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A Pilot Investigation on the Relationship Between Infant Vocal Characteristics at 12 Months and Speech Motor Impairment at 4–5 Years

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ABSTRACT

Purpose: The objective of this pilot study was to investigate the relationship between infant vocal characteristics and later speech motor impairment in children at risk for cerebral palsy (CP) to inform the early prediction of speech motor impairment.
Method: Vocal complexity, volubility, and consonant inventories of 13 infants at risk of CP were examined at approximately 12 months. We examined their association with later levels of speech motor impairment as measured by the Viking Speech Scale (VSS).
Results: Children in our sample with greater speech motor impairment at age 4 years produced lower rates of developmentally complex vocalizations in infancy but showed no significant differences in vocal stage attainment, volubility, or consonant diversity.
Conclusions: Our results are in line with trends found in prior literature examining vocal characteristics of infants at risk for speech motor involvement. These results can inform data-driven hypotheses in future studies aimed at the early prediction of speech motor impairment through the study of infant vocal production.

Cerebral palsy (CP) is the most common childhood physical disability in the world, characterized as a movement disorder arising from nonprogressive disturbances affecting neuromotor development in the fetal or infant brain (Rosenbaum et al., 2007). Between 50% and 80% of children with CP present with speech motor impairments, which refer to difficulties in planning, coordinating, and executing the movements required for speech production. Unlike phonological disorders, which primarily involve rule-based errors in the sound system of language (e.g., misarticulating sounds due to difficulties with underlying linguistic knowledge), speech motor impairments in CP are rooted in neuromuscular differences that directly affect speech execution and/or speech motor planning. These impairments may manifest as auditory perceptual speech features, such as imprecise articulation, reduced rate of speech, hypernasality, and voice quality differences, collectively impacting intelligibility and communication that can affect social participation and quality of life long term (Mei et al., 2020; Odding et al., 2006; Parkes et al., 2010).

Speech motor impairments in CP commonly result in specific diagnoses such as pediatric dysarthria affecting speech execution or childhood apraxia of speech affecting speech motor planning. However, diagnosing specific speech motor impairment (e.g., pediatric dysarthria and childhood apraxia of speech) cannot occur until children are able to participate in speech tasks (Shriberg et al., 2019). Conversely, the early detection of CP is feasible in infancy via neuroimaging techniques and gross motor assessment (Novak et al., 2017), which enables early intervention in gross and fine motor domains (Boychuck et al., 2019), while communication development is often monitored

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with a wait-and-see approach (A. L. Smith & Hustad, 2015; Thoms, 2020). As a result, children may miss critical early interventions to enhance communication development.

The early prediction of speech motor impairment is challenging in children with CP due to their heterogenous profiles of intellectual, language, and speech motor abilities (Geytenbeek et al., 2015; Hustad et al., 2010; Mei et al., 2016; Stadskleiv, 2020). Speech motor abilities in children with CP can range from no functional impairment to a total absence of speech. Recent studies have demonstrated the predictive value of early speech intelligibility on later outcomes (Darling-White et al., 2018; Hustad et al., 2017, 2019, 2020; Mahr et al., 2020). Children classified as having greater speech motor impairment at 4 years are also less likely to show improvement compared to those with some functional speech at this age (Long et al., 2022). However, studies on early speech intelligibility can only examine children at or above 2 years of age, leaving the early prediction of speech motor impairment at youngest ages unclear.

Research examining infant vocal development has been used to study vocal precursors of a range of developmental disorders (Ertmer et al., 2007; Ha, 2019; Masataka, 2001; Oller et al., 1998). This work is based in the assumption that foundational vocal stages emerge prior to speech in infancy (Oller, 1978, 2000; Stark, 1980), and disruptions in these stages may signal early disorders requiring intervention (Oller et al., 1999). For example, delays in the onset of the canonical babbling stage of vocal development indicate a risk for autism (Lang et al., 2019; Yankowitz et al., 2019, 2022). Several other studies have found canonical babbling delays in infants at risk for any speech motor impairment (Cobo-Lewis et al., 1996; Lynch et al., 1995; B. L. Smith & Stoel-Gammon, 1996). However, few studies have examined vocal precursors of speech motor impairment in CP.

In 2022, we conducted a scoping review and identified a small number of studies examining vocal characteristics of infants at risk for CP (Long, Christensen, et al., 2023). Although there was large methodological variability, these studies suggested high rates of marginal babbling (i.e., imprecise consonant–vowel syllables), low rates of canonical babbling (i.e., precise consonant–vowel syllables), and small consonant inventories (i.e., number of different consonants) in infants with or at risk for CP around 12 months. Similar trends have been found in recent studies (Long, Eichorn, & Oller, 2023; Long & Hustad, 2023; Ward et al., 2023), indicating an ongoing need to investigate the link between early vocal characteristics and later speech outcomes. Only one study was identified in the scoping review that compared vocal characteristics with later speech-language outcomes in children with neurodevelopmental disabilities, including CP (Nyman, Strömbergsson, Lindström, et al., 2021). Results showed a moderate but nonsignificant correlation between infant consonant inventories and later percentage of consonants correct in words produced during standardized testing. However, small samples limited their ability to examine CP-specific differences; thus, the relationship between vocal characteristics and later speech motor impairment remains unclear.

Since 2017, our laboratory has followed ~50 children at risk for CP to study their early speech and language development. We now have laboratory data available to compare infant vocal characteristics with later speech functioning in a sample of these children. In the present study, we used measures identified from our scoping review to examine vocal complexity, volubility, and consonant diversity and examine their relationship with children's levels of speech motor impairment, as measured by the Viking Speech Scale (VSS; Pennington et al., 2010) between 4 and 5 years of age. While preliminary, this pilot study is necessary to generate data-driven hypotheses for larger projects aimed at testing the predictive nature of vocal characteristics for later speech motor impairment in children with CP. Our research questions were as follows:

1. What are the patterns of infant vocal complexity at 12 months among children classified across different VSS levels between 4 and 5 years?
2. Is there a relationship between infant vocal characteristics (vocal complexity, volubility, and consonant diversity) and VSS classification in childhood?

We hypothesized that infants with less vocal complexity, lower volubility, and reduced consonant diversity in infancy would have greater speech motor impairment in later childhood. These preliminary findings would set the stage for future research aimed at improving the early prediction of speech motor impairment in children with CP from the earliest stages of development.

Method

This study was approved by the institutional review board at the University of Wisconsin–Madison (IRB #2018–0580). Informed consent was obtained from caregivers.

Participants

Thirteen children (seven females, six males) prospectively recruited for a risk of CP were included in the present study. These children were selected from a larger longitudinal cohort of 51 young children at risk for CP, who were recruited through local and regional medical centers, and social media advertisements in the Midwest region of

the United States. The inclusion criteria for this larger cohort were (a) neonatal intensive care unit (NICU) stay at birth, (b) referral for specialized newborn follow-up care, (c) diagnosed with at least one CP-related International Classification of Diseases (ICD) code in the NICU, (d) no caregiver-reported hearing loss or concerns, and (e) English as the primary language spoken at home. In the present study, children from this cohort were included if they had (a) a laboratory visit at approximately 12 months corrected age, involving a naturalistic ~10-min caregiver–child interaction session, and (b) a laboratory visit between 4 and 5 years of age. A total of 13 children met these criteria.

Participant demographics are outlined in Table 1. All children were White, from primarily English-speaking homes, and born between 2017 and 2018. At the time of enrollment, no children had a confirmed CP diagnosis; rather, a CP-related ICD code (e.g., perinatal stroke, periventricular leukomalacia, hypoischemic encephalopathy, preterm birth). While some children had received a formal diagnosis of CP by the Time 2 assessment, others had not. Since this study's primary focus was on classifying speech motor functioning, children were included based on their risk of CP, irrespective of whether they had received a formal CP diagnosis by Time 2.

The term status and medical diagnoses presented in Table 1 reflect information that was parent reported during follow-up when children were between 4 and 5 years old, including diagnoses identified after enrollment (e.g., 22q11.2 deletion syndrome). We did not exclude children who were diagnosed with co-occurring or other conditions (e.g., childhood apraxia of speech, 22q11.2 deletion syndrome) after enrollment, as these diagnoses were considered part of the diverse developmental outcomes associated with early risk of CP (Yuan et al., 2024).

Vocal Recording Material and Coding Procedures

Infant vocal characteristics were analyzed during laboratory-based, caregiver–child interaction sessions designed to last approximately 10–15 min (M = 12 min, SD = 1.7) during in-person laboratory visits at around 12 months corrected age (M = 12.9, SD = 1.5), hereafter referred to as Time 1. During these sessions, caregivers were instructed to interact naturally with their child using toys or interactive books. All caregiver and infant pairs were provided with the same range of toys and books but were allowed to choose items freely to encourage natural, ecologically valid interactions. These interaction sessions were conducted within a larger 1- to 1.5-hr laboratory visit that also included parent interviews and dynamic assessments. Video and audio of these interaction sessions were extracted for analysis.

Two graduate student research assistant coders were trained by the first author to classify speechlike vocalizations using the Stark Assessment of Early Vocal Development–Revised (SAEVD-R; Nathani et al., 2006). All training and coding was conducted using the Action Analysis Coding Training software (AACT; Delgado & Oller, 1999). The AACT software provides an interface for categorizing and analyzing behaviors in real time through video playback and a live-scrolling spectrogram, including integration with the time-frequency acoustic analysis (TF32) software (Milenkovic, 2001). AACT has been widely used in studies of early vocal development, allowing both real-time and repeat observation coding to support reliable analysis of vocal behaviors and characteristics across typically developing, clinical, and cross-linguistic group studies (Burkhardt-Reed et al., 2021; Franklin et al., 2014; Ha et al., 2021; Long et al., 2024; Yale et al., 1999). Formal coding began only after coding reliability with the first author exceeded 85% during training. Both student coders were blind to child age, speech outcomes, and the research questions. One student served as the primary coder for 100% of recordings; the second student served as the reliability coder.

The SAEVD-R is a coding scheme of 23 vocal types categorized across five levels of complexity (see Table 2). Coders labeled each infant utterance as a single vocal type, which were then grouped into one of these five levels. Utterances containing syllables across more than one level were classified into the highest level of complexity. Coders also marked the consonants of canonical syllables classified at Level 4 or Level 5. A total count of utterances classified within each level and the number of different consonants for each child were obtained to calculate measures of vocal complexity, volubility, and consonant diversity.

Vocal Measures

Level ratios were calculated for each of the five stages by dividing the number of utterances at each level by the total number of utterances for each child. Following the SAEVD-R protocol, non-speech-like sounds (i.e., vegetative sounds, cries, and laughs) were coded but excluded from analysis (Nathani et al., 2006). Five level ratios were quantified for each child to represent their distribution of speechlike vocalizations with varying degrees of well-formedness.

Vocal Complexity

Two measures of vocal complexity were calculated. An *established level* was designated as the highest level with a ratio ≥ 0.15, used as the conventional criterion to indicate vocal stage onset (Iyer & Oller, 2008; Lewedag, 1995; Lynch et al., 1995; Oller et al., 2001; Patten et al., 2014). Typically developing children have been shown to

Table 1. Participant demographics and data.

Child	Sex	Parent-reported term status and medical diagnoses	Time 1 variables							Time 2 variables		
			Age* (month)	Mullen RL	Mullen EL	Highest ratio	Est. level (≥ 0.15)	Vocal rate	Consonant inventory	Age (month)	VSS level	Receiving ST
P01	Male	Mod-late preterm	13	49	34	3	3	4.79	2: [d]	50	VSS I	No
P02	Female	Extremely preterm, PvL, meningitis	12	40	33	2	2	6.61	2: [m, n]	61	VSS I	Yes
P03	Male	Full term, hydrocephalus, intercranial hemorrhage	13	34	57	2	3	4.32	2: [d, t]	61	VSS I	No
P04	Male	Mod-late preterm, 22q11.2 deletion syndrome	14	62	65	2	2	1.66	0	63	VSS II	No
P05	Female	Mod-late preterm, twin, CAS	12	34	43	2	3	3.19	3: [b, d, g]	62	VSS II	Yes
P06	Female	Mod-late preterm, twin, selective mutism	12	39	43	3	3	2.29	1: [b]	62	VSS II	Yes
P07	Male	Mod-late preterm, CP	13	35	39	2	3	8.43	5: [b, d, k, m]	67	VSS II	Yes
P08	Female	Extremely preterm	11	62	48	2	3	3.07	1: [d]	59	VSS II	No
P09	Female	Very preterm, CP, Retinoic acid receptor beta genetic mutation	13	34	28	2	3	2.46	0	68	VSS III	Yes
P10	Female	Full term, HIE, Hypotonia, CAS	17	37	27	2	3	10.57	2: [b, m]	61	VSS III	Yes
P11	Female	Full term, perinatal stroke, CP, seizure disorder, breath holding episodes	12	40	21	2	2	9.70	0	63	VSS III	Yes
P12	Male	Full term, HIE, CP, seizures, hypotonia, reflux, dysphagia, g-tube, slow weight gain	13	21	31	1	2	1.74	0	54	VSS IV	Yes
P13	Male	Full term, HIE	13	28	30	1	2	0.53	0	64	VSS IV	Yes

Note. Birth-risk and diagnosed conditions were parent-reported across visits between Time 1 and Time 2; Mullen T-scores use $M = 50$, $SD = 10$; Full term: ≥ 37 weeks, Mod(erate)-late preterm: 32–37 weeks, Very preterm: 28 to 32 weeks, Extremely preterm: < 28 weeks; RL = receptive language; EL = expressive language; Est. = established; VSS = Viking Speech Scale; ST = speech therapy; PvL = periventricular leukomalacia; CAS = childhood apraxia of speech; CP = cerebral palsy; HIE = Hypoxic–ischemic encephalopathy.

*Corrected age used for Time 1.

Table 2. Summary of Stark Assessment of Early Vocal Development–Revised levels (Information from Nathani et al., 2006).

Level	Expected onset age	Vocalization types
Level 1: Reflexive	0–2 months	Vegetative noises (burp, cough, etc.), crying, fussing, short grunt-like vocalizations with muffled resonance
Level 2: Control of phonation	1–4 months	Vowel-like (i.e., quasivowel) vocalizations that are not fully resonant, closants, raspberries, trills, clicks, laughs
Level 3: Expansion	3–8 months	Fully resonant vowels, glides, ingresses, squeals, marginal CV syllables with slow formant transitions and imprecise consonant-like features
Level 4: Canonical syllables	5–10 months	Canonical CV syllables with rapid formant transition and precise consonantal features in single, reduplicated, and variegated combinations; whispers, and CVC or CVCV syllable structures
Level 5: Advanced Forms	9–18 months	Complex, multisyllabic strings (e.g., VC, CCV, VCVC), canonical utterances with varied intonation patterns (i.e., jargon), diphthongs with rapid vowel formant transitions

Note. C = consonant; V = vowel.

demonstrate an established level at Level 4 between 9 and 15 months and Level 5 between 16 and 20 months (Nathani et al., 2006). The level with the *highest ratio* was designated as the most frequent level of vocalization for each child. Typically developing children predominantly produce their highest ratio of Level 3 vocalizations between 9 and 15 months and Level 4 vocalizations between 16 and 20 months.

Volubility

The number of utterances per minute of recording, or vocal rate, was used to measure volubility. Prior work has established an average vocal rate of four to five utterances per minute for typically developing infants between 0 and 13 months (Oller et al., 2019).

Consonant Diversity

A consonant inventory was calculated as the total number of different true consonants produced at least once. A "true consonant" is defined as consonants with supraglottal articulation, excluding glides and glottal stops (Vihman et al., 1985). Previous research has reported typically developing infant consonant inventories of six to eight true consonants by the end of the first year (Morgan & Wren, 2018).

Speech Motor Function Classification

Children's speech motor functioning was assessed using laboratory-collected video–audio recordings between 4 and 5 years of age, hereafter Time 2 (M = 60.4, SD = 4.7). During these 1–1.5 hr laboratory visits, children completed a variety of tasks including a caregiver–child interaction session, speech and language standardized testing, and a speech elicitation task using the Test of Children's Speech+ (TOCS+, Hodge et al., 2009). For the purposes of this study, recordings of the caregiver–child interaction and the TOCS+ were used to observe conversational communication and word production during speech.

To classify speech production ability, two research speech-language pathologists (SLPs) observed recordings of the caregiver–child interaction and speech elicitation tasks produced during administration of the TOCS+ at 4–5 years. Both SLPs used the VSS (Pennington et al., 2010) to assign a level to each child. The VSS is a four-level, ordinal rating scale designed to classify speech production in children with CP (see Table 3). It has been validated for children with CP ages 48 months and older (Pennington et al., 2013).

The VSS focuses on functional speaking ability, with a primary emphasis on understandability of speech to listeners. Raters are also encouraged to consider factors such as breath support, phonation, articulation, prosody, and intelligibility when assigning VSS levels. The construct validity of the VSS has been supported by studies demonstrating strong correlations between VSS ratings and broader speech outcomes, including intelligibility and clinical assessments of motor speech functioning across multiple languages (Pennington et al., 2013; Pennington & Hustad, 2019; Seyhan-Biyik et al., 2023; Spaans et al., 2023).

The two research SLPs independently classified all 13 children at a single VSS level. The raters achieved 61.5% agreement, with a moderate level of agreement as indicated by Cohen's kappa (κ = 0.49, 95% confidence interval [CI; .14, .84]). Discrepancies between the two SLPs were settled

Table 3. Viking Speech Scale (Pennington et al., 2010). Printed with permission.

VSS level	Description
VSS I	Speech is not affected by a motor disorder
VSS II	Speech is imprecise but usually understandable to unfamiliar listeners
VSS III	Speech is unclear and not usually understandable to unfamiliar listeners out of context
VSS IV	No understandable speech

Note. VSS = Viking Speech Scale.

through consensus after their independent ratings, and no ratings differed by more than one level.

This study followed the children as part of a natural history design, with diagnoses and co-diagnoses, including CP, reported during laboratory visits between Time 1 (approximately 12 months of age) and Time 2 (4–5 years of age). We note that children were seen regularly between these 2 time points, but in-person visits were not possible because of the COVID-19 pandemic between approximately 2020 and 2022. Not all children had a CP diagnosis; however, the study's focus was on tracking speech motor function and development across a spectrum of risk for CP, regardless of formal diagnostic status.

Reliability of Vocal Coding

To calculate interrater reliability, we randomly selected five 12-month recordings (38%) for coding by a secondary coder, and another five (38%) for recoding by the primary coder to calculate intrarater reliability. We used the intraclass correlation coefficient (ICC; Shrout & Fleiss, 1979) with descriptive interpretations from Koo and Li (2016). We used single score, absolute agreement, two-way random effects models and found good interrater reliability, ICC (2, 1) = 0.85, 95% CI [.82, .89], $p < .001$, and excellent intrarater reliability, ICC (2, 1) = 0.91, 95% CI [.90, .93], $p < .001$.

Analyses

Descriptive trends of vocal complexity level ratios were examined to investigate patterns of infant vocal complexity among children by levels of speech motor impairment. Nonparametric chi-square tests of independence tested the association between each vocal measure at Time 1 and VSS levels at Time 2. Two-tailed Spearman's rank-order correlations (Spearman, 1904) using Cohen's interpretations (Cohen, 1988) were used to assess the strength of these relationships.

Results

A total of 709 utterances were coded and analyzed. SAEVD-R level ratios were interpreted using criteria outlined by Ertmer et al. (2007): *very high* ratios as ≥ 0.60, *high* ratios as 0.40–0.59, *moderate* ratios as 0.20–0.39, *low* ratios as 0.10–0.19, and *very low* ratios as ≤ 0.09. Figure 1 illustrates the five vocal complexity level ratios for each infant at Time 1 grouped by their level of speech motor impairment as measured by the VSS at Time 2.

VSS I

Three children were classified as VSS I at Time 2. They demonstrated low to moderate Level 1 ratios (range: 0.11–0.29), moderate to high Level 2 ratios (0.33–0.58), low to moderate Level 3 ratios (0.14–0.36), and very low Level 4 (0.00–0.09) and Level 5 ratios (0.00–0.03) at Time 1.

VSS II

Five children were classified as VSS II at Time 2. They had a range of low to high Level 1 ratios (0.13–0.43), moderate to high Level 2 ratios (0.29–0.52), a range of very low to high Level 3 ratios (0.05–0.42), low to very low Level 4 ratios (0.00–0.12), and very low Level 5 ratios (0.00–0.08) at Time 1.

Figure 1. Vocal complexity ratios by Viking Speech Scale (VSS) level. Vocal complexity ratios calculated across five Stark Assessment of Vocal Development–Revised (SAEVD-R) levels for individual children at Time 1 grouped by later classified VSS level of speech motor involvement at Time 2. Higher SAEVD-R levels correspond to greater vocal complexity. Higher VSS levels correspond to greater speech motor impairment. The dotted line represents the 0.15 criterion indicating vocal stage attainment.

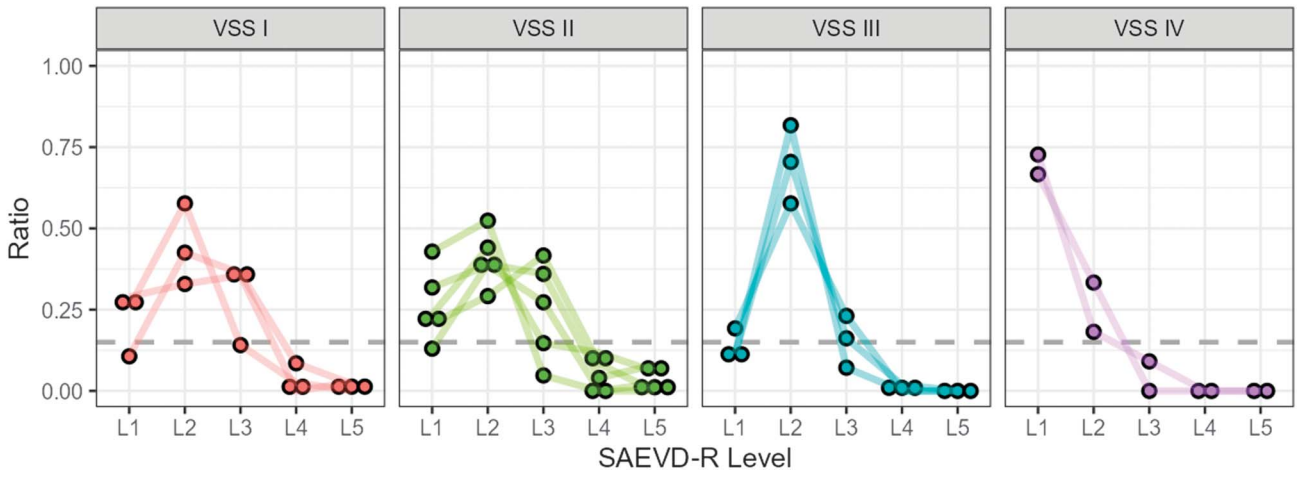


Table 4. Vocal measure by Viking Speech Scale level analyses.

Vocal measure	χ^2	*df*	χ^2 *p* value	ρ
Highest ratio	14.348	6	.026*	−0.657
Established level (≥ 0.15)	3.987	3	.263	−0.352
Vocal rate	39	36	.336	−0.304
Consonant inventory	17.42	12	.135	−0.623

Note. *df* = degrees of freedom.
*$p \leq .05$.

VSS III

Three children were classified as VSS III at Time 2. They demonstrated low Level 1 ratios (0.11–0.19), high to very high Level 2 ratios (0.58–0.82), very low to moderate Level 3 ratios (0.07–0.23), and very low Level 4 (0.00–0.02) and Level 5 ratios (0.00) at Time 1.

VSS IV

Two children were classified as VSS IV at Time 2. They produced very high Level 1 ratios (0.67–0.73), low to moderate Level 2 ratios (0.18–0.33), and very low Level 3 (0.00–0.09), Level 4 (0.00), and Level 5 ratios (0.00) at Time 1.

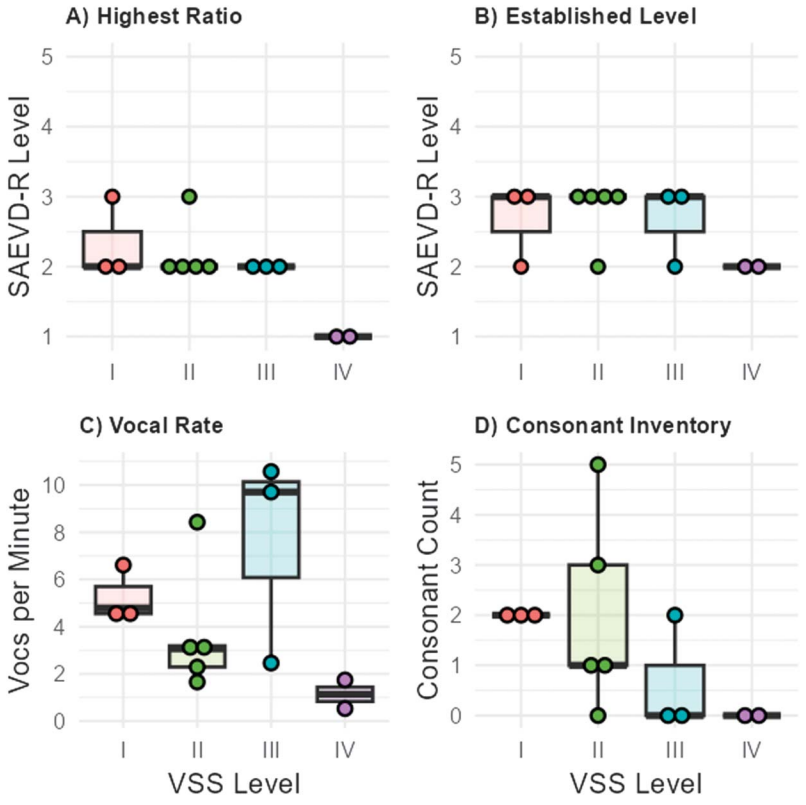
Relationship Between Infant Vocal and Later Speech Motor Function

Chi-square tests of independence and Spearman correlations between each vocal measure at Time 1 by VSS level at Time 2 are listed in Table 4. Data trends are illustrated in Figure 2. The relationship between children's highest ratio and later VSS level was the only significant association found. No other relationships were significant.

Vocal Complexity

Highest ratio. There was a significant negative association between highest ratio and VSS level, $\chi^2(6) = 14.348$, $p = .026$, $\rho = -.657$. The two children with a highest ratio of Level 3 at Time 1 were later classified as VSS I or VSS II. Nine children (69%) had a highest ratio at Level 2, who were classified across VSS Levels I, II, and

Figure 2. Infant vocal characteristics by later Viking Speech Scale (VSS) level. (A) Children's highest ratio of vocalizations across five levels of vocal stage complexity produced at Time 1, grouped by later classified level of speech motor involvement using the VSS at Time 2. (B) Highest established ratio of vocalizations ≥ 0.15 grouped by later VSS level. (C) Infant vocalizations per minute grouped by later VSS level. (D) Number of different true consonants grouped by later VSS level. Lower SAEVD-R levels correspond to lower levels of vocal complexity. Lower VSS levels correspond to more functional speech production with less speech motor involvement. SAEVD-R = Stark Assessment of Vocal Development–Revised.



III. The two children with the highest ratio at Level 1 were both classified as VSS IV. These findings indicate that children in our sample with severe speech motor impairment at Time 2 produced fewer developmentally complex vocalizations in infancy.

Established level. There was not a significant relationship between established level and VSS level (p = .263). Eight children (62%) had an established level at Level 3 at Time 1 who were later classified across VSS Levels I, II, and III. Five children had an established level at Level 2 who were classified across VSS Levels II, III, and IV.

Volubility

The total number of vocalizations produced across children ranged from 6 to 126. There was not a significant relationship between volubility and VSS level (p = .336). The three children later classified as VSS I had an average vocal rate of 5.2 vocalizations per minute (SD = 1.2) at Time 1. Children classified as VSS II and III demonstrated variable vocal rates between two and 10 vocalizations per minute. The two children classified as VSS IV had an average vocal rate of 1.14 per minute (SD = 0.9).

Consonant Diversity

The total number of different true consonants produced across our sample ranged from 0 to 5. There was also not a significant association between children's consonant inventories and VSS level (p = .315). We found a correlation between these variables; however, it was not statistically significant owing to variability among participants and an overall small N. Seven out of eight children who produced at least one true consonant at Time 1 were later classified as VSS I or II. Four out of five children who did not produce any consonants at Time 1 were classified as VSS III or IV.

Discussion

In this pilot study, we investigated the preliminary relationship between infant vocal characteristics at 12 months and later speech motor impairment at 4–5 years as indicated by VSS levels in 13 children at risk for CP. Nonparametric tests were conducted to examine the relationship between four types of vocal measures—vocal complexity, volubility, and consonant diversity—and later VSS levels. We found that children who produced more vocalizations at lower levels of complexity were later classified as having higher VSS ratings, reflecting greater severity of speech motor impairment. Because this study included only thirteen children and because children showed wide variability in their early vocal behavior, we did not have a large enough sample size to observe clinically meaningful trends; however, our findings reveal directions for future study in the early prediction of speech motor impairment.

We used the SAEVD-R to calculate vocal ratios classified across five stages of vocal development. Few studies have used the SAEVD-R with clinical populations (Ha, 2019; Pansy et al., 2019; Ward et al., 2023); however, this approach moves beyond the traditional focus on canonical babbling, as recent research has pointed to the potential significance of marginal babbling in these children (Long & Hustad, 2023; Ward et al., 2023).

Two measures were used to examine vocal complexity, the highest vocal level attained (established level) and the highest rate of complex vocalizations (highest ratio), using a 0.15 criterion as the widely accepted cutoff in infant vocal development research to indicate onset of the canonical babbling stage, specifically. This was a novel approach to examine vocal frequency and stage onset of infants at risk for speech motor impairment as a function of their proportion of vocalizations produced across the five developmental complexity levels. The differences between these two measures may offer unique insights for future work aiming to determine the most appropriate measure to support the early prediction of speech motor impairment in children with CP.

Specifically, children in our sample who produced higher frequencies of vocalizations at the Expansion stage (Level 3) showed significantly less severe VSS levels in later childhood, in line with prior pilot work (Long & Hustad, 2023; Ward et al., 2023). However, we note that some children with more severe VSS levels reached the Expansion stage (Level 3) when the 0.15 criterion was applied. This might suggest that the overall frequency of advanced vocal forms has more potential to differentiate children who later evidence speech motor impairment than the onset of specific vocal stages. Large-scale longitudinal research is necessary to examine this possibility along with the relative sensitivity and specificity of both measures. We note that a criterion of 0.14 was recently found to have slightly better specificity, but the same sensitivity as the 0.15 criterion, for canonical babbling onset in children with neurodevelopmental conditions (Nyman, Strömbergsson, & Lohmander, 2021); thus, the utility of measuring vocal stage onset continues to require further study.

All children in our sample produced very low rates of canonical babbling corresponding to SAEVD-R Levels 4 and 5, irrespective of later speech motor impairment. Previous studies have reported low canonical babbling rates at around 12 months of age in infants with or at risk for CP (Levin, 1999; Nyman & Lohmander, 2018; Ward et al., 2022). We anticipated higher canonical babbling rates in infants later classified as VSS Levels I and II, but our findings suggest broad canonical babbling delays in infants with early neurological disturbances leading to a risk of CP. Studying

longitudinal growth of vocal stages at narrow developmental intervals is likely to be crucial to understanding growth patterns and trajectories, given that all but two children in our study had some functional speaking abilities by 4–5 years of age, as evidenced by VSS Levels of I, II, or III. Older children with CP and speech motor impairment show protracted speech intelligibility growth compared to those without speech motor impairment (Hustad et al., 2020; Mahr et al., 2020), and prior studies with small samples have suggested protracted canonical babbling emergence in children at risk for CP (Long, Eichorn, & Oller, 2023; Ward et al., 2022, 2023). Thus, the consolidation and stabilization of vocal stages warrant further longitudinal research.

Consolidation refers to how children integrate new information into existing schemas, aiding the achievement and preparation for following developmental stages (Piaget, 1960; Pinard & Laurendeau, 1969). Developmental stability, on the other hand, is the ability to buffer developmental trajectories against disturbance (Møller & Swaddle, 1997). A key aspect of the stage model of vocal development is that consolidation of early vocal stages lays the foundation for more advanced stages and speech (Oller, 2000), and prolonged canonical babbling delays are linked to developmental disorders (Lang et al., 2019; Oller et al., 1994). Typically developing infants show a stable, monotonic increase in canonical babbling over time, with more complex vocalizations gradually "replacing" less advanced ones (Lewedag, 1995; Nathani et al., 2006). However, longitudinal canonical babbling instability has been demonstrated in children with Down syndrome and hearing loss (Iyer & Oller, 2008; Lynch et al., 1995) and is suggested in a small number of cases of infants at risk for CP (Long, Eichorn, & Oller, 2023; Ward et al., 2023).

Although the COVID-19 pandemic that occurred in 2020 and beyond prevented us from following the children in our sample at narrow time intervals to track vocal development between the ages of 1 and 5 years, the low canonical babbling rates across our sample at 12 months, irrespective of later speech motor impairment, highlight the need to examine these trajectories into early childhood. This could help us understand how differences in consolidation and stabilization may inform early prediction of speech motor impairment. In our sample, the vocal ratios in Figure 1 suggest an expected consolidation pattern of the Expansion Stage only for children at VSS Levels I and II, but only at a single age (i.e., approx. 12 months). We might hypothesize that these children would also demonstrate greater stability in the emergence of these and more advanced stages throughout the first 2 years. Longitudinal studies will enable testing of these hypotheses around consolidation and stabilization in children with different levels of speech motor impairment.

Regarding volubility, we found no significant differences in the rate of vocalizations per minute, a finding in line with some prior studies on infants at risk for speech motor impairment, although this evidence is mixed (Benassi et al., 2016; McCathren et al., 1999; Rvachew et al., 2005; Töröla et al., 2012; Zuccarini et al., 2018). However, the volubility patterns of children at the poles, VSS Levels I and IV, highlight unique differences to explore in future studies. Typically developing infants produce an average of four to five vocalizations per minute throughout the first year (Oller et al., 2019). The three infants later classified with no speech motor impairment (VSS I) demonstrated comparable rates to these norms. Conversely, the two children later classified with severe speech motor impairment (VSS IV) produced the lowest vocal rates of our sample, at or below two utterances per minute. Children between these levels showed variability. The mixed prior evidence and our small sample size limit conclusions about these patterns. Factors such as positioning, neck and trunk control, respiratory support for phonation, and temperament may also influence volubility in this population. Thus, the utility of using vocal rate to predict speech motor impairment remains unclear.

A similar trend was observed in the consonant inventories for children at the poles of VSS levels. All three children later classified with no speech motor impairment (VSS I) produced two different true consonants, while both children with severe speech motor impairment produced no consonants. Infants between these levels again showed variability. Notably, no children produced the age-expected six to eight different consonants at Time 1, highlighting the earlier discussed broad delays in producing consonants. Tracking the longitudinal development of consonant inventories may be promising for clinical use due to its relative ease in parent-reported screening and given that it already exists in commonly used tools like the Preschool Language Scales screening tool (Zimmerman et al., 2012).

This study aimed to classify the level of speech motor involvement in children at risk for CP, regardless of whether they had received a formal CP diagnosis by the Time 2 assessment. As a natural history study, children were recruited based on birth-risk factors associated with CP. Diagnoses and co-diagnoses, including CP, were reported over time between the Time 1 and Time 2 assessments. By the Time 2 visit, some children had received a formal diagnosis of CP, while others had not. Our findings suggest that the speech motor impairment patterns observed in this study are relevant across this spectrum of risk, highlighting the importance of monitoring speech motor function in all children at risk of CP, irrespective of diagnostic outcomes.

A primary goal of this work is to determine whether reliable markers for predicting speech motor impairment exist and to translate the findings to clinical practice. Additional research is necessary to develop and validate

assessment tools that capture vocal markers of impairment and monitor developmental progress in infants at risk. Adapting the SAEVD-R tool to a parent-reported ordinal classification system like the VSS is one potential avenue to advance this goal. Our study presents pilot data to support the development of data-driven hypotheses for identifying the most reliable markers for speech motor impairment to aid in the development of these future tools for children with CP. Future research should examine how formal diagnosis and early interventions influence speech motor development and outcomes over time.

Limitations

Several limitations of our study should be noted. First, our study is preliminary with a small sample size, so clinical interpretations should be made with caution. Although our sample included children at risk for CP, the diversity of diagnoses adds further complexity to the generalization of findings to specific neurodevelopmental conditions. Identifying and recruiting infants with a confirmed diagnosis of CP continues to pose challenges for studies on the early prediction of speech motor impairment, especially given the heterogeneous outcomes of children regardless of later diagnoses. Recent advancements in early CP detection guidelines offer potential to address these challenges in future research (Maitre et al., 2020, 2023; Novak et al., 2017), although further work is needed to understand the early communication developmental trajectories in these children.

We did not examine differences in intellectual or language functioning due to current limitations in testing cognitive abilities in very young children with motor limitations. Future work is necessary to examine longitudinal trajectories of vocal stage emergence across children based on language and intellectual abilities given their tight link to speech development. Future work should also increase the racial and socioeconomic diversity of samples to account for social determinants of health that may influence vocal development and caregiver–child interactions.

Despite these limitations, ongoing work based on our findings has potential to improve the early prediction of speech motor impairment. This work could reduce reliance on the wait-and-see approach to monitoring communication development and enable targeted speech and/or AAC therapies at earlier ages to enhance long-term communication outcomes in this population.

Conclusions

Future research should further explore the development of vocal characteristics across the first 2 years to determine their predictive value for speech motor impairment levels in children with CP. Our findings suggest that the frequency of increasingly complex vocalizations may be particularly important to investigate longitudinally. While our small sample warrants caution in interpreting specific findings, these pilot data are essential for informing future studies aimed at improving the early prediction of speech motor impairments. This work highlights the critical importance of facilitating early referrals and achieving optimal communication outcomes in children with CP.

Data Availability Statement

Raw audio recordings are identifiable and restrictions on access are required to protect the privacy and confidentiality of participants due to Health Insurance Portability and Accountability Act requirements. Data analysis materials are available on the Open Science Framework: https://osf.io/7t35n/.

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