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Early Vocal Patterns in Infants with Varied Hearing Levels

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To evaluate the relative contributions of auditory perceptual access and production system characteristics to early vocalization patterns, three infants identified with hearing loss at birth were followed longitudinally for 11 months beginning at 4 to 6 months hearing age (i.e. time of post-hearing instrument fitting). The infant with moderate-to-severe unaided hearing levels produced canonical syllables comparable to those of infants with typical hearing in the same developmental period; labial consonants with central vowels and coronal consonants with front vowels. The infant whose hearing levels began in the moderate to severe range and progressed to profound during the study exhibited a shift to less mature vocal patterns. The infant with unaided thresholds in the profound range produced a higher incidence of singleton consonants and vowels than canonical syllables, almost entirely labial nasal consonants and neutral vowels. These findings indicate the importance of considering vocal patterning in planning assessment and intervention for infants identified early with hearing loss.

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Universal newborn screening programs as well as early cochlear implantation have underscored the importance of including early vocalizations in evaluating very young infants. Understanding the effects of degree of loss on quality and quantity of vocalizations can help to make optimal intervention decisions (Gillis, Schauwers & Govaerts, 2002, Yoshinaga-Itano, 2002). In addition, study of vocalizations in infants with hearing loss can increase understanding of interactions between perception and production in vocal development. This study examines early vocalization patterns in three infants identified at birth with varying degrees of sensorineural hearing loss who received amplification within the first 6 months of life.

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Prelinguistic vocal development in infants with hearing loss can be evaluated relative to language acquisition in infants with typical hearing to consider the impact of degree of auditory access on vocal development. Precanonical vocalizations in infants with typical hearing occur around 4 to 6 months and approach the consonant and vowel qualities heard in mature speech without meeting timing requirements (see Oller, 2000 for a review). Canonical babbling begins around 7 to 8 months (e.g. Davis & MacNeilage, 1995; Roug, Landberg & Lundberg, 1989). Canonical syllables are characterized as rhythmic productions of one or more consonant-vowel (CV or CVCV) sequences that sound like speech. Oller and Eilers (1988) have proposed a perceptual/acoustic definition of canonical syllables to include at least one fully resonant nucleus (i.e., identifiable vocalic resonance without nasalization), one non-glottal margin (i.e. oral closure consonants), syllable and formant transition durations and pitch and phonation ranges perceptually consistent with mature syllables. Labial and coronal place, oral and nasal stop, and glide manners of articulation predominate. Orals are far more frequent than nasals (Locke, 1983; Stoel-Gammon, 1988, Vihman, 1996). Velar place and fricative, affricate, and liquid manners of articulation occur rarely (Gildersleeve-Neumann, Davis, & MacNeilage, 2000). Favored vowels tend to be in the lower left quadrant of the vowel space (e.g., / e, ε, ʌ, ↔, æ, a/) (Kent & Bauer, 1985; MacNeilage & Davis, 1990). Diphthongs are also rare.

MacNeilage, Davis, and colleagues have proposed an articulatory basis for canonical syllables in *rhythmic close-open movements of the jaw accompanied by phonation*, resulting in alternations between closed and open vocal tract states (MacNeilage & Davis, 1993). These rhythmic close and open cycles produce a listener perception of syllable alternations between consonants and vowels (i.e. [baba] or [daedae]). Their rhythmicity supports the listener's perception of syllable-like timing in that they "sound like" speech. Davis & MacNeilage (1995) have suggested that the active articulators (i.e. the tongue and velum) do not move independently from the jaw oscillations within these early syllable-like sequences. As a consequence, three preferred within-syllable patterns emerge: labial consonants with central vowels (i.e. [ba]), coronal consonants with front vowels (i.e. [dae]), and velar consonants with back vowels (i.e. [ku]). These preferred CV co-occurrences are based on biomechanical inertia in articulators since the active articulators do not move from their preset position at the initiation of the syllable (i.e. [d] + [ae] have the same front tongue position and [k] + [u] have the same back tongue position). This perspective has been termed the "Frames then Content" hypothesis. The "frame" for the syllable in canonical babbling is created by the close-open rhythmic movements of the jaw, resulting in regularities in sound qualities perceived. Emergence of "content" is related to differentiation of individual segments from this "frame" as the infant develops more mature control of the independent articulators (i.e. tongue and velum) from the jaw cycle in the syllable.

Multisyllabic babbling takes two forms, *reduplicated* or *variegated* (e.g. Mitchell & Kent, 1990; Smith, Brown-Sweeney, & Stoel-Gammon, 1989). In *reduplication*, consonant and vowel qualities remain the same (e.g. [bababa]). In *variegation*, consonants, vowels, or both change (e. g. [daejae], [daedi], [daeji]). Variegation has also been demonstrated to conform to the "Frames then Content" hypothesis (Davis & MacNeilage, 1995) where variegation results primarily from changes in degree of jaw constriction. Change in height for vowels (e. g. [daedi] not [daedu]) or manner for consonants (e. g. [daeji] not [daeki]) is predicted, based on jaw oscillation without independent tongue movement.

Oller's "infraphonological" perspective encompasses the full spectrum of vocal qualities, accounting for all types of sound qualities that may not appropriately match the timing requirements employed for mature speech (Oller, 2000). He terms these diverse sound qualities *protophones*. In describing their characteristics he focuses on four developmental phases across the first year. In the quasivowel period (0–1 month) infants evidence normal phonation. Emergence of closure articulation within the oral tract occurs in the "going" period (2–3 months). Marginal babbling and full vowel resonance is typically exhibited around 4–5 months, reflecting capacities supporting resonance, but not rhythmic close and open alternations supporting canonical syllables. Canonical babbling at 6–7 months reflects a capacity to produce rapid formant transitions between close and open aspects of syllable-like vocalizations. Oller's proposals are relevant for understanding the emergence of vocalizations in infants with hearing loss, where various types of sound qualities may persist.

Vocal Development in Infants with Hearing Loss

Studies of children with hearing loss have shown similarities and differences relative to typical vocal development. Fewer canonical syllables and more "isolated" vowels or consonants (Oller, Eilers, Bull & Carney, 1985; Oller & Eilers, 1988; Stoel-Gammon, 1988) and delayed onset of babbling (Oller & Eilers, 1988) have been reported. Babbling onset around 11 months has been reported in infants with various degrees of hearing loss (Eilers & Oller, 1994; Stoel-Gammon & Otomo, 1986). Some infants with profound hearing loss either do not produce babble-like vocalizations (Oller & Eilers, 1988) or do not babble until much later (Gillis et al., 2002). Differences in the syllabic timing considered characteristic of canonical babbling (Oller, Eilers, Bull, & Carney 1985) are also common. Rather than maintaining a rhythmic cadence, infants with hearing loss may employ prolongation of sounds or rapid rises and falls in amplitude creating irregular, inappropriately timed patterns that do not meet the criteria of rapid formant transitions proposed for canonical syllables (Oller & Eilers, 1988; Oller et al., 1985).

Segments also differ from infants with typical hearing. Labial consonants predominate, with far lower incidence of coronals than infants with typical hearing (Davis, MacNeilage, & Matyear, 2002; Ertmer & Mellon, 2001; Oller, 1991; Stoel-Gammon, 1988). The predominance of labials in infants with hearing loss has been generally attributed to greater visual accessibility (Osberger & McGarr, 1982; Stoel-Gammon & Kehoe, 1994). Larger proportions of nasal consonants are also characteristic (Stoel-Gammon, 1988). Both acoustic and transcription studies show a restricted vowel space with a tendency toward a predominance of central vowels and fewer front or back vowels (Ertmer, 2001; Yoshinaga-Itano, Stredler-Brown, & Jancosek, 1992).

Although segmental characteristics in infants and children with hearing loss have been widely explored, *serially ordering* patterns described for infants with typical hearing have not received similar attention. To obtain a complete picture of vocalization patterns in infants with hearing loss, sequential relationships in canonical syllables should be explored. Patterns predicted by the "Frames then Content" hypothesis suggest that serial ordering patterns in canonical babbling are based on propensities intrinsic to the developing motor production system as opposed to auditory perceptual influences. This proposal has not been evaluated in infants with hearing loss.

Serial patterns have been investigated in a 25-month-old child with profound hearing loss before and after cochlear implant (McCaffrey, Davis, MacNeilage, & von Hapsburg, 2000). Prior to receiving her cochlear implant, she produced predominantly labial-nasal consonants and central vowels, and few canonical syllables. These syllables adhered to the "Frames then Content" prediction of labial consonants with central vowels. Around 7 months post-implant, canonical syllable production increased dramatically. Coronal place emerged and the vowel space expanded to include high front and a few back vowels. Coronal-front vowel CV co-occurrences emerged. Her patterns began to resemble infants with typical hearing as nasality decreased and oral vocalizations increased.

Rationale for the Study

Currently, infants with hearing loss may be fit with amplification within the first 6 months and potentially attain near-normal language milestones by school entry (Yoshinaga-Itano, 1999). Newborn screening protocols are identifying infants with more moderate hearing loss compared to techniques used at previous investigations (Joint Committee on Infant Hearing, 2000). To fully understand patterns of vocal acquisition in all infants identified with hearing loss at birth, it is important to explore the consequences of degree of hearing loss on the quality and quantity of vocalizations across the earliest developmental period after identification. This type of inquiry poses a basic question regarding the relationship between availability of auditory perceptual input and the nature of emerging vocalizations.

Little data are presently available to longitudinally assess vocal patterns in infants identified at birth with hearing loss (although see Wallace, Menn, & Yoshinaga-Itano, 2000) for a large-scale longitudinal study). Although individual analyses restrict generalization to the overall population of infants with hearing loss, these data can contribute to the information regarding early vocal development in this important emerging arena. This study is a longitudinal investigation of the vocalizations of three infants identified with hearing loss at birth and fit with amplification within their first 6 months. They presented with varied hearing levels, ranging from moderately severe through profound. These infants, in whom auditory access is compromised, offer an opportunity to evaluate types of vocalizations observed relative to degree of auditory access as well as predictions that the serial order patterns in canonical syllables, *when* CV's occur, may be similar to characteristic patterns of infants with typical hearing in earliest periods of development.

Method

Two males (Infant A and Infant B), and one female infant (Infant C) who had failed newborn hearing screening and were subsequently diagnosed between 2 to 3 months as having congenital, bilateral, sensorineural hearing loss participated. Infant A presented with stable moderate-to-severe hearing loss. Infant B initially presented with a moderate-to-severe hearing loss in the left ear and a severe-to-profound loss in the right. He experienced a bilateral decrease in hearing levels to the profound range at 12 months, confirmed by change in auditory brainstem responses. Infant C presented with a stable profound hearing loss bilaterally. Minimal unaided hearing levels based on visual reinforcement audiometry (see Table 1).

Infant A was fit binaurally with programmable wide dynamic range compression (WDRC) hearing aids. Infant B wore a programmable WDRC aid on the left and a linear aid on the right ear until his hearing decreased to the profound range bilaterally. He was then fit binaurally with a linear instrument. Infant C wore linear high gain hearing instruments binaurally. To improve the signal-to-noise ratio of acoustic input, a wireless personal FM system, set to receive both FM and environmental signals so that she could hear her own voice as well as that of her caregivers, was added to her hearing aid fitting at 9 months. Her personal FM system was used during therapy and in 60% of waking hours, according to parents.

Hearing aids were fit using average age-appropriate Real-Ear to Coupler Differences (RECD) (Kuk, 1998; Moodie, Seewald, & Sinclair, 1994) and programmed (WDRC) or adjusted (linear) using the Desired Sensation Level (DSL) method (Seewald et al., 1997) to bring the long-term average speech spectrum (LTASS) (Cox & Moore, 1988) within the infants' range of audibility as much as possible. Minimal aided soundfield responses observed using visual reinforcement audiometry is shown in Table 1.

The infants were chronologically (CA) 7 to 9 months at the beginning of the study, the approximate onset age for canonical babbling onset in infants with typical hearing (Stark, 1980). Based on their use of hearing aids, all were 4 to 6 months hearing age (HA). "Hearing age" refers to duration under

Table 1. Minimal Unaided and Aided Hearing Levels.

			Hearing Levels in dB HL (re: ANSI 1989)				
Infant	*Conditions*	*Session*	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*
A	L Unaided		65	60	70	70	60
	R Unaided		60	55	55	55	50
	L Aided		25	25	35	25	35
	R Aided		30	25	25	25	30
B	L Unaided	1		50	60	75	
	R Unaided	1		80	100	100	
	L Aided	1		30	35	45	
	R Aided	1		60	75	NR*	
		2	Auditory responses in therapy Sessions observed to decrease				
	L Unaided	3–5	NR**	120	115	120	NR***
	R Unaided	3–5	NR**	NR***	NR***	NR***	NR***
	L Aided	3–5	55	55	65	NR*	NR*
	R Aided	3-5	50	55	70	NR*	NR*
C	L Unaided		80	95	110	100	NR***
	R Unaided		75	95	105	100	90
	L Aided		25	45	50	70	65
	R Aided		20	40	45	55	45

** No response at 70 dBHL*

*** No response at 100 dBHL*

**** No response at 120 dBHL*

amplification (i.e. time of post-hearing instrument fitting). Four to 6 months is the *pre-canonical* stage, characterized by vocalizations lacking timing regularities of canonical babbling (Oller, 2000). At the end of the study, they were 19 to 20 months CA and 15 to 16 months HA, within the first word period in infants with typical hearing. Birth and medical histories were unremarkable. Developmental milestones were within the normal range throughout the study, with the exception of speech, language, and auditory skills based on results from the *Rosetti Infant-Toddler Language Scale* (Rosetti, 1990).

Infant A participated in an Auditory-Verbal intervention program. Infant B participated in an Auditory-Verbal program until his hearing decreased to the profound range. His parents then initiated a change to an English-based simultaneous communication program. Infant C's parents selected an English-based simultaneous communication program.

Fifteen 1 hour sessions were recorded monthly during aural rehabilitation therapy at a university clinic, providing comparable opportunity for vocalizations in a setting familiar to the infants and their parents. Sessions were selected for analysis to make the infants' hearing ages (HA) and chronological ages (CA) as comparable as possible. Table 2 displays CAs and HAs at each session; CAs ranged from 7–20 months and HAs ranged from 4–16 months. Sessions were separated by approximately 2 to 3 months, with the exception of a 1 month separation between sessions 1 and 2 for Infant A, and a 5 month separation between sessions 2 and 3 for Infant C. Each session included listening and vocalization-with-intent goals using play-based, developmentally appropriate materials. A parent and clinician were always present.

Vocalizations were audiotaped using a Sony® TCM-5000 portable cassette tape recorder or Tascam digital audio recorder with a Telex Pro Star FM remote microphone clipped to the shoulder to maintain a consistent mouth-to-microphone distance of about 10 inches. The FM transmitter was placed in a fanny pack secured around the infant's waist. After a few minutes of orientation to the recording equipment, infants generally ignored it. Sessions were also videotaped to disambiguate intent and content of vocalizations during transcription.

Four speech-language pathology graduate students and a faculty member trained in audiology and speech-language pathology transcribed vocalizations. Vegetative sounds (i.e. coughs, hiccups, squeals, growls, or grunts and crying) were excluded. Audiotapes were randomly distributed across transcribers. Each transcriber listened to three tapes. Transcription training sessions were conducted prior to and regularly throughout the study to assure transcriber consistency and to resolve questions about specific vocalizations and clear patterns of difference across transcribers.

Broad phonetic transcription was employed supplemented by transcription diacritics to indicate prolongation of durational characteristics perceived by transcribers as exceeding the timing requirement for canonical syllables (i.e. [m:a] indicated a prolonged closure for the [m] portion of the syllable that exceeded timing expectations for assignment to the *canonical syllable* category). Consonants were coded by labial, coronal, and velar place and oral, nasal, glide, and [h] manner of articulation categories. Vowels were coded according to height and front/back dimensions in seven categories /i, I/, /e, E/, /ae/, / ↔, ℘/, /a/, /o, /, /u, Y/.

Vocalization types were classified as *precanonical* or *canonical*, according to Oller's (2000) definition. *Precanonical vocalizations* included unspecified protophones, syllabic and prolonged consonants and vowels, /h/ + vowel combinations, and marginal syllables. The *unspecified protophone* category contained bilabial trills, unspecified syllables, and unspecified vowels lacking a sufficient percept of resonance properties to allow unambiguous categorization. Syllabic (e. g. [m]) and prolonged consonants (e. g. [m:]) and vowels differed with respect to duration as coded with the narrow transcription diacritic indicating duration. All /h/ + vowel CVs were also included in this precanonical category due to lack of oral articulation of the glottal fricative /h/. *Marginal syllables* included prolonged CV or VC vocalizations not meeting perceptual timing requirement for canonical syllables. *Canonical Syllables* were based on transcriber percept of speech-like timing regularities. Canonical CV syllables were further described as mono- (minimally CV or VC), di- (minimally CVCV or VCVC), or poly- syllabic (more than two syllable nuclei).

Frequency counts and percentages were obtained within each session for: (1) *overall frequency of vocalizations*; (2) *frequency of vocalization types:* canonical syllables and precanonical vocalizations (i.e. unspecified protophones, syllabic and prolonged consonants and vowels, /h/ + vowel combinations, and marginal syllables); (3) *frequency of canonical CV syllables* (i.e. monosyllables, disyllables, or polysyllables); (4) *consonant place and manner* including isolated consonants and canonical syllables; (5) *vowel types* including isolated vowels and canonical syllables; (6) *CV co-occurrences* in canonical syllables (analyzed by place for consonants and front-back for vowels); and, (7) *frequency of reduplication/ variegation* in canonical vocalizations of more than one syllable.

Within syllable consonant-vowel co-occurrences in canonical syllables were analyzed related to rates predicted from the frequency of occurrence of individual consonant and vowel types within the corpus of canonical CV's produced by each infant. These levels were calculated as the product of the *observed* frequency of occurrence for the individual consonants and vowels in canonical CVs (i.e. the Chi Square analysis). For example, a sample with 70% canonical CV syllables containing labials and 30% syllables containing central vowels would be *expected* to have 21% of CV syllables to be comprised of labials + central vowels (e.g. 0.7 * 0.3 = 0.21, or 21%). An observed/expected ratio was calculated. A ratio larger than 1.0 indicated that observed canonical CV co-occurrence patterns appeared at levels higher than expected by chance, based upon frequency of occurrence of individual segments in the corpus of canonical syllables.

Reduplication/variegation analysis was completed for each successive pair of canonical CV syllables in polysyllables. In utterances of more than two canonical CVs, each except the first and last was analyzed twice; once as the second of two alternations and once again as the first. There were four possible outcomes: (1) *Total reduplication*: both consonants and vowels in the two CV syllables were the same; (2) *Vowel reduplication with consonant variegation:* the vowel was the same and the consonant changed; (3) *Consonant reduplication with vowel variegation*: the consonant was the same and the vowel changed; and, (4) *Total variegation*: both consonant and vowel changed. Criteria for consonant change included place or manner of articulation changes. Criteria for vowel changes were height and front-back differences in a vowel space divided into high, mid, and low cells, and front, central, and back regions.

Reliability calculations involved two listeners from the original team who retranscribed the first 20% of utterances from each of the 15 audiotapes. One listener transcribed eight sessions; the other transcribed seven sessions. Neither listener retranscribed sessions that she had originally transcribed. In disagreements between these transcribers, the faculty member listened to the utterances with both until a consensus was reached. Consensus transcriptions were included in the data set analyzed.

Reliability was calculated as percentage agreement between first and second transcriptions. Pre-canonical/canonical syllable type agreement was 97.12%. Segmental lengthening reliability was 88.83%. Consonant reliability was 98.36% (95% agreement for consonant place and 100% agreement for manner). Vowel reliability was 91.03% (87.16% agreement on vowel place to 94.91% agreement on vowel height).

Results

A total of 3,995 syllables were analyzed. Infants A, B, and C produced 1,519, 1,155, and 1,321 vocalizations, respectively (see Table 2). Infant A produced an average of 303.8 vocalizations with a range of 245–471 per session; Infant B produced an average of 231.0 with a range of 56–738; and Infant C produced an average of 264.8 with a range of 64–559. Vocalization frequency in Infant B decreased markedly in sessions 2 and 3, during the period that his hearing levels dropped from the moderately severe to profound range. Infant C exhibited relatively low vocalization frequency in earlier sessions but increased vocalizations by the end of the study.

Vocalization Types

Table 2 displays frequencies of vocalization type occurring by session. Unspecified protophones, syllabic and prolonged C or Vs occurring in isolation, /h/ + V syllables, marginal syllables, and CV and VC canonical syllables were analyzed. "Unspecified" or non-transcribable vocalizations occurred at a relatively low frequency, with the exception of Infant A in session 2 (42.2%). Vegetative sounds occurred 27 times in 15 sessions (constituting less than 5% of vocalizations in any given session).

Isolated consonants, either syllabic or prolonged, accounted for less than 5% of Infant A and C's vocalization types, with the exception of a rate of 7.2% reported from Infant C (session 5). Infant B was the only participant using isolated consonants to any extent; 31.9% of his overall output. In session 4, isolated consonants accounted for 95.9% of his vocalizations (i.e. 708 productions of labial nasal /m/). Syllabic and prolonged isolated vowels predominated in all three infants across sessions, accounting on average for 57.7%, 53%, and 91.6% of vocalization types produced by infants A, B, and C respectively. Other pre-canonical categories (i.e., /h/ + V or marginal syllables) were produced at less than 10% in any session and less than 5% per child.

Table 2. Percentage of Vocalization Types.

						% Syllable Types								
						Pre-canonical							Canonical		
Infant	Session	CA (mo)	HA (mo)	N Utt.	N Syll.	Unspecified* Proto-phones	Syllabic C	Prolonged C	Syllabic V	Prolonged V	H + Vowel	Marginal syllables	CV	VC	CBR
A	1	9	4	121	471	14.9	0.6		38.2	13.4	0.4	1.1	31.4		0.31
	2	11	6	176	268	42.2	0.4	0.4	29.5	7.5		1.1	16.8	2.2	0.19
	3	14	9	212	272	1.8	2.9	0.7	64.0	7.7	7.0	0.4	15.4		0.15
	4	17	12	127	263	0.4			72.6	7.6	1.5	1.1	16.7		0.17
	5	20	15	148	245		1.2	0.4	41.6	6.5	1.6	3.3	45.3		0.45
	Mean			156.8	303.8	11.9	1.0	0.3	49.2	8.5	2.1	1.4	25.1	0.4	0.26
B	1	10	6	103	108		4.6	0.9	42.6	45.4	2.8		3.7		0.04
	2	11	7	49	82	6.1			30.5	28.0	1.2	3.7	1.2	29.3	0.30
	3	14	10	39	56		16.8	26.8	32.1	12.5				1.8	0.02
	4	17	13	525	738		80.9	15.0	2.0	1.5		0.1	0.1	0.3	0.00
	5	19	15	56	171		11.1	3.5	59.1	11.1	8.8	0.6	2.3	3.5	0.06
	Mean			154.4	231.0	1.2	22.7	9.2	33.3	19.7	2.6	0.9	1.5	7.0	0.08
C	1	7	4	142	213	5.2		0.9	62.4	31.5					0.00
	2	9	6	104	144	1.4			76.4	22.2					0.00
	3	14	11	60	64				70.3	29.7					0.00
	4	16	13	182	341		1.2	1.5	79.5	10.3		0.3	7.3		0.07
	5	19	16	248	559	1.8	4.5	2.7	60.1	15.7		2.2	11.6	1.4	0.13
	Mean			147.2	264.2	1.7	1.1	1.0	69.7	21.9		0.5	3.8	0.3	0.04

*Unspecified – could not be transcribed using IPA

Frequency of canonical syllables varied across infants. CV syllables were far more likely than VC syllables. VCs appeared at a mean rate of 2.6% across sessions. Only Infant A produced a substantial number of *canonical* CV syllables, ranging from 15.4% to 45.3% and averaging 25.1%. A canonical babbling ratio (CBR; Oller & Eilers, 1988 was calculated for each infant for each session. Infant A achieved CBR values ranging from .15 to .45. Ratios below the .20 used to mark the onset of canonical babbling in infants with typical hearing occurred in three of five sessions. Infant B showed a CBR of .30 in session 2, before his decrease in hearing sensitivity. All other CBRs were in the range of .0-.08, indicating that he did not achieve consistent use of canonical syllables relative to other types of vocalizations throughout the whole period. His most frequent output was isolated vowels, balanced between "syllabic" vowels (speech-like durations) and "prolonged" vowels. Infant C produced almost no canonical syllables. In session 5 when she was 19 months CA and 16 months HA, she produced a .13 CBR.

Canonical Syllables

Table 3 lists canonical CV syllables categorized by frequency of mono-, di-, and poly-syllables. Infant A produced canonical syllables in each session and was the only participant for whom a mean number of syllables per utterance was calculated. The majority of canonical syllables produced by all three infants were di- and polysyllables, accounting for a mean 82.5% of Infant A's canonical syllables.

Consonant Types

Table 4 lists percentages of consonant types categorized by place and manner. Place was coded according to labial, coronal, and velar and manner by plosives, nasals, or glide categories. Fricatives and liquids occurred at frequencies less than 5%. The fricative /h/ was, however, observed with some frequency. It appears as a separate manner category as it represents a non-oral closure. Infant A produced a sufficient number of consonants to permit mean calculations.

Infant A produced the most diverse manner and place characteristics. There were more coronals than labials or velars, although all three place categories were observed in each session. Oral consonants exceeded all other manners of articulation. Overall, Infant B produced a larger percentage of labials than all other places of articulation. However, some coronals and velars did appear in sessions 1–3 just prior to and after his decrease in hearing, accounting for 6.25% of consonants across the three sessions. Nasal manner dominated Infant B's productions, although oral consonants and [h] were produced in sessions 1 and 2, and to a lesser extent, [h] appeared in session 5. Infant C produced the labial nasal [m] almost exclusively across the entire study.

Table 3. Percentages of Monosyllabic, Disyllabic, and Polysyllabic Canonical CV Syllables.

			% Canonical Utterance Types		
Infant	*Session*	*N*	*Monosyllabic*	*Disyllabic*	*Polysyllabic*
A	1	148	0.7	4.1	95.3
	2	45	15.6	17.8	66.7
	3	42	59.5	40.5	0.0
	4	44	11.4	56.8	31.8
	5	111	11.7	35.1	53.2
	Mean	78.0	19.8	30.9	49.4
B	1	4			100.0
	2	1			100.0
	3	0			
	4	1	100.0		
	5	4			100.0
C	1	0			
	2	0			
	3	0			
	4	25	12.0	16.0	72.0
	5	65	12.3	30.8	56.9

Table 4. Percentage of Consonant Types by Place and Manner of Articulation.

			% Place			*% Manner*			
Infant	*Session*	n	*Labial*	*Coronal*	*Velar*	*Oral*	*Nasal*	*Glide*	*[h]*
A	1	141	21.3	49.6	29.1	51.8	2.8	44.7	0.7
	2	55	21.8	72.7	5.5	72.7	20.0	7.3	
	3	77	18.2	45.4	36.4	42.9	15.6	10.4	31.2
	4	51	17.6	58.9	23.5	58.8	5.9	27.4	7.8
	5	120	6.6	84.2	9.2	70.0	10.8	15.8	3.3
	Mean	88.8	17.1	62.2	20.7	59.2	11.0	21.1	8.6
B*	1	16	81.2		18.8	25.0	56.2		18.8
	2	2			100.0	50.0			50.0
	3	32	90.6	9.4			100.0		
	4	712	100.0				100.0		
	5	47	74.5		25.5		74.5		25.5
C*	1	2	100.0				100.0		
	2	0							
	3	0							
	4	35	100.0			2.5	97.5		
	5	125	98.4	1.6			87.1	12.9	

** Mean values were not calculated for Infants B and C because the overall frequencies were too low.*

Vowels

Vowels are reported in Table 5, categorized according to height and front/back dimensions. Infant A produced all categories of vowels. Mid and low vowels accounted for over 70% of vowel height categories across all sessions. Mid vowels exceeded low vowels except in session 1. Central and front vowels predominated in the front/back dimension. Front vowels exceeded central vowels in three of five sessions. Concurrent with increases in back vowels, the combined occurrence of central and front vowels diminished from 90% in session 1 to 59.7% in session 5. Diphthongs were rare until session 5 when they accounted for 13% of all vowels.

Infant B's vowel patterns can be described in two periods. Vocalizations prior to and just after his decrease in hearing acuity consisted predominantly of low vowels with a secondary use of mid vowels. Front followed by central vowels predominated in the front/back dimension. Session 4 was noteworthy for an almost complete absence of vowels (only one token). In session 5 vowels were mid/central. Vowels were so different in sessions 4 and 5 in comparison to sessions 1–3 that means were not calculated. Diphthongs occurred only in session 1; four out of 100 vowels.

Infant C produced vowels in the mid and low vowel height and front and central front/back dimensions. Low vowels tended to outnumber mid vowels and front vowels tended to outnumber central vowels, until session 5 when a small corpus of labial consonants and CV/VC syllables were produced incorporating a majority of mid and central vowels.

Intrasyllabic Organization

Infant A was the only participant to produce a sufficient number of canonical syllables to permit observation of either intra- or intersyllabic serial organization tendencies. These were observed by comparing rates of consonant-vowel co-occurrences within canonical syllables to rates expected based on frequency of occurrence of individual consonants and vowels in his corpus. Ratios greater than 1.0 indicate that a CV pattern appeared at a greater than chance level. Three CV co-occurrence patterns are predicted by the "Frames then Content" hypothesis (MacNeilage & Davis, 1990) to occur at above chance levels: labials with central vowels, coronals with front vowels, and velars with back vowels. Table 6 shows the obtained CV co-occurrence ratios for Infant A. Labial consonants were paired with central vowels, coronals with front vowels, and velars with central and front vowels at rates greater than chance. The overall distribution of his CV co-occurrence patterns was statistically significant.

Most of the back vowels produced by these three infants appeared as isolated vocalizations rather than in canonical syllables. Of the 249 back vowels produced by all three participants, 215 occurred in isolation (86%). Only 34

Table 5. Vowel Percentages by Height and Front/Back Dimensions.

Infant	Session	n	*Height* High	Mid	Low	*Front/Back* Front	Central	Back	Diphthongs
A	1	276	24.3	24.7	50.2	67.5	22.5	9.2	0.8
	2	153	19.3	44.6	36.1	47.7	43.9	8.5	
	3	263	14.4	44.8	40.1	40.2	44.7	14.4	0.7
	4	261	15.4	66.5	16.9	28.1	48.8	21.9	1.2
	5	243	8.4	43.4	31.8	38.5	21.2	23.9	16.4
	Mean	239.2	16.4	44.8	35.0	44.4	36.2	15.6	3.8
B*	1	100		20.0	70.0	71.0	18.0	7.0	4.0
	2	76	2.8	29.0	68.2	69.5	29.1	1.4	
	3	40		36.8	63.2	65.8	34.2		
	4	1		100.0			100.0		
	5	200	3.9	96.1			96.1	3.9	
C	1	200	0.5	23.4	75.2	70.1	28.5	0.5	0.9
	2	142		42.2	57.1	56.4	42.9		
	3	76		44.7	55.3	50.0	50.0		
	4	332	5.7	43.5	50.8	53.5	42.9	3.6	
	5	520	5.8	61.8	31.6	41.7	53.5	4.1	0.8
	Mean	254	2.4	43.1	54.0	54.3	43.6	1.6	0.3

* *Mean values were not calculated for Infant B due to variability across sessions.*

Table 6. Ratio of Observed to Expected Frequencies of Co-occurrences of Labial, Coronal, and Velar Consonants with Central, Front, and Back Vowels for Infant A.

Infant	Consonant	*Vowel* Central	Front	Back
A	Labial	**1.12**	0.84	0.18
n=405	Coronal	0.95	**1.04**	0.91
	Velar	**1.09**	**1.7**	0.7

occurred in canonical syllables. Infant A produced most of the back vowels (166/ 195 or 85%) in isolation.

Inter-syllabic Organization

Infant A's use of total reduplication decreased with longer syllable sequences from an average of 78% in Syllable 1-Syllable 2 sequences to 40–50% in later occurring syllable pairs. When he variegated, he predominantly changed vowels (81%). Vowel variegation was largely in the *height* rather than front-back dimension, as predicted by the "Frames then Content" hypothesis (related to jaw height changes rather than tongue front back changes for vowels). Infant A did not variegate consonants frequently, although variegation increased from 0 to 13% as utterance length increased. When he variegated consonants, manner changed rather than place most often, as predicted. Infants B and C produced few long utterance sequences and showed total reduplication for both consonants and vowels.

Discussion

Vocalization patterns were described longitudinally in three infants with differing degrees of hearing loss identified and fit with hearing instruments in the first 6 months of life. This population of infants identified early with varying degrees of hearing loss will present new challenges for assessment and habilitation. Understanding of their patterns of vocalization development can help to design and implement assessment and intervention protocols. Although these findings are based on three case studies, results can contribute to the needed dialogue on the unique nature of vocal development in these young children. It also points to fruitful areas of inquiry for work with larger participant populations.

These infants vocalized at approximately the same frequency, regardless of differences in auditory threshold. When all types of vocalizations were accounted for, rate of vocalization did not appear to relate to auditory threshold. The CBR was largely below the .20 levels reported for infants with typical hearing in the 7–12 month range, suggesting that vocalizations were less mature than the canonical syllables typical of infants with typical hearing by 12 months (Davis & MacNeilage, 1995). The mouth close-open alternation should be visually apparent. It has been noted in infants with typical hearing and with hearing loss as "silent jaw wags" (Meier, McGarvin, Zakia, & Willermann, 1997). In infants with hearing loss (even for Infant A with the mildest degree of loss), it may not be supported by sufficient simultaneous auditory input to result in consistent use of canonical vocalizations. Data on more infants relative to degree of hearing loss is needed to clarify the issue of distribution of vocalization types in infants with hearing loss. Analyses should properly include all vocalization types to understand the relationship between canonical and non-canonical vocalizations in the emergence of speech production capacity.

Consistency and frequency of canonical syllables was related to hearing level. Infant A produced canonical syllables more consistently and frequently than Infants B and C (CBR range, .15 to .45). Infants B and C continued to produce isolated consonants or vowels. Infant B produced mostly isolated consonants and some syllables when his aided hearing levels fell within the conversation speech spectrum. His highest CBR was .30, before his decrease in hearing acuity. CV syllables did not reappear until his hearing age was much greater. Infant C produced almost all isolated vowels. Her few canonical syllables did not occur until her hearing age was greater. However, all three infants produced *some* di- and poly-syllables in all sessions. Like consonant onsets, multiple alternations of consonants and vowels appear to be robust enough to appear even in the absence of intact auditory perception. This has been noted in other research on infants with profound hearing loss (e. g. Lynch, Oller, & Stephens, 1989). Future research with larger groups of infants with hearing loss should evaluate whether diverse utterance types appear in this early period.

However, it should be noted that in canonical syllables, consonant onsets were predominant. As in infants with typical hearing, the predominance of consonant onset is characteristic of syllabic output. Predominance of CV over VC onsets is also typical of most languages (Bell & Hooper, 1978). The propensity for onset from a mouth close position in CV syllables seems resistant to the sensory perceptual differences in these infants. This pattern may be seen as an intrinsic characteristic of the production mechanism unperturbed by sensory differences. These findings are consistent with Wallace and colleagues (2000) who studied 20 infants who are deaf or hard of hearing. Their results also supported a production-based explanation for canonical babbling.

Segmental qualities showed the interaction of audition and vision with production system effects. Infant A produced predominantly coronal and labial place and oral stop and glide consonant manner articulation as reported for infants with typical hearing. Infants B and C produced labial-nasal consonants almost exclusively, frequently attested in children with hearing loss. High labial frequencies are consistent with previous reports on older children with severe-to-profound hearing loss (Ertmer & Mellon, 2001; Locke, 1983; Stoel-Gammon, 1988). In contrast, in infants with typical hearing coronal stops occur with the highest frequency in babbling (Stoel-Gammon, 1985). Visual information is available regarding labial but not coronal closure. However, the labial preference may not be attributable to visual input from adults, as lip closure is not the most common closure mode (i.e. coronals predominate, Maddieson, 1994). Neither visual nor auditory perception is clearly responsible for the predominance of labials in these three infants.

Vowels showed an effect of degree of hearing loss. Infant A produced front and central, and mid and low vowels and a few high back vowels, consistent with patterns for infants with typical hearing (e.g. Kent & Bauer, 1985). Infant B produced mostly low, front or central vowels and more central vowels after his decrease in auditory sensitivity. Infant C produced central vowels throughout. Infant B and C's strong preference for neutral and front vowel qualities may be related to lack of auditory access to acoustic characteristics of particular vowels. It is commonly assumed that central vowels are also a default mode resulting from lack of visual and auditory information about non-central vowel qualities. The "Frames then Content" prediction suggests that these default labial closings and central vowel openings result from rhythmic jaw cycles without independent movements of other articulators. A labial consonant-central vowel pairing could occur with labial closure and following open phase without change in tongue position.

From the "Frames then Content" perspective (MacNeilage & Davis, 1990), CV co-occurrences in canonical syllables are seen as being based on rhythmic jaw close and open cycles without the necessity of independent movements of other articulators. Infant A, with the greatest degree of residual hearing, produced predicted labial-central and coronal-front CV co-occurrences. Velars did not follow the predicted back vowel association patterns. However, almost all of his back vowels were produced alone. Most canonical syllables produced were largely based on minimal movement of articulators other than the jaw within the syllable.

Infants B and C, with the least residual hearing, produced reduplication in virtually all instances of utterances containing more than one syllable. Similar to infants with typical hearing, Infant A produced reduplication *and* variegation. Although he mostly reduplicated, variegated utterances showed the "Frames then Content" predicted predominance of height over front-back changes for vowels, indicating changes in degree of jaw closure rather than in independent tongue movement He produced little consonant variegation. However, manner variegation occurred more frequently than place, indicating more variation in jaw height than in tongue front back movement, as predicted from the "Frames then Content" hypothesis.

Interpretation of these findings assuming relative auditory access to speech must, however, be cautiously submitted. Data regarding aided performance merely indicates the lowest intensities at which each participant was reported to respond to sound by the audiologist. Without probe microphone measures of hearing aid output, we cannot conclusively describe bandwidths in the LTASS potentially available to a listener. Nevertheless, differences between Infant A and Infants B and C suggest that the vocalization outcomes of listening through a hearing aid with moderate-to-severe hearing loss are distinct from profound deafness.

Implications

These results have implications for assessment and intervention procedures. Current assessment procedures (e.g. Levitt, Youdelman, & Head, 1990; Ling, 2002; Moog, Beidenstein, & Davidson, 1995) do not consider spontaneous vocal output but frequently focus on imitation of single sounds, syllables, then on sequences of non-meaning based syllables. Assessment approaches relying on functional spontaneous output for assessment of oral development are needed, as early identified infants may not as easily comply with imitation tasks. Patterns noted in these three infants' vocalizations could contribute to build expectations for vocal patterning related to degree of hearing loss, even when children are aided early.

Earliest phases of intervention for children with hearing loss have frequently emphasized production of vowels and consonants in syllables without reliance on knowledge of typical developmental sequences. In addition to stimulating pre-canonical vocalizations, the serial order patterns noted in canonical vocalizations from these infants suggests that assessment and treatment profiles might profit from assessing and stimulating serial regularities seen in infants with typical hearing at the onset of babbling. Infants with typical hearing do not consistently produce vowels and consonants independently of each other in canonical babbling. Sequential patterns seen in babbling and first words can be introduced in vocal play by parents and clinicians using lexical models containing within-syllable regularities of labials with central vowels, coronals with front vowels, and velars with back vowels. Additionally, vocal play might begin with reduplicated patterns (e. g. [bababa], followed by variegated patterns incorporating manner changes for consonants (e; g; [bawa]) and height changes for vowels (e. g. [daedi].

Confirmation of these patterns in a larger cohort of infants is needed to generalize these findings. However, patterns persisting across the study in these three infants highlight important factors for understanding acquisition of speech production skill not apparent from studies of infants with typical hearing. Level of auditory access is important to understanding differences in these infants. However, production system patterns that seem resistant to auditory deficit, such as the within syllable associations in canonical syllables, point to intrinsic characteristics of the production system common to both infants with typical hearing and infants with hearing loss. Types of vocalizations observed can produce expectations for development of assessment and intervention protocols for this growing population of young infants identified with hearing loss.

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