendencies. For example, all infants in Group I showed preferences for monosyllabic CV syllable alternations over singletons. However, some infants differed in the specific consonants and vowels they were producing most frequently at the time of data collection, and in preferences for individual syllable patterns. Individual differences for some patterns were not discussed in this study, but should be explored further in future studies, as variability plays an important role in understanding the process of development.

Additionally, the two groups of hearing-impaired infants tended to vary along many other dimensions. For example, the infants were referred from different geographic areas. The diagnostic tools used to diagnose and obtain auditory thresholds varied. Each infant participated in aural habilitation sessions, but the content of instruction varied as well. The involvement of the parents with their infant also seemed to vary. However, no attempt was made to quantify how much time the parent spent working with the infant outside of aural habilitation sessions. The methods employed to fit and verify amplification systems for these infants also varied. Beyond, making sure that the hearing aids were working properly throughout the data collection session, adequacy of amplification fitting could not be verified. Future studies should attempt to control these variables to determine the role they play in determining production outcomes in early-identified infants with hearing impairment.

Relationships between auditory sensitivity and production patterns using the PTA as a measure of auditory sensitivity have been explored here. As a first approximation, the pure-tone average might seem adequate to establish general peripheral auditory sensitivity. However, the PTA does not provide information about the auditory processing skills present beyond the auditory periphery. Future studies should measure auditory system development beyond the PTA, in order to determine the relationship between observed production behaviors and more accurate measures of auditory function. The clinics from which the infants were referred provided limited information outside of the routine click and tone-burst ABR. These tests were performed as initial diagnostic tools to confirm hearing loss. Additionally, for many of these infants, complete ear and frequency specific aided auditory thresholds were not available at the time of the study. As a result, it was uncertain how much of the speech signal the infant was actually receiving. Future studies should examine the correlation between signal audibility (aided thresholds) and speech production outcomes.

Whereas this study focused on the speech-like vocalization behaviors of infants, it should be noted that alternate patterns of supra-segmental behaviors were noted for many of the infants with HI. For example, many infants in the profound group had an unusually high frequency of utterances perceived as grunted, forced, aggressive, breathy, ingressive, creaky, and nasal. The level of analysis in this study did not capture these differences that are potentially related to auditory sensitivity, but should be explored in future studies, as these qualities tend to affect intelligibility of speech in adult speakers.

Conclusion

Studies of pre-linguistic vocal acquisition have suggested that many of the observed vocal patterns in typically developing infants evidence mechanical production characteristics. Specifically, these studies have suggested that mandibular oscillations may underlie the syllable-based patterns observed during canonical babbling. However, studies of “typical systems” tend to yield only the net effects produced by a cohort of contributing variables (i.e., motor, auditory, visual, and kinesthetic). It is difficult to infer the underlying role of each contributing factor, such as auditory input, on the observed vocal patterns. In order to gain more biologically meaningful knowledge about how the cohort of system variables might become organized and how each variable contributes to the observed effects, studies must also look at “different” systems, in which the cohort of variables is known to have changed from the typical system organization. To that end, the present study used a systems metaphor to evaluate production patterns in infants with varying degrees of auditory sensitivity. A systems perspective emphasizes the contribution and interaction of sub-system components to the overall complex output of the system. This approach is important for understanding how the general production system becomes organized in early vocal acquisition.

Auditory sensitivity is a key *control-parameter* determining a number of the emerging patterns of production behavior that have been used to characterize the babbling period. These results suggest a general model for how auditory sensitivity interacts with other system components in the development of pre-linguistic vocal patterns and provides a window into how the typical production system might re-organize in the absence of an important *control-parameter* such as auditory sensitivity. With changes in the degree of auditory sensitivity, some behaviors decreased in frequency of occurrence (i.e., CV syllables, high, and back vowels, dorsal consonants, and inter-syllabic place variegation) and some increased (i.e., singleton vowels, VC shapes, consonant manner variegation). The differing patterns observed in the context of severely limited auditory sensitivity suggested that the typical developing system depends on auditory sensitivity as a co-operative of the system cohort. The results of this study suggest that auditory sensitivity acts as a feedback mechanism that provides sufficient and necessary influence in driving the organization of the output of the system into the full range of typical vocal behaviors observed in hearing infants.

At the system level, auditory sensitivity plays a key role in determining the complexity of output organization in the “typical” system in hearing infants. Although syllable behaviors are suggested as being based on the nature of the production mechanism, their stochastic presence in typical systems is dependent on auditory sensitivity as well. By examining the output behavior of non-typical systems (hearing impaired infants), the extent to which auditory sensitivity contributed to characteristics proposed as being based on mechanical properties of the production system was tested. At the system level, the interaction between motor-mechanical processes and auditory input is perhaps of utmost importance, as this combined influence ultimately determines the extent to which a successful oral mode of communication is established. Infants with profound hearing impairment tend to produce very few syllable tokens. These infants also tend to have less success becoming oral language users, without the use of CI technology. Infants with moderate hearing loss produce significantly more syllables than infants with profound HI. However, despite this, the same general production disturbance patterns were apparent in moderately impaired infants. Thus, infants with moderate HI will likely also require aural habilitation strategies that promote different patterns of organization.

In addition to determining the effect of auditory sensitivity on the frequency of occurrence of syllables, specific patterns of within-syllable organization were analyzed. Intra-syllabic organization patterns were not generally affected by auditory sensitivity. Thus, when infants with profound hearing loss produced syllables, they tended to be organized according to mechanical principles observed in typically developing infants. This suggests that given sufficient auditory input, the frequency of occurrence of syllables will increase but the intra-syllabic organization of those syllables may not change, as they are more based on characteristics of the production mechanism. Inter-syllabic organization, on the other hand, might be affected by auditory sensitivity, with profoundly impaired infants producing less sequences involving place variegation. Improvements in auditory sensitivity might allow for increased diversification of combinatorial complexity across syllables. Future studies should evaluate this in more infants with profound hearing impairment.

One of the most important intervention strategies for early-identified infants with hearing impairment is timely and appropriate amplification of the speech signal. By providing early and adequate access to the signal, the re-organization of the production system might show the similar self-organizing patterns observed in typically developing infants, related to the nature and frequency of syllables and sequences in pre-linguistic vocalizations. Through adequate exposure to the specifics of the speech signal (exteroceptive and proprioceptive) the system will organize into patterns that are recognized as prominent characteristic of the babbling period. Additionally, the cycle of experience-dependent exploration and learning may be interrupted by disturbances in the auditory sensitivity. Vocalization behaviors that appear at a low frequency of occurrence in typically developing infants (those that might involve more complex manipulation of the articulators) might be more susceptible to disturbances in the auditory realm as well and might require more attention for both groups of hearing impaired infants studied here.

The observed patterns of vocal behavior are seen as resulting from interactions of system forces operating within the infant and forces external to the infant (environmental). The dynamic systems principles as well as probabilistic epigenesis accounts (Gottlieb, 1998) of development suggest that developmental outcomes are not deterministic, but are probable based on the properties of a system. This study highlighted how alternate arrangements in influential system factors (i.e., decreased auditory sensitivity) resulted in different outcomes in vocal behaviors, as well as demonstrating factors that seem resilient to perturbations in the auditory realm.

Appendix A: Infant Profiles

GROUP II

CR

Infant CR was born at 32 weeks gestational age with no reported complications during pregnancy or delivery. During an at-birth neonatal screening, he was identified and subsequently diagnosed with a bilateral, mild-to-moderate sensorineural hearing loss of unknown etiology. There was no history of familial hearing loss and there were no complications or other known causes that may have contributed to CR's hearing loss. He received behind-the-ear (BTE) hearing aids bilaterally at five months of age. CR attended aural habilitation sessions once a week to develop sound awareness and stimulate speech and language development. CR had no significant history of middle ear problems at the onset of the study. At the time of the study CR was 13 months of age and had been wearing his hearing aids for eight months. Furthermore, at the onset of the study CR was not receiving any other type of developmental intervention.

Vision, motor and cognitive development was reportedly developing normally according to information provided by the parent and aural habilitation specialist. CR's motor function was reportedly normal as he was achieving typical motor milestones on time or ahead of schedule. He began crawling at 7 months and was walking by the time of data collection, 13 months.

JH

JH was born at full term, delivered under an emergency C- section. He suffered from hyper-bilirubinemia, (a liver condition in which the infant produces too much bilirubin) shortly after birth. During an at-birth neonatal screening he was identified with potential hearing loss. He was not re-tested until three months of age, when he was diagnosed with a bilateral, moderate-to-severe sensorineural hearing loss. Subsequent genetic screening confirmed a mutation of the Connexin 26 gene. Mutations in the Connexin 26 gene are the most common cause of hereditary hearing loss and account for approximately 26% of hearing impairment in children (Hone, 2002). This mutation most often results in non-syndromic hearing loss. That is, it is not accompanied by any other complications such as blindness. It is thought that the mutation interrupts the exchange of ions in the cochlea (Hone, 2001).

JH received BTE hearing aids bilaterally at 7 months of age. At the time of the study JH was 15 months CA and had been wearing his hearing aids for 8 months. JH attended aural habilitation sessions once a week to develop sound awareness and stimulate speech and language development. JH's parents also received weekly counseling provided by the local early childhood intervention program. He had no middle ear problems at the onset of the study. However, his mother reported that he had experienced several bouts of otitis media without effusion since birth. At the onset of the study, JH was not receiving any other type of developmental intervention.

Vision, motor and cognitive development was reportedly normal according to information provided by the parent and a developmental battery administered by the state infant parent program. Infant-parent assessment showed him to be functioning at age level or better for cognitive, gross-motor, fine-motor, social and self-help measures. JH achieved typical motor milestones on time or ahead of schedule. He began crawling at 8 months and was walking at 11 months. His only delay, according to the Infant Parent Program assessment, was in the area of language. Based on the SKI*HI at 12 months of age, JH's expressive language skills were at an 8-10 month level, while his receptive language function was at a 10-12 month level suggesting a 2-4 month delay in expressive language and no delay in receptive language skills. JH's mother reports that he began saying "ma ma ma" in a repeated fashion at approximately at 8-9 months. According to his mother, he began to make "more regular and varied babbles" such as "dae dae dae" at around 11 months CA. This use of babbling vocalizations is documented in the SKI*HI Language Developmental Scale report at 12 months C.A. as follows: "…is babbling many consonant-vowel combinations with delightful intonation." At the time of data collection JH had just begun to use words referentially.

NL

NL was born at 37 weeks gestational age with no apparent complications. He passed a neonatal hearing screening prior to being discharged from the hospital. However, he returned to the hospital suffering from severe jaundice five days after birth. Following a five-day hospitalization, he failed a hearing re-screening. Subsequent diagnostic testing confirmed a mild sensorineural hearing loss in the right ear and a moderate sensorineural hearing loss in the left ear. The cause of the hearing impairment was attributed to jaundice. Thus, NL might have had normal fetal hearing based on the at-birth screening results.

NL received BTE hearing aids bilaterally at 6.5 months of age. At the onset of the study NL was 11 months CA and had been wearing his hearing aids for 4.5 months. NL wore his hearing aids approximately 7 hours per day. He attended aural habilitation sessions weekly to develop sound awareness and stimulate speech and language development. NL's parents also received weekly counseling prior to the time of data collection.

NL's vision had been screened and was reportedly normal. His motor and cognitive development had not been assessed at the time of the study. However, his mother's impression was that motor development might be slightly delayed. NL began crawling at 8 months. He had not started babbling as of 11 months of age. His mother reported that he played with vowel-like sounds mostly, as well as with raspberries. Testing performed several months after data collection, revealed that NL's hearing had improved to within the normal range, bilaterally. Consequently, his amplification devices were removed.

AM

AM was born at 32 weeks gestational age, eight weeks premature. He was an identical twin. His birth weight was 2lb, 3 oz. AM was hospitalized in neonatal intensive care unit for 1 month and his brother was hospitalized for 2 months. While AM was the healthier twin, he suffered from respiratory problems. During an at-birth neonatal screening he was identified with hearing loss. Subsequent diagnostic testing confirmed a moderate-to-severe sensorineural hearing loss, bilaterally. CT scans of the ear revealed a malformation of the cochlear partition. AM's twin brother did not suffer from hearing impairment, but suffered other complications such as severe motor and cognitive delay.

AM received BTE hearing aids bilaterally at 7 months of age. At the time of the study, AM was 14 months CA and had been wearing his hearing aids for 7 months. According to parental report AM wore his hearing aids approximately 8-10 hours daily. AM attended aural habilitation sessions once a week to develop sound awareness and stimulate speech and language development. AM's parents also received weekly counseling provided by the local early childhood intervention program.

At the time of the study AM was not receiving any other type of intervention. Initially, AM was receiving services from a physical therapist. Prior to the onset of the study AM's physical therapy services had been terminated as it was deemed these services were no longer necessary. Vision was reported as normal. At 8 months CA, AM's motor and cognitive development was assessed with the Bayley Scales of Infant Development. Results from this initial evaluation showed a mental index score of 85, within normal limits. A motor index score of 84 showed him to be mildly delayed in motor skill development. However, he achieved typical motor milestones on time or ahead of schedule. He was crawling at 8 months and walking by 13 months. AM's parents report that he began babbling at approximately 9 months CA.

EC

EC was the product of a full-term pregnancy. His mother reported a normal pregnancy with no complications during pregnancy or delivery. EC had no complications at birth. Prior to being discharged, his hearing was screened in a routine neonatal hearing screening. Hearing loss was confirmed one week later. The cause of the hearing impairment in EC was undetermined.

Initial diagnosis for EC was consistent with a moderate sensorineural hearing loss, bilaterally. However, subsequent testing at 6 months CA revealed a change in hearing thresholds in the right ear. At the time of the study it was believed that EC had a mild (25-30 dB) hearing loss in the low frequencies, sloping to a moderate (50-55 dB) hearing loss in the mid to higher frequencies, for the left ear. For the right ear a mild

(35 dB) low frequency hearing loss sloping to a severe/profound high frequency hearing loss was suspected.

EC received hearing aids bilaterally at 2.5 months of age. At the onset of the study, EC was 7 months CA and had been wearing his hearing aids for 4.5 months. A week prior to data collection, the hearing aid for his right ear was changed to one that would better fit his more severe hearing impairment. EC's mother reported that he wore his hearing aids approximately 12 hours per day. Like the other infants, EC attended aural habilitation sessions once a week to develop sound awareness and stimulate speech and language development. EC's parents also received weekly counseling provided by the local early childhood intervention program. He had no history of middle ear problems.

Vision, motor and cognitive development had not been evaluated at the onset of the study. EC had also not started crawling at the onset of the study. His mother reports that he started babbling at around 6 months CA, making babbles such as "ba, ba, ba". Several months after data collection, EC's mother reported that his hearing in the right ear improved to moderate levels.

AW

AW was born at 42 weeks gestational age with no apparent complications during the pregnancy. He was delivered through Caesarean delivery, and weighed 11 lbs. During an at-birth neonatal screening, he was identified and subsequently diagnosed with a moderate-to-severe sensorineural hearing loss in the left ear and a profound sensorineural hearing loss in the right ear. Testing performed five months after data collection revealed a change in hearing to profound loss in the left ear. He was subsequently implanted in the right ear. The etiology of his hearing impairment is unknown. He received BTE hearing aids bilaterally at 5 weeks of age. At the time of the study AW was 12 months CA and had been wearing his hearing aids for approximately 11 months.

AW's parents reported that he wore his hearing aids approximately 6 hours a day. AW was attending aural habilitation sessions once a week with one therapist and once a month with another therapist to develop sound awareness and stimulate speech and language development. Although, both of AW's early intervention programs emphasized an auditory-verbal approach, his parents were using some sign language with him in order to facilitate communication in situations in which he could not wear amplification (e.g., during bathing, car-rides). AW had a positive history of middle ear problems. He had long-term pressure-equalizing (PE) tubes placed at the age of three months. He did not have any middle ear problems during or immediately prior to data collection.

Vision, motor and cognitive development was reportedly developmentally appropriate. Delays were documented in the area of expressive language. AW began crawling at 7 months and was walking at 10 months. His parents reported that AW was very active and agile. According to an evaluation performed by an occupational therapist at 8 months, his motor development was considered to be at the 12-13 month level.

GROUP III

GW

Infant GW is a female, product of a normal full-term pregnancy. The mother reported no complications during pregnancy or delivery. Profound hearing impairment was discovered during a routine neonatal hearing screening. Diagnostic testing later confirmed a bilateral, moderately-severe-to-profound sensorineural hearing impairment. Her hearing impairment was due to an inherited autosomal recessive genetic disorder known as Deafness, Onychodystrophy, Osteodystrophy, and Mental Retardation (DOOR). DOOR is an extremely rare inherited disorder characterized by hearing impairment (Deafness), malformation of certain bones (Osteodystrophy), malformation of the nails (Onychodystrophy), and mild to severe mental retardation (Retardation). The deafness is often caused by a malformation of the inner ears. Retardation does not always accompany the syndrome. It has been suggested that GW's particular syndrome may not have involved mental retardation. She exhibited malformation of some of her fingers and had missing nails on some fingers and toes. DOOR did not appear to affect her ability to move around or manipulate objects with her hands.

GW was fit with BTE hearing aids, bilaterally at six weeks of age. GW also used an FM system coupled to her amplification devices. The FM system was used during data collection. Her mother wore a microphone that fed directly into GW's hearing aid. Whenever GW was watching television, the FM microphone would be placed near the television set so that she would benefit from an improved signal-to-noise ratio. GW wore her hearing aids approximately 11-12 hours per day. She was 16 months of age at the time of the study and had an average HA of 14 months. GW attended aural habilitation sessions once a week to develop sound awareness and stimulate speech and language development. GW had no significant history of middle ear problems at the onset of the study.

Prior to data collection, GW was receiving physical therapy services. However, at the time of the study those services were no longer being provided, as it had been determined that those services were no longer required. She began crawling at 10 months and walking at 15 months. GW began babbling after 9 months of age according to parental report. Her mother described the vocalizations as more frequent, louder, longer, and not just one syllable. GW's parents are bilingual and they speak primarily English to each other and to GW. They speak Spanish occasionally and when visiting with the grandparents.

SP

SP was born full term with no apparent complications in pregnancy or delivery. During a routine at-birth neonatal screening, she was identified and diagnosed with a bilateral, profound sensorineural hearing loss of unknown etiology. SP is the youngest of four siblings. One of her brothers was also born with profound sensorineural hearing impairment, and received a cochlear implant at the age of 3 years. Although the etiology of the hearing loss has not been confirmed, it is believed that the cause of hearing loss for both siblings might be genetic. SP received her BTE hearing aids bilaterally at 1;2 months CA. At the onset of the study infant SP was 13 months of age and had been wearing her hearing aids for 11-12 months.

According to parent report SP wore her hearing aids for approximately 6 hours per day. She was attending aural habilitation sessions once a week to develop sound awareness and stimulate speech and language development. SP had no significant history of middle ear problems during the study. Furthermore, SP was not receiving any other type of intervention during the study, as it was not deemed necessary.

Vision, motor and cognitive development (with the exception of language delays) was reportedly appropriate developmentally according to information provided by the parent. Her motor function was reportedly normal as she was achieving typical motor milestones on time or ahead of schedule. She began crawling at around 8 months but had not started walking by the time of data collection at 13 months. She could hold herself up, and walk with assistance. Parents reported that by the onset of the study most of SP's vocalizations consisted of vowel-like sounds.

MB

MB is a female, product of a normal full-term pregnancy. Her mother reports no complications during the pregnancy or delivery. Profound hearing impairment of unknown etiology was discovered during a routine neonatal hearing screening. Diagnostic testing later confirmed a bilateral, profound sensorineural hearing impairment. MB was fit with hearing aids, bilaterally at 4 months of age. Her aided responses were just within the upper levels of the conversational speech spectrum. A wireless personal FM system was added to the hearing aid fitting at age 9 months and set to receive both FM and environmental signals. The personal FM system was used during therapy sessions and throughout 60% of waking hours, according to her parents' estimation. Infant MB participated in weekly aural habilitation sessions that incorporated English-based simultaneous communication.

BB

Infant BB was identified at birth during a neonatal newborn hearing screening. He was subsequently diagnosed with a moderate-to-severe sensorineural hearing loss in the left ear and a severe-to-profound loss in the right ear. The etiology of his hearing impairment was unknown. At 12 months of age his auditory thresholds changed to profound in both ears.

Infant BB was initially fit with programmable wide dynamic range compression hearing aids at 3 months of age. Aided responses were obtained within the intensity range of the conversational speech spectrum. When Infant B's hearing decreased to the profound range, his fitting was changed to linear high gain amplification. At that time, his aided responses were just outside the conversational speech spectrum. Infant MB participated in weekly aural habilitation sessions that incorporated English-based simultaneous communication. He had no significant motor or visual delays. He wore his hearing aids for the majority of waking hours.

For infants MB, and BB, developmental milestones were attained at ages within the normal range with the exception of speech, language, and auditory skills. Each child was assessed using the Rosetti Infant-Toddler Language Scale (Rosetti, 1990). For these infants the results fell within age level for the assessment categories "interaction/attachment", "gesture", and "play." Delays were obtained in "language comprehension" and "expression."

LB

LB, was identified with a profound bilateral sensorineural hearing loss of unknown etiology at the age of 12 months. The etiology of her hearing loss is unknown as her birth and medical history were unremarkable. She received binaural amplification at the age of 13 months. She participated in bi-weekly aural habilitation sessions in which an auditory-verbal approach was used to stimulate speech and language development.

According to parental reports, LB's developmental milestones, outside of speech and language development, were achieved within the normal range. Her language skills were tested with the Rossetti Infant-Toddler Language Scale (Rossetti, 1990) at age 22 months of age. Results from that evaluation suggested a 12-month delay in language comprehension and expression.However, her performance for the assessment categories interaction/attachment, gesture, and play were appropriate for her age.

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Vita

Deborah von Hapsburg was born in Mexico City, Mexico on May 6, 1967. She is the daughter of Ferdinand von Hapsburg and Macrina Sanchéz. She completed secondary education at Westwood High School in Austin, Texas in 1986. She attended The University of Texas at Austin from 1986 to 1989, graduating with a Bachelor of Science in Communication Sciences and Disorders. She attended the University of North Texas in Denton, Texas from 1989 to 1991, graduating with a Master of Science in Audiology in 1991. During the following years she worked as a clinical audiologist in Texas, and volunteered as an audiologist on humanitarian medical missions to Mexico and Central America. She is married to Sean M. McMahon.

Permanent address: 8008 Davis Mountain Cove, Austin, Texas, 78726
This dissertation was typed by the author.