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Frame Dominance in Infants with Hearing Loss

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Abstract

Purpose: According to the Frames, then Content hypothesis (MacNeilage & Davis, 1990), the internal structure of CV syllables during canonical babbling is determined primarily by production system properties related to rhythmic mandibular oscillations (Motor Frames). The purpose of this study was to investigate the role of auditory input in emerging canonical syllables during the babbling period. Method: the internal structure of spontaneous CV syllables produced by 13 infants with varying degrees of hearing sensitivity (normal hearing (n=4), mild-to-moderately-severe loss (n=6), and severe-to-profound loss (n=3)) was investigated. Results: Specifically, the coronal-front association was confirmed in 69% of the infants. The labial-central association was confirmed in only 38% of the infants, primarily those with normal and severe-to-profound hearing sensitivity. Additionally there was no association between the infants' PTA and any pattern of CV co-occurrences. Conclusions: Frame dominance was observed in the majority of infants. These results suggest that auditory sensitivity may not influence intra-syllabic organization within CV syllables once infants obtain sufficient auditory input to begin canonical babbling. However, large variability was observed across the infants, especially those with mild-to-moderately-severe hearing sensitivity.

Frame Dominance in Infants with Hearing loss

The link between auditory-perceptual and motor processes in early speech development is not yet well understood. Evidence from naturally occurring production and physiologic experiments together with computational models of the developing speech production system suggest a strong association between perceptual and motor processes in early speech development (Callan, Kent, Guenther & Vorperian, 2000; Green, Moore, & Reilly, 2002; Oller & Eilers, 1988; Westermann & Miranda, 2003). Infants identified at birth with varying degrees of hearing loss offer a natural opportunity to study the relationship between perceptual input and the emergence of vocalization patterns in the canonical babbling period.

Previous studies of infants with hearing loss have demonstrated that many aspects of their vocalizations are affected by reduced hearing sensitivity (e.g., Eilers & Oller, 1994; Koopmans-van Beinum, Clement, & van den Dikkenberg-Pot, 2001; Oller & Eilers, 1988; Stoel-Gammon, 1988; Stoel-Gammon & Otomo, 1986; Ertmer, Strong, & Sadagopan, 2003). Canonical babbling, marking the first appearance of rhythmic syllable-like output, is often considerably delayed in infants with hearing loss relative to acquisition milestones in hearing infants (Eilers & Oller, 1994; Oller & Eilers, 1988). Additionally, infants with profound hearing loss are reported to have reduced canonical babbling ratios. The canonical babbling ratio (CBR) is the ratio of number of canonical syllables to overall utterances (Oller & Eilers, 1988). The CBR for infants with severe-to-profound hearing loss is lower relative to hearing infants, even when they have reached the canonical babbling stage (Davis, Morrison, von Hapsburg & Warner-Czyz, 2005). Eilers and Oller (1994) found that the CBR in infants with severe hearing loss is not consistent over time and may not progressively increase as is typically observed in hearing infants.

Transcription studies of early vocalization patterns have also suggested that infants with profound hearing loss tend to produce a higher proportion of glottal stops than infants with normal hearing (Oller, 1991; Stoel-Gammon & Otomo, 1988). However, the internal organization of canonical CV syllables has not been studied extensively in infants with early-identified hearing loss. Understanding the nature of syllable-level organization in rhythmic speech-like vocalizations is crucial to tracing potential contributions of auditory perception to the emergence of basic properties underlying speech production acquisition.

One production system based model of speech acquisition, the Frames then Content (F/C) hypothesis (MacNeilage & Davis, 1990; Davis & MacNeilage, 1995), suggests that the internal organization of canonical syllables, (i.e., consonant-vowel co-occurrences within a CV or VC canonical syllable) is primarily derived from rhythmic mandibular oscillations ("Motor Frames") with little independent movement of other articulators within canonical syllables (Davis & MacNeilage, 1995). This hypothesis emerged out of observations that hearing infants tend to show evidence of high articulatory compatibility between the consonant and vowel-like qualities occurring within canonical syllables in babbling (Davis & MacNeilage, 1995) and early speech (Davis, MacNeilage, & Matyear, 2000). 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 in this early phase of speech development. The closed phase of the mandibular cycle produces the percept of consonant sounds and the open phase gives the percept of vowel-like sounds. Three types of syllable-internal consonant-vowel co-occurrences are predicted from the F/C concept: labial consonants with central vowels (e.g., [ba]), front consonants (coronal) with front vowels (e.g., [di]), and back consonants (dorsal) with back vowels (e.g., [gu]). These patterns were first observed in typically developing infants with an English language background during both babbling and first words (Davis & MacNeilage, 1995, 2000). They have also been widely observed in other language environments (see Davis & MacNeilage, 2002, for a summary). Neurophysiological studies of the development of motor control during this period have shown that the mandible develops prior to other articulators and achieves maturity or adult-like characteristics between one and two years of age, prior to any other articulator, including the upper lip and lower lip (Green et al., 2002), consistent with the frame dominance concept. However, the extent to which these syllable-internal patterns are influenced by degree of auditory sensitivity has not been explored extensively.

Davis, Morrison, von Hapsburg, and Warner Czyz (2005) studied the early vocalization patterns of three infants who were identified at birth and received early intervention. The three infants varied in hearing levels, one with moderate hearing loss, one with moderate loss at the beginning of the study and whose loss progressed to profound, and a third infant with severe-to-profound loss. The vocalization development of these infants was followed longitudinally for 11 months. Only the infant with moderate hearing loss evidenced canonical syllables; they contained the predicted coronal-front and labial-central co-occurrences. The infants with more severe loss were not producing mature syllables during the period of analysis. Thus, currently there is little information available regarding the effect of varying degrees of hearing loss on the internal organization of CV canonical syllables in babbling.

The present study was undertaken to evaluate the role of audition on the emergence of internal syllable organization patterns in infants identified in the first year of life with hearing loss. First, canonical syllables of CV shape were analyzed to determine whether the expected CV associations were present in infants with hearing loss. Additionally, the relationship between degree of hearing sensitivity and CV co-occurrence patterns predicted by the Frame/Content perspective was explored. It was expected that hearing sensitivity would not affect frame dominance in infants with hearing loss once they were babbling, as intra-syllabic organization is thought to be determined primarily by motor factors and not perceptual factors.

Method

Participants

Thirteen infants with pure-tone averages ([PTA], the average of hearing thresholds at 500Hz, 1000 Hz, and 2000 Hz) ranging from 25 dB HL to 120 dB HL in the better hearing ear participated. Four infants exhibited hearing sensitivity within normal limits in at least one ear as suggested by soundfield screening at 25 dB HL. Six infants had mild-to-moderately-severe sensorineural hearing loss, bilaterally. Three infants had severe-to-profound sensorineural hearing loss, bilaterally. Table 1 describes participant demographic characteristics. For purposes of description ease, the infants are grouped according to the PTA in the better hearing ear as follows, normal (PTA = 25 dB HL), mild-to-moderately-severe (PTA= 26-70 dB HL), and severe-to-profound (PTA > 71).

Infants with normal hearing. Data from four (M=2, F=2) infants with normal hearing who participated in a larger study of early speech acquisition reported by Davis and MacNeilage (1995) were used for comparison with the hearing impaired groups (for more details on these infants see Davis & MacNeilage, 1995 a). The average age of the hearing infants was 12.3 months (range = 11-14 months). This age range was chosen to match the average chronological age of the infants with hearing loss. It was also the age at which the hearing infants were still producing a predominance of canonical babbling. Only pre-linguistic vocalizations were analyzed, although two infants (R and N) were entering the first-word stage, based on parent report of spontaneous word use. Tokens believed to be words were not analyzed. All infants in this group passed a sound field hearing screening at 25 dB HL for the frequencies 500-4000 Hz.

Because these infants were screened in the sound-field, it is possible that unilateral losses might have been missed. However, these infants were followed longitudinally over 3 years and developed speech and language normally.

Infants with hearing loss. Data were collected for 9 (F = 3, M = 6) infants with bilateral sensorineural hearing loss. The six infants with bilateral mild-to-moderately-severe sensorineural hearing loss (mean PTA = 47 dB HL in the better hearing ear) were all male. Table 2 shows the PTAs obtained for each ear, for each participant. Because the infants were referred from multiple centers, there were varying amounts of audiological information available in each infant's record. Audiometric threshold information also varied with some having only sound field information at select frequencies, and others yielding ear-specific data at many of the audiometric frequencies, binaurally. Infant AM had missing information at 2 kHz bilaterally, therefore a two-frequency PTA (500 Hz and 1000 Hz) was used to calculate his PTA. The average age at which the infants received their first hearing aids was 4.9 months. Average chronological age at the onset of the study was 12 months (range = 7-15 months). The average hearing age (i.e., time since hearing aid fitting) was 7.1 months (range = 4.5 - 10.8 months).

Three infants with bilateral, severe-to-profound sensorineural hearing loss (mean PTA = 102 dB HL in the better ear) participated (see Table 2 for auditory threshold information). Infants with severe-to-profound loss were, on average, five months older than those with mild-to-moderately-severe hearing loss or those with normal hearing. Additionally, the hearing age of these infants exceeded that of the infants with mild-to-moderately severe loss by approximately five months, but approximated that of the infants with normal hearing. For some infants in the severe-to-profound group, no response was obtained at the limit of the audiometer, at some frequencies. Table 2 shows these as no response "NR (120 dB HL)". The average chronological age of infants with severe-to-profound hearing loss was 18.7 months (range = 16-24 months) and their average hearing age was 13.3 months (range =11-14 months). The average age of amplification was approximately 5.3 months (range = 1.5-13.0 months).

Infants were referred to this study from three cities in the southern United States. All participants had hearing parents who used oral communication. All except for one infant (GW) were from English speaking homes. Infant GW was from a bilingual Spanish/English home. None of the infants demonstrated severe motor or cognitive delays, although some showed mild motor delays based on available testing.

All of the hearing impaired infants were attending oral/aural habilitation sessions at least once a week. A description of the severity of hearing loss for each infant was obtained from case histories and medical/audiological records provided by parents. Click and tone-burst auditory brainstem response audiometry was used for initial diagnosis and confirmation of hearing loss. All participants had hearing and hearing aid evaluations performed by the audiologist at their local clinic within a month of data collection. Behavioral pure-tone information was obtained either in the sound field or through headphones by the referring clinics. With the exception of one infant, all hearing aids were fit using probe microphone procedures (real-ear-to-coupler difference, RECD) and the Desired Sensation Level (DSL; Cornelisse, Seewald, & Jamieson, 1995) procedure. All participants wore behind-the-ear (BTE) hearing aids binaurally. Parents and the investigator monitored hearing aid function (i.e., made sure the hearing aid batteries were working, listened to the hearing aids, and monitored hearing use) immediately prior to data collection. Prior to data collection, hearing aid batteries were tested and a listening check of the hearing aids was performed to determine function.

Data Collection

Recording. All infants were video and audio recorded with a wireless microphone (Audio Technica ATW-1030 or a Telex ProStar FM remote microphone) clipped to one shoulder of a bib specially made to hold the wireless receiver. All data except for one infant was recorded on digital audio recorders (Sony TCM-5000 or Tascam DA-P1). Once the microphone and receiver were in place, infants were not typically aware of their presence. The investigator observed the infant and parent interact, mostly in their home, while monitoring the equipment and interacted only as needed for equipment adjustments.

The amount of data collected for each infant varied according to parent availability and vocalization volubility. Data were collected at home or during aural habilitation sessions conducted in center-based environments. Data collection did not exceed a period of one month per child. A total of 360 (Mean = 90), 869 (Mean = 144), and 338 (Mean = 113) minutes of data were analyzed for infants with normal, mild-to-moderately-severe, and severe-to-profound loss, respectively. Table 3 shows the number of minutes, utterances, canonical syllables, and CBR (ratio of the number of canonical syllables per total number of utterances) for each infant. All infants were in the canonical babbling stage according to the criterion (CBR >.2) described by Oller and Eilers (1988).

Transcription. Data were transcribed using the International Phonetic Alphabet (IPA) system of notation (1996). The primary investigator transcribed data for the infants with hearing loss. Tokens were digitized, and played back through Sony MVR-V500 headphones. Video was used only to corroborate unclear tokens on the audio recordings, or to verify lip rounding when there was uncertainty. Data for typically developing infants was originally transcribed by four transcribers trained in infant vocalization sampling (Davis & MacNeilage, 1995).

Broad transcription of canonical CV syllables was analyzed. Designation of canonical syllable was based on perceptual judgment using Oller and Eilers (1988) perceptual definition for a canonical syllable. Canonical syllables had (1) at least one fully resonant nucleus (i.e., vowel with an identifiable quality), (2), one non-glottal margin (consonant other than glottal stop or glottal fricative), (3) duration of syllable and formant transitions that fit within the range of mature syllable production (perceptually), and (4) normal phonation and pitch range. Oller (1986) provides acoustic parameters for each of these aspects of the syllable. However, acoustic analysis was not performed to verify categorization of canonical syllables. Therefore, it is possible that some slow-transition syllables, known as marginal syllables, were included in the analysis. Reliability for canonical versus non canonical syllable judgments was high, suggesting that the likelihood of categorizing marginal syllables as canonical syllables may have occurred infrequently.

For consonants, three places of consonantal articulation were specified: labial (i.e., [p, b, m, w, β]), coronal (i.e., [t, d, n, z, s, ʒ, θ, ð, ʃ, tʃ, dʃ, l, j]), and dorsal (i.e., [k, g, ŋ, x]). Glottal and uvular consonants were excluded from this analysis. Consonants were also classified in terms of the following manner categories, plosive (i.e., [p, b, t, d, k, g]), nasal (i.e., [n, m, ŋ]), fricatives and affricates (i.e., [β, f, v, z, s, ʒ, θ, ð, ʃ, tʃ, dʃ, h, x]), and approximants (i.e., [l, ɹ]). All phones were transcribed regardless of whether they are phonemes in English. (i.e., [i, ɪ, e, ɛ, y, æ]), central (i.e., [ə, ʌ, a]) or back (i.e., [u, ʊ, o, ɔ, ɑ]). Vowels were also classified by height as high, (i.e., [y, i, ɪ, u, ʊ]), mid (i.e., [e, ɛ, o, ɔ, ə, ʌ]), or low (i.e., [æ, a, ɑ]). Vocalizations separated by approximately one second were considered to be different utterances. Sound Studio Classic software (Kwok, 2001) was used to verify utterance boundaries.

Data Analysis

Intra-syllabic Organization. Data were analyzed using the Logical International Phonetics Programs (LIPP, Oller & Delgado, 1990). For analysis of CV co-occurrence patterns consonants and vowels within a CV syllable were grouped according to place of articulation. Consonants were divided into one of three places: labial, coronal or dorsal. Vowels were divided into one of three dimensions: front, central, or back. Thus, an inventory of CV syllables with labial, coronal, and dorsal consonant onsets was created for analysis.

Reliability. Twenty percent of each infant's tokens were randomly chosen and digitized on a DAT tape. A phonetician with over 10 years experience transcribing hearing and hearing-impaired infant vocalizations re-transcribed these tokens. Both the first author and the phonetician participated in bi-weekly transcription training sessions over a two-year period. The second transcriber was blind to the hearing status of the infant producing the tokens but the first transcriber was not. Reliability was assessed in two ways: a) canonical versus non-canonical syllables and b) consonant and vowel place agreement within the CV syllable.

Agreement on whether tokens were considered canonical or non-canonical was obtained first. The transcribers categorized each token within an utterance as canonical or non-canonical. For example, for an utterance such as [a di], the singleton vowel was considered a non-canonical token and the [di] was considered canonical syllable. The utterance was coded as [non-canonical, canonical]. If the second transcriber recorded [ʔa ni] it was coded as [non-canonical, canonical] and counted as 100% agreement. If the secondary transcriber recorded [da ni] as [canonical, canonical], one disagreement was counted. Agreement on this dimension ranged from 84% to 100% across infants. The overall mean agreement was 91%.

Consonants were also compared on place and manner and vowels on front/back and vowel height dimensions. Agreement was calculated using a multidimensional analysis procedure (see Oller & Delgado, 1990). Consonant agreement was 91% for both groups of infants with hearing loss. For infants with mild-to-moderately-severe loss, approximately 62% of consonant disagreements involved manner disagreements and fewer place disagreements (38%) were observed. For infants with profound loss, manner (52%) slightly exceeded place (48%) disagreements. Vowel agreement was 89% and 88% for infants with mild-to-moderately-severe and severe-to-profound hearing loss, respectively. Specifically, disagreements in vowel height (56%) exceeded disagreements in front/back (43%) dimension for vowels.

Statistical analysis. The data are presented in tabular form for each infant. Tables 4, 5, and 6 show the data for infants with normal, mild-to-moderately-severe, and severe-to-profound hearing sensitivity, respectively. Consonant-vowel associations were examined using a contingency table analysis of independence. A three-by-three contingency table was created for each infant individually, within each hearing group (normal, mild-to-moderately-severe, and severe-to-profound, see Tables 4, 5, and 6, respectively). The overall null hypothesis is that the consonant and vowel variables are independent within syllables and that the observed degree of association is no stronger than would be expected by chance occurrence. 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. Based on the predictions of the Frame Content hypothesis, the following three CV associations were expected to exhibit greater than expected occurrences in each infant: labial-central, coronal-front, and dorsal-back. The statistical significance of individual cells showing an observed-to-expected ratio greater than 1.0 was tested using methods established by Bishop et al. (1975), whereby the difference between observed (O_{ij}) and expected (E_{ij}) values in each cell was tested by calculating a Freeman-Tukey deviates statistic. Values that are asterisked identify the cells of the table in which the number of observations (O_{ij}) significantly differs from the corresponding expected frequencies (E_{ij}). In this method, cells for which the expected value is less than 5 are not tested. A Holm's sequential Bonferroni (Holm, 1979) correction was applied in order to account for multiple testing; a contingency table-wide probability value was set at .05.

Additionally, regression analyses were used to determine any significant associations between the infants' better-ear, unaided PTA (dependent variable) and the percentage of CV co-occurrences (labial-central, coronal-front, and dorsal-back) in each infant's repertoire. Three regression analyses were performed in total, one for each of the sequences examined (labial-central, coronal-front, dorsal-central). For each regression performed, a t-value, p-value and R^2 value are reported when significance was obtained. A probability value of .05 was considered significant. The analyses determined whether the relationship between PTA and the independent variables was significant across the 15 infants, not across the hearing loss groups.

Results

An inventory of CV canonical syllables classified by consonant onsets was created for each infant. A total of 1,274 CV syllables were analyzed for the infants with normal hearing; 2,175 for infants with mild-to-moderately-severe loss; and 1,195 for infants with severe-to-profound loss. Canonical syllables with labial, coronal, and dorsal onsets were divided according to front, central, and back vowel categories for individual infants within each group. Figure 1 shows the percent occurrence of each of the predicted CV associations (coronal-front, labial-central, and dorsal-back) for each infant within the three groups. The individual data is shown for purposes of highlighting the variability from infant to infant. All CV associations are shown in Figure 2 for purposes of comparing the relative percentage occurrence of the predicted co-occurrences to those that were not predicted. Figure 2 shows the percent distribution of the CV co-occurrences for canonical syllables with coronal, labial and dorsal onsets averaged across the infants within each group. Coronal-front syllables account for most of the syllable co-occurrences that have coronal-onsets for all three groups of infants, accounting for 53%, 47%, and 50% of the syllable inventory for infants with normal, mild-to-moderately-severe loss, and severe-to-profound hearing loss. For canonical syllables with labial onsets, the labial-central pattern was the predominant pattern, accounting for 56%, 54%, and 57% of the labial-onset inventory for the infants with normal, mild-to-moderately-severe, and severe-to-profound hearing loss, respectively. Finally, for dorsal-onset syllables different patterns were observed for each of the groups of infants.

Contingency tables (Tables 4, 5, and 6) were created for each infant in each group and display the raw (observed) data in parentheses, observed-to-expected ratios, and significance tests for each of the predicted CV co-occurrences. Table 4 shows the three-by-three contingency table for the individual infants with normal hearing sensitivity. Numbers in bold highlight the instances for which the observed-to-expected ratio exceeds a value of 1.00. For hearing infants, 12 co-occurrences were predicted to exceed 1.0 (3 predictions for each of 4 infants) and 11 were confirmed (11/12). Specifically, all coronal-front and all labial-central co-occurrences occurred at a ratio greater than 1.0. Three dorsal-back associations were observed. Only six above chance co-occurrences were observed in the 24 instances in which CV associations were not predicted. Of the six above-chance occurrences of CV subtypes that were not predicted by the hypothesis, three involved labial-back associations and three involved dorsal consonants (2 dorsal-front and 1 dorsal-central).

Tests of the significance of the difference between the observed and expected values in each cell of the contingency table showed that 58% (7/12) of predicted cells were significant ($p < 0.05$) for the infants with normal hearing. Specifically, 75% (3/4) of the coronal-front associations, 75% (3/4) of the labial-central associations, and 25% (1/4) dorsal-back associations were significant at the .05 level. Additionally, of the six non-predicted associations that occurred above chance, only 2 were considered significant, both were instances of labial-back association. Thus 58% (7/12) predicted associations were significant, and only 8% (2/24) of the non-predicted associations were significant.

Table 5 displays the three-by-three contingency tables for infants with mild-to-moderately-severe loss. For this group 18 co-occurrences were predicted (3 predictions for each of 6 infants) and 13 predictions were confirmed (13/18). Specifically, 83% of the coronal-front (5/6), and 83% of labial-central (5/6) associations were confirmed above 1.0. Fifty percent (3/6) of the dorsal-back associations were confirmed above chance. Only 13 above-chance co-occurrences were observed in the 36 instances in which CV associations were not predicted. Of the 13 above-chance occurrences of non- predicted CV subtypes, five involved labial associations (4 involved the labial-back association and 1 involved the labial-front association), two involved coronal associations (coronal-central and coronal-back) and six involved dorsal associations (three dorsal-central associations and 3 dorsal-front associations).

Tests of the significance of the difference between observed and expected values in each cell of the contingency table showed that 28% (4/18) of the predicted cells were significant for the infants with mild-to-moderately-severe hearing loss. Specifically, 67% (4/6) of the coronal-front associations were significant. No labial-central or dorsal-back associations were significant ($p > 0.05$). Additionally, Infant JH had none of the predicted CV associations but had two statistically significant associations, the labial-front and coronal-back associations. Infant EC had no CV associations (predicted or unpredicted) that were significant.

Table 6 shows the three-by-three contingency tables with the observed-to-expected ratios in each cell for each infant in the severe-to-profound group. Numbers in boldface highlight observed-to-expected ratios exceeding 1.0. For infants with severe-to-profound sensorineural loss, nine co-occurrences were predicted (3 predictions for each of 3 infants) and six were confirmed (three labial-central and three coronal-front). None of the infants showed the dorsal-back co-occurrence; however, dorsals were produced relatively infrequently. Only six above chance co-occurrences were observed in the 18 instances in which CV associations were not predicted. Of the six above chance occurrences of CV subtypes that were not predicted, two involved labial-back associations, one involved a coronal-back association, and three involved dorsal-central associations.

Tests of the significance of the difference between the observed and expected values in each cell of the contingency table showed that 44% (4/9) of the predicted cells were significant for the infants with severe-to-profound hearing loss. Specifically, 67% (2/3) of the coronal-front associations, and 67% (2/3) of the labial-central associations were significant ($p < 0.05$). None of the dorsal-back associations were significant ($p > .05$). Additionally, there were no instances in which non-predicted associations were significant.

In order to examine the relationships between the unaided PTA and CV co-occurrence patterns across the 13 infants, three separate regression analyses were calculated with PTA as the dependent variable and the percent occurrence of (a) coronal-front, (b) labial-central, and (c) dorsal-back associations each as independent variables. The PTA was not significantly associated with any of the CV co-occurrences. This result suggests that auditory sensitivity (PTA) is not influencing within-syllable organization.

For this cohort of 13 children, we predicted a total of 39 CV co-occurrences (3 predictions times 13 children) to occur at a ratio of greater than 1.0, and 30 (77%) predictions were confirmed above chance (11 for infants with normal hearing, 13 for infants with mild-to-moderately-severe hearing loss, and six for infants with severe-to-profound hearing loss). Overall 50% (15/30) of the co-occurrences that had observed-to-expected ratios greater than 1.0 were statistically confirmed. Figure 3 shows the percentage of confirmed predictions that were statistically significant for each of the hearing groups. Infants with normal hearing had the highest percentage of statistically significant cells, followed by infants with severe-to-profound, and infants with mild-to-moderately severe hearing loss. The most common association to be statistically confirmed was the coronal front-association appearing in 69% (9/13) of these infants. Specifically, 75% (3/4), 67% (4/6), and 67% (2/3) of infants with normal, mild-to-moderately-severe, and severe-to-profound hearing sensitivity showed the coronal-front association at statistically significant levels. The labial-central association was statistically significant in 38% (5 /13) of these infants. It was statistically significant in 75% (3/4), and 67% (2/3) of infants with normal and severe-to-profound hearing loss, respectively. Although not considered significant, the trend for labial-central association was found for infants with mild-to-moderately-severe loss as it was evident above chance in all but one of the six infants in that group. Finally, the dorsal-back association was statistically significant only in one occasion for infants with normal hearing and was not observed at all for infants with mild-to-moderately-severe, and severe-to-profound hearing sensitivity.

Discussion

The onset of canonical syllable production in vocal development forms the foundation for intelligible speech. In infants with normal hearing sensitivity, the rhythmic jaw cycle contributes to intrasyllabic CV associations in canonical babbling. In order to better understand how intrasyllabic organization might be affected by hearing loss, the internal organization of canonical syllables in thirteen infants with hearing sensitivity ranging from normal hearing to severe-to-profound loss was investigated.

One production-system-based perspective, the Frame Content hypothesis, proposes that the rhythmic mandibular oscillations commonly observed in the canonical babbling period account for most of the internal organization of canonical syllables (Davis & MacNeiilage, 1990, 1995) observed in hearing infants. The internal organization of the canonical CV syllables of the infants in the present study, tended to fall within the general predictions of the Frame Content hypothesis, regardless of hearing sensitivity. Specifically, for this cohort of 13 children, approximately 77% (30/39) of the predicted associations were confirmed above chance across the 13 infants**.** Additionally, no significant associations were found between PTA and any of the predicted CV co-occurrences, suggesting that hearing sensitivity does not contribute significantly to intrasyllabic organization. However, a general trend emerging from this data shows that as hearing sensitivity diminishes, fewer predicted CV co-occurrences are observed at above chance levels. Thus, infants with normal hearing may be more likely to evidence predicted CV co-occurrences than infants with mild-to-moderately-severe hearing loss, and infants with severe-to-profound loss.

The labial-central and coronal-front co-occurrence patterns observed in typically developing infants (Davis & MacNeilage, 1995) accounted for the highest percentage of CV associations and were generally present at above chance levels regardless of level of auditory sensitivity (See Figure 2). Although, the labial-central pattern for infants with mild-to-moderately-severe hearing loss shows relatively fewer statistically significant labial-central associations than in infants with normal hearing; the trend showing the labial-central association accounting for more the associations relative to other labial onset productions is evident (see Figure 2). The dorsal-back association was statistically confirmed in very few of these infants, regardless of hearing level (see Figure 3). It should be noted that frequencies of dorsal consonants and back vowels were very low in the infants with hearing loss, complicating statistical analysis. This data were obtained from a limited number of children, especially those with severe-to-profound loss; therefore, continued examination of these patterns in more infants with poor hearing sensitivity will help to confirm the generality of these findings.

Does diminished hearing sensitivity lead to other patterns of intra-syllabic associations within the canonical babbling stage? Results from this study suggest that relative to the predicted patterns, few of the non-predicted cells occurred above chance and very few were statistically confirmed, suggesting that diminished hearing sensitivity is not leading children to explore vastly different patterns of CV associations than children with normal hearing. Interestingly, the majority of significant non-predicted cells came from the infants with mild-to-moderately-severe hearing loss (see Table 5). The data from this group of infants shows the highest variability in terms of the non-predicted CV associations. In general the non-predicted associations were spread somewhat evenly among the infants with mild-to-moderately-severe hearing loss. No one infant accounted for more than two non-predicted associations. Future studies should determine what additional factors contribute to the variability observed in infants with this degree of loss. Infant JH evidenced none of the predicted patterns and showed a propensity for producing labial-front and labial-back associations. He was the oldest infant in the cohort with mild-to-moderately-severe hearing loss and it is uncertain what factors where influencing his production repertoire. These children may not clearly fit the profile of children who will receive cochlear implantation, so gaining a clear understanding of their unique developmental profile may be important for developing supportive remediation protocols. The speech development of infants with milder hearing losses has not been studied as extensively as that of infants with severe-to-profound hearing loss; therefore it is important to understand the sources of the variability evidenced in early identified infants with this degree of loss.

Taken together, the present results suggest that internal organization of CV co-occurrence is not significantly affected by reduced perceptual input in infants with hearing loss who have entered the canonical babbling stage (i.e., CBR >.2 [Oller & Eilers, 1988]). These infants generally did not seem to be producing different patterns of within syllable-organization relative to infants with normal hearing at a similar stage of development. The pattern of results for this cohort seems to suggest that the syllable frame provided by mandibular oscillations provides a dominant and stable production mode for canonical syllables despite relative differences in auditory input. Once sufficient audition has been achieved for canonical syllables to emerge, differences in auditory sensitivity may not be sufficient to alter or affect the structure of within-syllable organization. Thus, if developmental requirements for instantiating frequent mandibular oscillations are met, the general biomechanical properties of the developing speech production system become apparent in the vocalizations of infants with hearing loss. The most diversity in production of canonical syllables was observed for the infants with mild-to-moderately-severe hearing loss.

Some models of production development suggest that the auditory perceptual system and the motor production system are coupled through feed-back or forward mechanisms (Westerman & Miranda 2004; Callan, Kent, Guenther and Vorperian, 2002). In these models, initially, the production system is suggested as relying on auditory feed-back to "train" acoustic-articulatory associations. Other studies of vocal development in infants with hearing loss suggest that auditory feed-back is a requirement for mature syllable production. For example, Koopmans van Beinum et al. (2001) suggest that auditory feedback is required in order for infants to successfully couple the articulatory and phonatory systems in early vocalizations. They assert that this coupling is a requirement for mature syllable production to emerge. Thus, evidence suggests that the developing production system relies on a strong link between perception and motor processes for mature syllable forms to appear. Accordingly, the results of the present study seem to confirm that once infants have met the acoustic feedback requirements that lead to well-formed canonical syllables, CV associations are not significantly affected by differences in hearing sensitivity. In these children, production output seems resilient in the face of diverse auditory input.

The present study only included three infants with severe-to-profound hearing loss; therefore, it is uncertain to what extent differences in signal audibility may affect developing production repertoires. A larger sample would be beneficial to understand emergence of vocalization patterns in this population more clearly. In a previous study with the same cohort, von Hapsburg & Davis (in press) analyzed several aspects of the vocalization repertoire including utterance organization, and other aspects of canonical syllable production and found that auditory sensitivity was significantly associated with the organization of utterance strings, syllable shapes, and consonant onset patterns. No influence of hearing sensitivity was found on how infants sequence syllables. All infants preferred monosyllabic utterances followed by bi-syllabic and tri-syllabic sequences, regardless of degree of hearing loss. Thus, it seems that effects of decreased hearing sensitivity may be evidenced in some aspects of production but not others. For example, differences in movement variability related to changes in audition (Goffman, et al., 2002) were apparent in kinematic measurements of mandibular movements in a toddler with profound hearing loss prior to and after receiving a cochlear implant, suggesting that a combination of perceptual and physiological analyses may enhance our understanding of the effects of hearing loss on early canonical syllable production. It is not clear how pervasive these differences are in infants with milder levels of hearing loss.

For the group of infants with severe-to-profound loss, the most important intervention likely to improve oral speech production is one that will afford sufficient signal audibility to increase the proportion of canonical syllables present in their vocalizations. Although the three infants with severe-to-profound loss were producing types of canonical syllables consistent with the Frame Dominance concept; the relative number of canonical syllables was low compared to infants with normal hearing and mild-to-moderately-severe loss (see Table 3). It is important to note that the infants with severe-to profound hearing loss were about six months older than the other participants, and had not reached the first word stage despite early amplification and extended experience with amplification, relative to the infants with mild-to-moderately-severe hearing loss. It may be that the presence of these syllables in early production of infants with severe-to-profound hearing loss may not guarantee the timely occurrence of first words without more intervention. For example, infant GW was implanted at age 24 months due to lack of word production, despite her ability to produce canonical syllables with conventional amplification at a younger age.

Additionally, the infants in the severe-to-profound group showed a mean hearing aid fitting age of 8 months, and a mean hearing age of 12 months. Despite early identification and intervention, these infants were not producing many canonical syllables relative to the mild-to-moderate and the hearing groups, indicating that early intervention with amplification may not be sufficient to allow development to proceed at a level to support age-appropriate speech patterns. Examination of syllable-based output patterns can form another part of the decision making package to evaluate the appropriateness of amplification.

The present data on canonical syllable patterning in infants with diverse sensory backgrounds adds an important cornerstone to our understanding of the co-development of sensory and production processes in speech acquisition. The link between auditory perception and production system development in instantiation of early speech-like vocalizations in the canonical babbling stage is not yet well understood. As the age of identification and intervention for infants with hearing loss decreases, it becomes increasingly important to understand how the vocalizations of infants with varied hearing levels diverges from those of infants with normal hearing sensitivity. In this study, infants with varied hearing levels, who were in the canonical babbling stage, showed intra-syllabic organization patterns consistent with predictions of the Frame Content hypothesis. These findings suggest that if sufficient auditory feedback is obtained to instantiate canonical syllable production, the within-syllable structure imposed by mandibular oscillations operates largely independent of degree of auditory access.

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Table 1

Age Characteristics of Infants: Age at Time of Initial Fitting of Amplification (AA), Chronological Age (CA), and Hearing Age (HA) at the Time of Study

Infant	Gender	AA (months)	CA (months)	HA (months)
Infants with Normal Hearing				
C	F	-	12.0	12.0
M	M	-	14.0	14.0
N	M	-	11.0	11.0
R	F	-	12.0	12.0
Total			49.0	49.0
Mean			12.3	12.3
SD			1.7	1.7
Infants with Mild-to-Moderately-Severe Hearing Loss				
CR	M	5.0	13.0	8.0
JH	M	7.0	15.0	8.0
NL	M	6.5	11.0	4.5
AM	M	7.0	14.0	7.0
EC	M	2.5	7.0	4.5
AW	M	1.8	12.0	10.8
Total		29.8	72.0	42.8
Mean		4.9	12.0	7.1
SD		2.3	2.8	2.4
Infants with Severe-to-Profound Hearing Loss				

GW	F	1. 5	16.0	14.5
MB	F	1.5	16.0	14.5
LB	F	13.0	24.0	11.0
Total		16.0	56.0	40.0
Mean		5.3	18.7	13.3
SD		6.6	4.6	2.0

Table 2

Auditory Threshold Information for Infants with Hearing loss. A Three-Frequency Pure-Tone Average (PTA) was Calculated. When No-Response was Obtained at the Limits of the Audiometer, a Value of 120 dB HL was Entered as the Threshold for that Frequency

		Auditory thresholds in dB HL (re: ANSI, 1989)					
Infant	Ear	500 Hz	1000 Hz	2000 Hz	4000 Hz	PTA	PTA
		Infants with Mild-to-Moderately Severe Hearing Loss					
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	23
		Infants with Severe-to-Profound Hearing Loss					
GW	R	80	95	95	90	90	85
	L	85	75	95	95	85	
MB	R	95	105	100	90	100	100
	L	95	110	100	NR (120)	102	
LB	SF	NR (120)	NR (120)	NR (120)	NR (120)	120	120
Group PTA						102	54

* PTA estimated from thresholds at 500 and 1000 Hz.

Table 3

Data Collected Including Total Number of Minutes, Utterance Strings, Syllables, and Canonical Babbling Ratio (CBR) Obtained for Each Infant

Infant	# of Minutes	# of Utterances	# of Syllables	CBR
		Infants with Normal Hearing		
C	60	394	407	1.03
M	120	325	308	.95
N	120	249	354	1.34
R	60	257	285	1.10
Total	360	1225	1354	4.42
Mean	90	306	338	1.11
		Infants with Mild-to-Moderately-Severe Hearing loss		
CR	152	254	235	.93
JH	90	385	843	2.12
NL	119	285	166	.58
AM	177	377	428	1.14
EC	181	297	619	2.08
AW	150	361	139	.39
Total	869	1959	2430	7.23
Mean	144.8	326.5	405	1.21
		Infants with Severe-to-Profound Hearing Loss		
GW	148	466	963	2.07
MB	70	415	238	.57
LB	120	281	103	.37
Total	338	1162	1304	3.01
Mean	112.6	387.3	434.6	1.00
SD	39.5	95.5	462.5	.929

Table 4

Observed-to-Expected Ratios for CV Co-occurrences of Infants with Normal Hearing. Numbers in Parentheses Show Raw Occurrence Data for Each Cell

Infant		CONSONANTS		
Group I	VOWELS	Coronal	Labial	Dorsal
C	Front	(50) **1.57***	(56) 0.87	(9) .47
N = 406	Central	(40) .80	(128) **1.27***	(13) .43
	Back	(22) .72	(42) .69	(46) **2.5***
M	Front	(112) **1.20***	(45) .68	(14) **1.20**
N = 293	Central	(43) .81	(49) **1.31***	(5) 0.76
	Back	(5) .37	(19) 1.97*	(1) .59
N	Front	(80) **1.61***	(13) 0.35	(13) .68
N = 298	Central	(53) .85	(53) **1.15**	(26) 1.09
	Back	(7) .24	(38) 1.81*	(15) **1.34**
R	Front	(76) **1.17**	(5) 0.29	(12) 1.12
N = 277	Central	(97) .93	(37) **1.35***	(15) .87
	Back	(21) 0.86	(9) 1.40	(5) **1.24**

* $p < .05$

Table 5

Observed-to-Expected Ratios for CV Co-occurrences of Infants with Mild-to-Moderately-Severe Hearing Loss. Numbers in Parentheses Show Raw Occurrence Data for Each Cell

Infant		CONSONANTS		
Group II	VOWELS	Coronal	Labial	Dorsal
CR	Front	(11) **2.86***	(16) .71	(0) 0
N = 218	Central	(14) .67	(132) **1.08**	(0) 0
	Back	(6) .93	(34) .91	(5) **4.84**
JH	Front	(187) .90	(111) 1.16*	(37) 1.12
N = 770	Central	(181) 1.01	(77) .93	(33) 1.15
	Back	(107) 1.20*	(31) .76	(6) .42
NL	Front	(6) **8.02***	(0) 0	(1) 4.67
N = 131	Central	(7) .91	(65) **1.05**	(0) 0
	Back	(1) .18	(48) 1.07	(3) **1.89**
AM	Front	(49) **1.88***	(27) 0.55	(3) .88
N = 346	Central	(49) .74	(140) **1.11**	(12) 1.38
	Back	(16) .74	(50) 1.21	(0) 0

EC	Front	(204) **1.03**	(10) 0.61	(21) 1.04
N = 614	Central	(235) 1.00	(22) **1.13**	(22) .91
	Back	(79) 0.94	(11) 1.57	(10) **1.16**
AW	Front	(17) **3.16***	(3) 0.21	(2) .78
N = 86	Central	(0) 0	(23) **1.20**	(7) 2.01
	Back	(4) .48	(29) 1.33	(1) .25

* $p < .05$

Table 6

Observed-to-Expected Ratios for CV Co-occurrences for Infants with Severe-to-Profound Hearing Loss. Numbers in Parentheses Show Raw Occurrence Data for Each Cell

Infant		CONSONANTS		
Group III	VOWELS	Coronal	Labial	Dorsal
GW		(205)	(18)	(10)
	Front	**1.05**	0.85	.58
N = 906		(326)	(56)	(40)
	Central	.92	**1.47***	1.28
		(226)	(8)	(17)
	Back	**1.07**	.35	.92
MB		(37)	(17)	(0)
	Front	**2.32***	.45	0
N = 210		(18)	(102)	(1)
	Central	.50	**1.20***	1.74
		(7)	(28)	(0)
	Back	.67	1.14	0
LB		(8)	(12)	(0)
	Front	**2.26***	0.74	0
N = 79		(6)	(50)	(1)
	Central	.59	**1.08**	**1.39**
		(0)	**(2)**	(0)
	Back	0	**1.2**	0

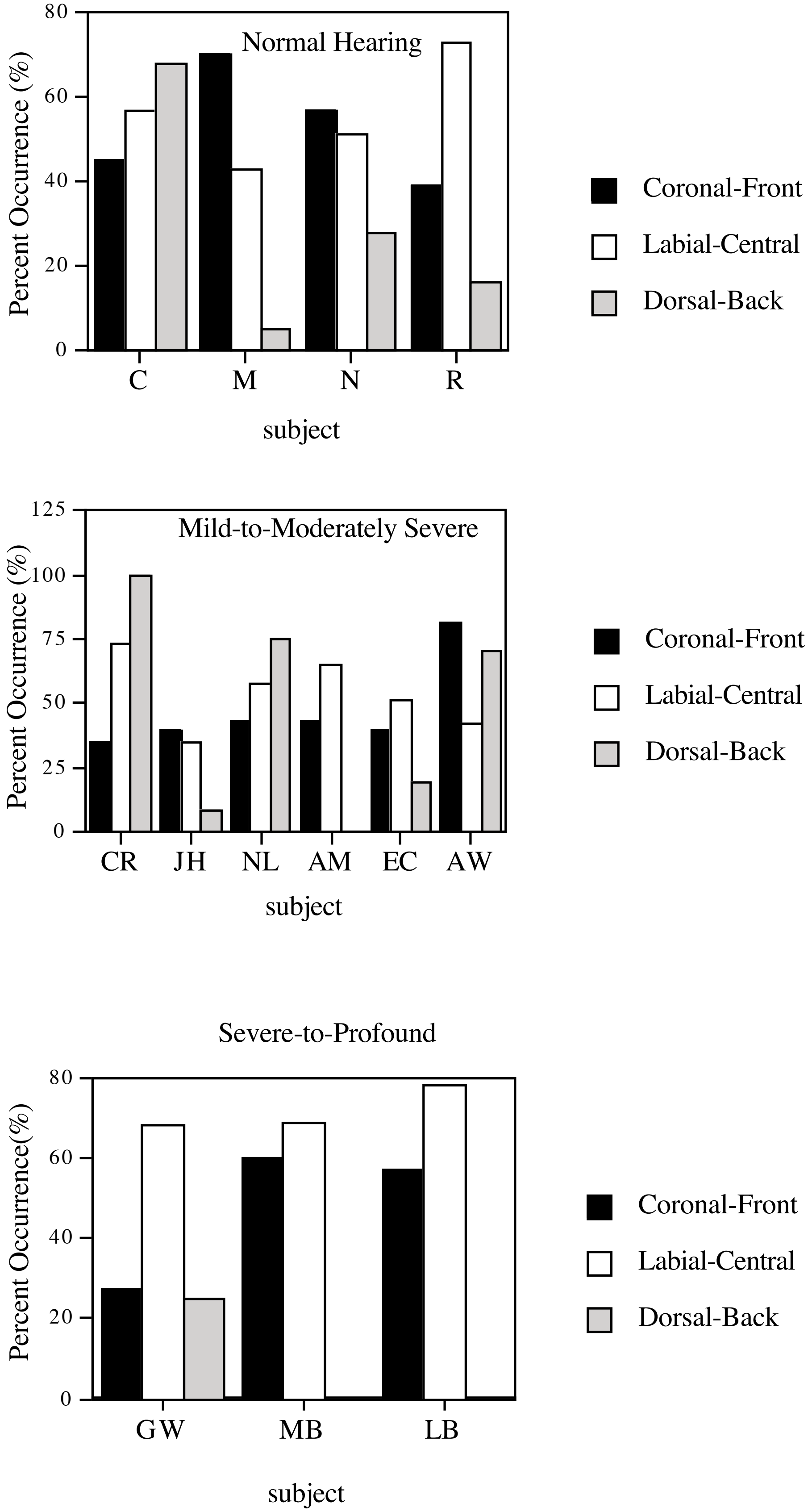
* $p < .05$

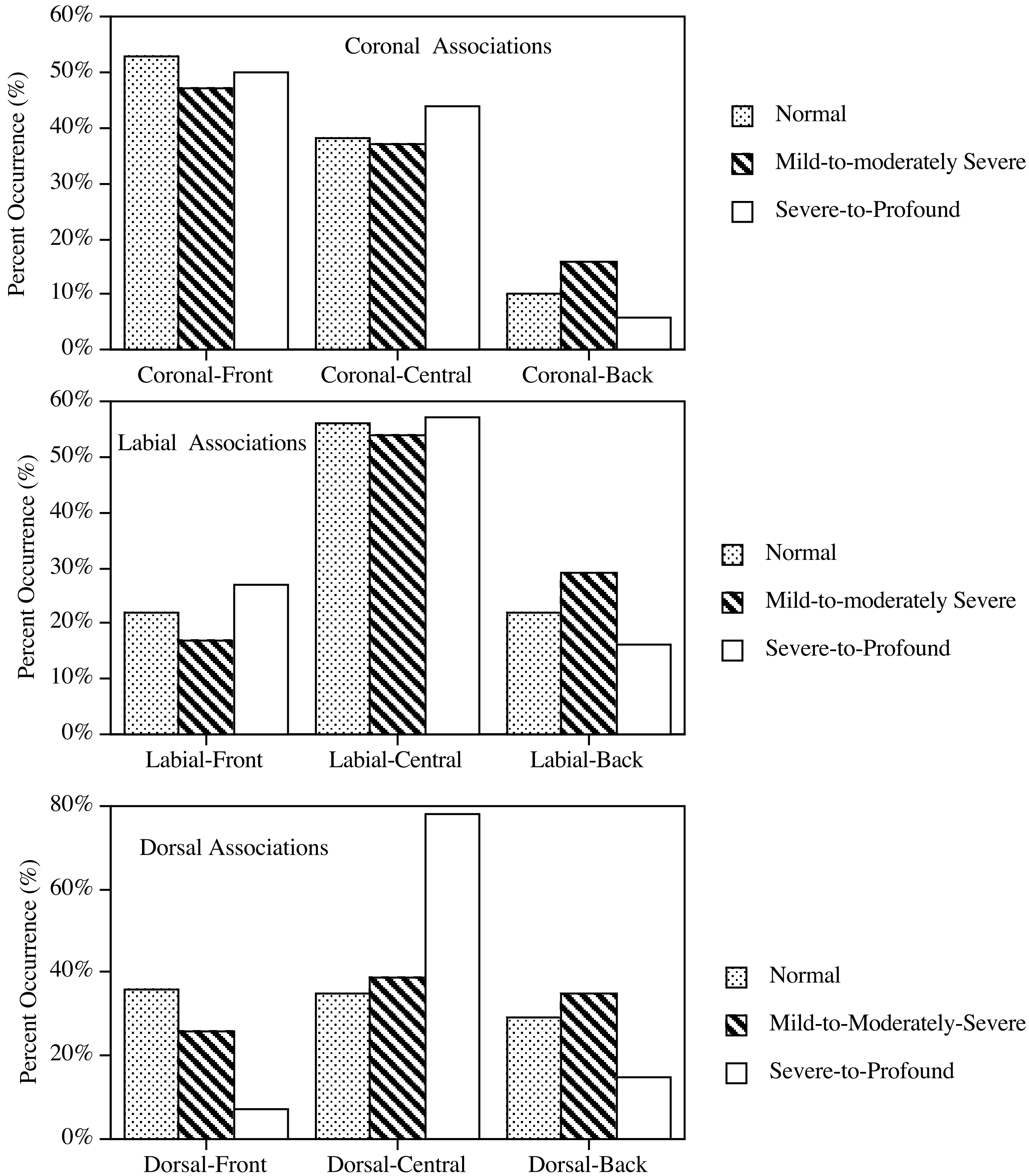
Figure captions

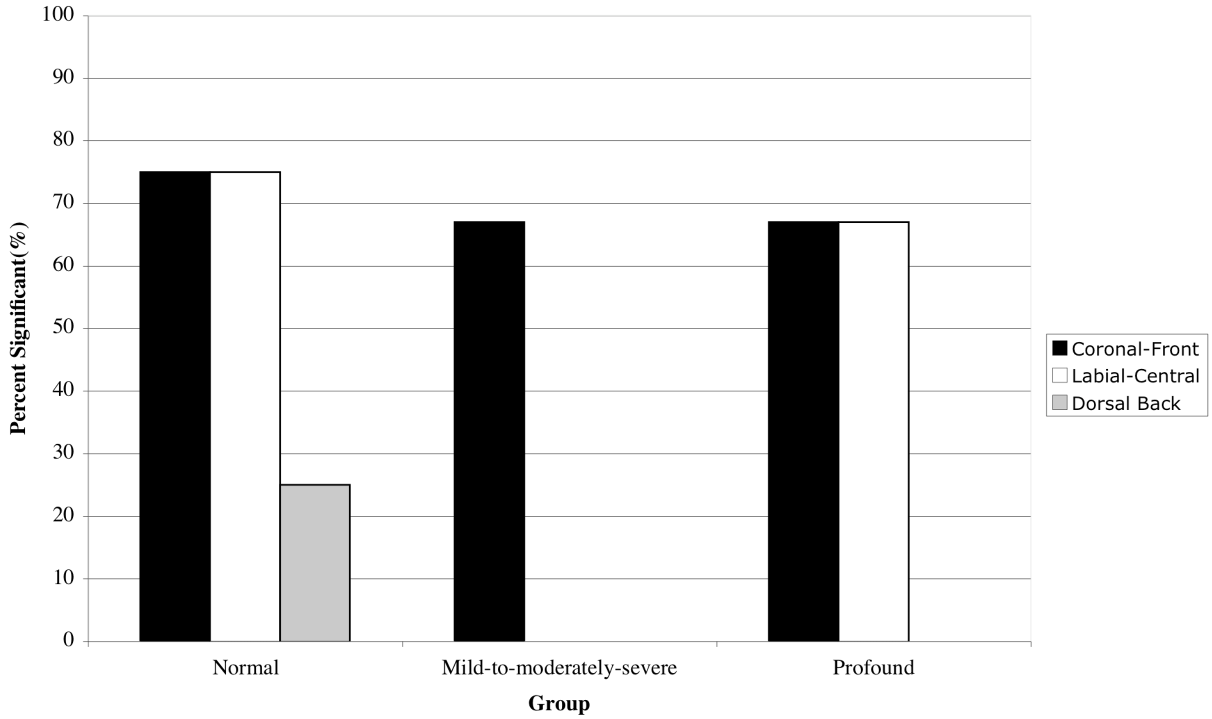
Figure 1 Percent occurrence of each of the predicted CV associations for individuals within the three hearing groups.

Figure 2. Percent distribution of CV associations averaged across infants within each hearing group, normal hearing, mild-to-moderately-severe, and severe-to-profound hearing loss.

Figure 3. Percentage of predicted CV co-occurrences that were statistically significant for averaged across hearing group.


Normal Hearing
Percent Occurrence (%)
0
20
40
60
80
C
M
N
R
subject
Coronal-Front
Labial-Central
Dorsal-Back
Mild-to-Moderately Severe
Percent Occurrence (%)
0
25
50
75
100
125
CR
JH
NL
AM
EC
AW
subject
Coronal-Front
Labial-Central
Dorsal-Back
Severe-to-Profound
Percent Occurrence(%)
0
20
40
60
80
GW
MB
LB
subject
Coronal-Front
Labial-Central
Dorsal-Back


Coronal Associations
Percent Occurrence (%)
60%
50%
40%
30%
20%
10%
0%
Coronal-Front
Coronal-Central
Coronal-Back
Normal
Mild-to-moderately Severe
Severe-to-Profound
Labial Associations
Percent Occurrence (%)
60%
50%
40%
30%
20%
10%
0%
Labial-Front
Labial-Central
Labial-Back
Normal
Mild-to-moderately Severe
Severe-to-Profound
Dorsal Associations
Percent Occurrence (%)
80%
60%
40%
20%
0%
Dorsal-Front
Dorsal-Central
Dorsal-Back
Normal
Mild-to-Moderately-Severe
Severe-to-Profound


100
90
80
70
60
50
40
30
20
10
0
Percent Significant(%)
Normal
Mild-to-moderately-severe
Profound
Group
Coronal-Front
Labial-Central
Dorsal Back