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Authors
Nip, Ignatius SB
Garellek, Marc

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Research Note

Voice Quality of Children With Cerebral Palsy

Ignatius S. B. Nip[a] and **Marc Garellek**[b]

Purpose: Many children with cerebral palsy (CP) are described as having altered vocal quality. The current study utilizes psychoacoustic measures, namely, low-amplitude (H1*–H2*) and high-amplitude (H1*–A2*) spectral tilt and cepstral peak prominence (CPP), to identify the vocal fold articulation characteristics in this population.
Method: Eight children with CP and eight typically developing (TD) peers produced vowel singletons [i, ɑ, u] and a story retell task with the same vowels in the words "beets, Bobby, boots." H1*–H2*, H1*–A2*, and CPP were extracted from each vowel. Results were analyzed with mixed linear models to identify the effect of Group (CP, TD), Task (vowel singleton, story retell), and Vowel [i, ɑ, u] on the dependent variables.
Results: Children with CP have lower spectral tilt values (H1*–H2* and H1*–A2*) and lower CPP values than their TD peers. For both groups, vowel singletons were associated with lower CPP values as compared to story retell. Finally, the vowel [ɑ] was associated with higher spectral tilt and higher CPP values as compared to [i, u].
Conclusions: Children with CP have more constricted and creaky vocal quality due to lower spectral tilt and greater noise. Unlike adults, children demonstrate poorer vocal fold articulation when producing vowel singletons as compared to story retell. Finally, low vowels like [ɑ] seem to be produced with less constriction and noise as compared to high vowels.

Cerebral palsy (CP) is a group of disorders caused by perinatal damage to the central nervous system resulting in movement, sensory, communication, and cognitive impairments (Rosenbaum et al., 2007). Many children with spastic CP have dysarthria (Cockerill et al., 2014; Himmelmann & Uvebrant, 2011; Hustad et al., 2010; Nordberg et al., 2013; Otapowicz et al., 2007; Parkes et al., 2010). Dysarthria is a neuromotor speech disorder that results in reduced intelligibility (e.g., Ansel & Kent, 1992; Hodge & Gotzke, 2014b; Hustad et al., 2012; Nip, 2017; Patel, 2002; Pennington et al., 2006), increased production errors (Kim et al., 2011; Nordberg et al., 2014; Whitehill & Ciocca, 2000), and slower speaking rates (Darling-White et al., 2018; Hodge & Gotzke, 2014a; Hustad et al., 2010; Nip, 2012).

These children also have voice changes including reduced ability to manipulate loudness (Patel, 2002, 2003; Workinger & Kent, 1991) and altered voice quality (Allison & Hustad, 2014; Hanson et al., 2001; Nip, 2017; Workinger & Kent, 1991). Voice quality appears to be a highly salient feature for individuals who listen to dysarthric speech (Lansford et al., 2014), and studies have demonstrated that listeners will rate these children as having strained–strangled, harsh, wet hoarseness, and creaky voice qualities (Nordberg et al., 2014). Furthermore, the voice quality differences observed in this group are inconsistent. Voice quality changes in children with CP are only present during a portion of the sentence rather than being sustained throughout (Allison & Hustad, 2014).

Although previous research has identified that voice quality differences are present (e.g., Ansel & Kent, 1992; Hanson et al., 2001; Workinger & Kent, 1991), few studies have attempted to quantify these differences, which is needed to identify the underlying cause of the voice quality differences in this population. One approach has been to use rating scales (e.g., Schölderle et al., 2016); however, such approaches do not provide information about vocal fold articulation. Furthermore, one difficulty in quantifying voice quality differences in this population, which would provide a window into vocal motor control, is determining which variables to examine. For example, observations of spectrograms (e.g., Hanson et al., 2001) can identify that the acoustic signal is noisier and less stable than in healthy controls. However, variables that may be associated with stability in individuals with dysphonia, such as jitter and shimmer, were not able to distinguish the voices of children with CP from

[a]San Diego State University
[b]University of California, San Diego
Correspondence to Ignatius S. B. Nip: inip@sdsu.edu
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their typically developing (TD) peers (Lee et al., 2014). Therefore, our understanding of how the vocal folds function differently in children with CP is still incomplete.

Motor Control

Because CP is a neuromotor disorder, speech motor control is the likely reason for differences in speech and voice production between children with dysarthria secondary to children with CP and TD peers (Hustad et al., 2012; Nip, 2017; Nip et al., 2017). Multiple acoustic studies suggest that although articulatory motor control accounts for over 50% of the variance in speech intelligibility of children with dysarthria secondary to spastic CP, laryngeal control is the next biggest contributor to intelligibility (Lee et al., 2014). Furthermore, laryngeal control may actually play a larger role in intelligibility for speakers of languages that rely on tonal contrasts, such as Cantonese. For instance, 62% of the variance of intelligibility can be accounted for by articulatory movements for English speakers of adults with dysarthria secondary to CP (Ansel & Kent, 1992). However, in Cantonese, which uses tonal contrasts to distinguish lexical items, articulatory control accounts for approximately 38% of the variance for intelligibility, whereas laryngeal functioning is responsible for 43% of the variance (Whitehill & Ciocca, 2000). Laryngeal functioning accounts for a smaller yet significant proportion of the variance for intelligibility in English speakers in children with dysarthria secondary to CP (Lee et al., 2014).

Because children with CP demonstrate oral articulatory movement differences when compared to their TD peers, potentially the voice quality differences observed in children with CP may be due to motor control deficits of the laryngeal subsystem and/or coordination of the laryngeal and respiratory subsystems. Therefore, examining acoustic variables that provide information of vocal fold articulation may provide a greater understanding of the laryngeal functioning in this population. The goal of this study is therefore to determine how children with CP differ from their TD peers in terms of their voice quality and vocal functioning.

Measuring the Acoustics of Voice Quality

The acoustic correlates to perceived changes in voice quality can be measured using both temporal and spectral domains. Of particular interest for our study is to determine how the voice quality differences between TD children and those with CP relate both to possible differences in vocal fold articulation and to changes in perceived quality. Consequently, we choose to focus on three acoustic measures: low-frequency spectral tilt (H1*–H2*, the difference in amplitude between the first and second harmonics), high-frequency spectral tilt (H1*–A2*, the difference in amplitude between the first harmonic and the harmonic nearest the second formant), and cepstral peak prominence (CPP).

Spectral tilt and noise measures, when analyzed together, provide appropriate differentiation of voice qualities ranging from modal, breathy, creaky, and pressed (Garellek, 2019). Additionally, studies have shown that H1*–H2*, H1*–A2*, and CPP are perceptible to listeners of American English (Garellek et al., 2016; Hillenbrand et al., 1994; Kreiman & Gerratt, 2010, 2012) and that they relate systematically to changes in vocal fold articulation. Both spectral tilt measures H1*–H2* and H1*–A2* are correlated with changes in glottal open quotient and constriction; the more the open the vocal folds are over the course of a glottal cycle, the higher the value of H1*–H2* and H1*–A2* (Kreiman et al., 2012; Samlan & Story, 2011; Samlan et al., 2013; Zhang, 2016). The asterisks in these measures' names indicate that they are taken from the audio output (rather than from the voice source) and are corrected for the effects of vowel formants and bandwidths. The correction thus facilitates cross-vowel comparisons (see Hanson, 1997; Iseli et al., 2007). Both H1*–H2* and H1*–A2* were included because some children with spastic CP (e.g., Fox & Boliek, 2012; Nip, 2017) have been reported to have a strained–strangled or pressed voice quality. Such voice quality may be reflected in lower H1*–H2* and lower H1–A2* values, the latter of which might be related to the closing velocity of the vocal folds, to the presence of a posterior glottal opening, and to the simultaneity of ligamental closure (Hanson et al., 2001; Stevens, 1977).

We will also investigate changes in CPP, a harmonics-to-noise ratio measure that is correlated with noise due to aspiration (derived from glottal spreading) and irregular vocal fold vibration common during creaky voice or asymmetrical vocal fold vibration (Garellek, 2019; Samlan & Kreiman, 2014; Zhang et al., 2013). Some children with a mild dysarthria secondary to spastic CP may demonstrate more use of creaky voice or glottal fry (e.g., Nip, 2017), which may be observed as lower CPP values (e.g., Keating et al., 2015). Another advantage of analyzing spectral tilt measures in conjunction with a harmonics-to-noise ratio measure such as CPP is that the articulatory basis of changes in spectral tilt measures can be difficult to interpret in isolation (Garellek, 2019; Garellek & White, 2015; Simpson, 2012). Finally, having objective measures of vocal functioning obtained from acoustic recordings would be a first step in identifying norms that distinguish between normal and disordered phonation in children and provide clinicians with a noninvasive way to estimate laryngeal functioning in children with CP.

Task Demands

Increasingly, recent research demonstrates that task demands alter the speech motor control of both TD children and children with CP. Furthermore, these task demands are present from early childhood and into adulthood. For example, very young TD children move their lips and jaw with faster speeds and larger movements (Nip et al., 2009). In addition, language formulation demands (e.g., retelling a story vs. repeating sounds) can affect speeds and magnitude of movements (Nip & Green, 2013). Other studies have also shown that factors such as syntax (Kleinow & Smith, 2006), syllable structure (Goffman & Malin, 1999), and semantics (Gladfelter & Goffman, 2013) can change speech movements in TD children. Similarly, task effects affect speakers with CP. These speakers also produce larger oral movements when producing tasks with greater language formulation demands, such as stories (Nip, 2012). In addition, coordination between articulators in children with CP and TD children was best for sentences in comparison to syllables (Nip, 2017).

No similar investigation of task effects has been reported for laryngeal control for this population. If speech motor control similarly affects laryngeal functioning and/or laryngeal–respiratory coordination as it does oral articulation, it might be expected that task demands would affect voice quality in children with CP. Adults with and without voice disorders do not demonstrate voice quality changes between connected speech and isolated vowels (Gerratt et al., 2016). However, speech motor control is known to change over development and may last into adolescence (Nip et al., 2009; Walsh & Smith, 2002). Furthermore, it has been suggested that speech production that requires holding static postures (e.g., fricatives) may be more difficult for those with more immature or impaired speech motor control (Kent, 1992). Potentially, children with impaired and immature speech motor control, such as children with CP, may show voice quality differences between vowels produced in connected speech as compared to isolated vowels, which are typically extended in duration and require a more static posture.

Research Questions

In the current study, we attempt to determine how acoustic measures in voice quality differ in children with CP and their TD age- and sex-matched peers in vowels produced in isolation and story retell. We hypothesize that, overall, children with CP will have more constricted and irregular vocal qualities, as indexed by lower spectral tilt (H1*–H2* and H1*–A2*) values and lower CPP. Furthermore, we hypothesize that there will be differences between tasks (vowels in isolation vs. in a story retell task) on these measures.

Method

Participants

Eight children with CP and eight age- and sex-matched TD peers were included from a larger project for this study. The ages of the participants ranged from 4 to 15 years (M = 10;0 [years;months], SD = 3;2). Table 1 shows the characteristics of the participants. Three certified speech-language pathologists (SLPs) each with at least 15 years of clinical experience, including the first author, identified the voice quality characteristics of the children with CP. When there were differences between raters, all three SLPs would discuss their clinical judgments until a consensus was attained. All participants passed a hearing screening at 0.5, 1, 2, and 4 kHz in at least one ear. Intelligibility was assessed using the Test of Children's Speech+ (Hodge et al., 2009), and language was assessed using the Clinical Evaluation of Language Fundamentals–Fourth Edition (Semel et al., 2004). Voice quality was determined by consensus between three certified SLPs.

Data Collection

Participants were audio recorded (16 bits, 44.1 kHz) using a head-mounted microphone. Participants were recorded while producing the vowel sequence [i, ɑ, u] 10 times and during a story retell task. The task used to elicit the story retell was the" Bats, Boots, Beets" story (Green et al., 2010) that has been used with children and adolescents in previous studies (Nip & Green, 2013). The story elicits productions of the corner vowels in a consistent phonetic /bVC/ context (i.e., /i/ in /bits/, /u/ in /buts/, and /ɑ/ in /bɑbi/ or "Bobby"). In the story task, we were able to extract an 8–17 repetitions of [i] and [u] but only four to five repetitions of [ɑ] for each participant. One participant (Speaker 4 in the CP group) was unable to complete the story retell task.

Data Analysis

The corner vowels [i, ɑ, u] were identified for each participant and task in Praat. The vowels were extracted from the story retell from the words "beets" [i], "boots" [u], and "Bobby" [ɑ]. Each vowel production was analyzed with VoiceSauce (Shue et al., 2011) to obtain values of H1*–H2*, H1*–A2*, and CPP. VoiceSauce (Shue et al., 2011) calculates the amplitude of each harmonic. The algorithm then takes into account the formants, which would amplify the surrounding harmonics, so that it can correct the harmonic amplitudes that are affected by formant frequencies and their bandwidths. This method allows for estimation of quantitative measures of vocal fold articulation independent of oral articulation (as this would impact the harmonics). Therefore, articulation (imprecise or otherwise) should not affect these measures. We included both the low-frequency spectral tilt measure H1*–H2* and the wider-band H1*–A2* because they provide slightly different information about spectral slope. H1*–H2* is correlated with the glottal open quotient (Kreiman & Gerratt, 2012; Samlan et al., 2013) and different degrees of medial fold stiffness (Zhang, 2016). In contrast, the amplitude of higher frequencies in the spectrum (such as those that can affect A2) may instead be related to vocal fold closing speed and symmetry (Hanson et al., 2001; Stevens, 1977). CPP is used as a measure of both aspiration noise and the regularity of vocal fold vibration (Blankenship, 1997; Hillenbrand et al., 1994; see discussion in Garellek, 2019).

We first screened the data for outliers by participant. Outlier values were winsorized (Blaine, 2018) to reduce the bias of extreme values. Mixed linear models were estimated using PROC MIXED for each of the three dependent variables using SAS 9.4 (SAS Institute Inc., 2014) with Participants

Table 1. Participant characteristics.

Speaker	Age (years; months)	Sex	CP type	GMFCS	Dysarthria/ speech	Voice quality	Word intelligibility	Sentence intelligibility	CELF-4 *SD* score	Age of TD peer (years; months)
1	4;8	F	Spastic quadriplegia	V	Spastic	Strained–strangled	23%	16%	106	4;7
2	6;6	M	Spastic diplegia	III	Spastic	Mild strain	72%	83%	106	6;2
3	7;5	F	Spastic hemiplegia	III	Mild	Mild strain/fry	68%	65%	102	7;4
4	9;2	M	Spastic diplegia	II	Mild	Mild strain	80%	72%	98	8;4
5	9;9	M	Spastic hemiplegia	III	Mild	Mild strain	81%	66%	67	9;4
6	10;7	M	Spastic quadriplegia	IV	/r/ error	Mild strain	85%	96%	127	10;11
7	12;4	M	Spastic diplegia	II	None	WNL	91%	95%	112	13;2
8	15;0	F	Spastic diplegia	II	None	Occasional fry	82%	93%	129	15;7

Note. CP = cerebral palsy; GMFCS = Gross Motor Functional Classification Scale; CELF-4 = Clinical Evaluation of Language Fundamentals–Fourth Edition; TD = typically developing; F = female; M = male; WNL = within normal limits.

used as the repeated factor. All models included Group (CP, TD), Task (isolation, story retell), and Vowel ([i, ɑ, u]) and their interactions. Age and Sex were included as covariates for all models. To account for multiple comparisons, we used an α level of .01 to identify which results were significant. Using GLIMMPSE (Kreidler et al., 2013), all comparisons were determined to have power > 0.9.

Results

Low-Frequency Spectral Tilt (H1–H2*)*

The findings for H1*–H2* are shown in Table 2 and Figure 1. Means and standard error of the means for all variables are shown in Table 3. For H1*–H2*, a measure of glottal open quotient and constriction, here was a main effect of Sex, $F(1, 918) = 15.77$, $p < .001$, with females having greater spectral tilt than males. There was a significant main effect for Group, $F(1, 938) = 8.24$, $p < .01$, with the TD group having greater low-frequency spectral tilt than the CP group. There was also a main effect of Vowel, $F(2, 937) = 30.46$, $p < .001$, with [i] having significantly lower spectral tilt than [ɑ] or [u]. There was also a main effect of Task, $F(1, 938) = 12.02$, $p < .001$, with greater spectral tilt for stories than sustained vowels. There was a significant Group × Vowel interaction, $F(2, 937) = 5.95$, $p < .01$, which indicated that the spectral tilt difference for vowels is only found for the TD group. Finally, there was a significant Task × Vowel interaction, $F(2, 937) = 4.71$, $p < .01$, that demonstrated that [i] had significantly lower spectral tilt than the other two vowels for the sustained vowel task. Furthermore, [i] had significantly lower spectral tilt for [u] for the story task. There was no significant main effect of Age. There were no Group × Task and Group × Task × Vowel interactions.

Table 2. Statistical model for H1*–H2*.

Variable	*df*	*df* error	*F*	*p*
Age	1	940	0	.98
Sex	1	918	15.77	< .0001
Group	1	938	8.24	.004
Task	1	938	12.02	.0005
Vowel	2	937	30.46	< .0001
Group × Task	1	938	0.3	.58
Group × Vowel	2	937	5.95	.003
Task × Vowel	2	937	4.71	.009
Group × Task × Vowel	2	937	0.28	.76

Note. Significant at the *p* < .01 level.

High-Frequency Spectral Tilt (H1–A2*)*

The results for H1*–A2* are shown in Table 4 and Figure 2. The mixed linear model for mean H1*–A2* found a significant main effect of Age, $F(1, 925) = 21.48$, $p < .001$, indicating that spectral tilt decreased significantly with age. There was also a main effect of Group, $F(1, 930) = 8.52$, $p < .01$, with the TD group having greater spectral tilt than the CP group. There was also a significant main effect of Vowel, $F(2, 931) = 151.63$, $p < .001$, with [ɑ] having significantly higher spectral tilt than [u], which in turn had significantly higher spectral tilt than [i]. There was a significant Group × Vowel interaction, $F(2, 931) = 26.67$, $p < .001$. Specifically, the TD group had higher spectral tilt than the CP group for [ɑ] and lower spectral tilt than the CP group

Figure 1. H1*–H2* for the cerebral palsy (CP) and typically developing (TD) groups by task and vowel.

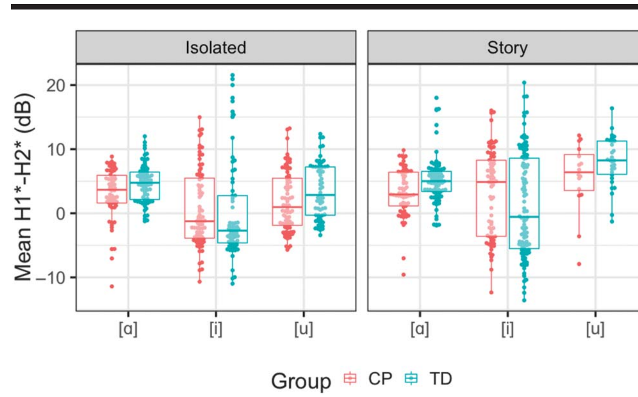


Table 3. Means and standard error of the means for H1*–H2*, H1*–A2*, and cepstral peak prominence (CPP) for the cerebral palsy (CP) and typically developing (TD) groups by task.

	CP		TD	
Vowel	**Story**	**Sustained**	**Story**	**Sustained**
		H1*–H2*		
ɑ	3.07 (1.59)	3.34 (1.45)	4.71 (1.33)	4.78 (1.18)
i	2.41 (2.48)	0.60 (2.06)	1.61 (2.79)	0.12 (2.55)
u	4.10 (2.14)	1.98 (1.65)	7.10 (2.14)	3.88 (1.63)
		H1*–A2*		
ɑ	18.28 (3.62)	18.24 (2.40)	22.67 (3.51)	24.10 (3.21)
i	11.02 (3.79)	12.38 (3.70)	9.40 (3.39)	6.35 (3.48)
u	15.97 (2.40)	16.49 (2.24)	20.89 (2.77)	19.72 (2.18)
		CPP		
ɑ	19.64 (3.31)	20.52 (1.18)	22.51 (1.12)	22.33 (0.95)
i	17.77 (2.82)	18.74 (1.06)	20.14 (1.21)	20.53 (0.87)
u	16.62 (2.91)	16.08 (0.83)	19.15 (1.32)	16.33 (0.59)

for [i]. There were no differences between the groups for [u]. For both groups, [i] has lower spectral tilt than [ɑ] or [u]. There was no significant main effects of Sex or Task. The interactions for Group × Task and Task × Vowel and the three-way interaction of Group × Task × Vowel were not significant.

CPP

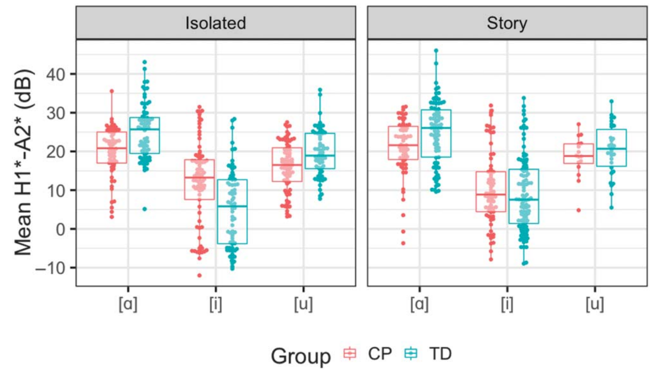
The model for CPP (see Figure 3 and Table 5) found a significant main effect of Age, $F(1, 643) = 157.53$, $p < .001$, with older participants having greater CPP values than younger participants. There was a significant main effect of Group, $F(1, 636) = 42.68$, $p < .001$, with TD participants having greater CPP values than the participants with CP. A significant main effect of Vowel, $F(2, 638) = 61.16$, $p < .001$, demonstrated that [ɑ] had significantly greater CPP values than [i], which had significantly greater CPP values than [u]. There was a significant Task × Vowel interaction, $F(2, 638) = 5.14$, $p < .01$. The sustained vowels demonstrated significantly greater CPP values for [ɑ] than [i], which was significantly greater than [u], whereas for the stories, [ɑ] had significantly greater CPP values than the other two vowels. There was no significant main effect of Sex or Task, and there were neither significant Group × Vowel and Group × Task interactions nor a significant three-way interaction.

Table 4. Statistical model for H1*–A2*.

Variable	*df*	*df* error	*F*	*p*
Age	1	925	21.48	< .0001
Sex	1	942	3.86	.05
Group	1	930	8.52	.004
Task	1	930	0.04	.84
Vowel	2	931	151.63	< .0001
Group × Task	1	930	2.02	.16
Group × Vowel	2	931	26.67	< .0001
Task × Vowel	2	931	0.79	.45
Group × Task × Vowel	2	931	2.49	.08

Note. Significant at the $p < .01$ level.

Figure 2. H1*–A2* for the cerebral palsy (CP) and typically developing (TD) groups by task and vowel.



Discussion

The current study examined quantitative measures of voice quality obtained from children with CP and their TD peers. Analyses from the current study indicated that children with CP do have a different voice quality than their TD peers, which could detrimentally affect their ability to communicate effectively.

Vowels Differ in Spectral Tilt and CPP

Both the CP and TD groups had higher values of H1*–H2* and H1*–A2* for [ɑ, u] than [i]. Similarly, CPP values were highest (least noisy) for [ɑ]. Overall, the findings suggest that for both groups, [ɑ] may be produced with the least constricted and most regular vocal quality. This suggests that producing a vowel that requires a low jaw and tongue position may facilitate a less constricted voice quality. These results are somewhat surprising, given that constricted

Figure 3. Cepstral peak prominence (CPP) for the cerebral palsy (CP) and typically developing (TD) groups by task and vowel.

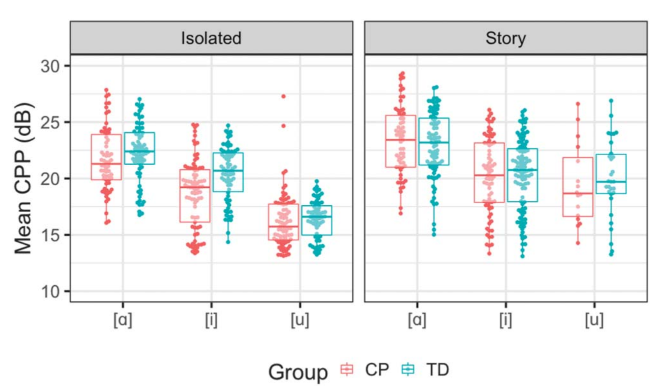


Table 5. Statistical model for cepstral peak prominence.

Variable	*df*	*df* error	*F*	*p*
Age	1	643	157.53	< .0001
Sex	1	693	5.51	.02
Group	1	636	42.68	< .0001
Task	1	636	0.62	.43
Vowel	2	638	61.16	< .0001
Group × Task	1	637	3.69	.06
Group × Vowel	2	638	0.67	.51
Task × Vowel	2	638	5.14	.006
Group × Task × Vowel	2	638	0.61	.54

Note. Significant at the $p < .01$ level.

voice quality and glottal stops are more often associated with lower vowels than with higher ones, in terms of both vowel identification and phonological patterning (Esling et al., 2019).

Children With CP Have Lower Spectral Tilt and CPP Values

The results for both spectral tilt measures, H1*–H2* and H1*–A2*, suggest that the CP group had more constricted voice quality (lower spectral tilt) than their TD peers. This constricted voice quality appears to affect how listeners judge the speech of individuals with dysarthria. Preferred speech samples have a more equal distribution of energy across the harmonics (Neel, 2009). Potentially, with a more constricted voice quality, listeners may detect more energy in high-frequency harmonics than what is typically expected, and studies have suggested that an optimal spectral tilt is required for good speech intelligibility (Lu & Cooke, 2009).

Overall, the TD group had generally higher spectral tilt values in the low-frequency range (H1*–H2*). This finding may relate to other studies hypothesizing that force control in the articulators, such as in the jaw, is impaired in children with CP (e.g., Nip, 2012; Nip et al., 2017). Similarly, children with CP may not be able to make fine adjustments to the vocal folds to change H1*–H2*, which is closely related to open quotient and vocal fold thickness. However, the findings were more mixed for high-frequency spectral tilt (H1*–A2*), which reflects vocal fold closing velocity and symmetry (Hanson et al., 2001; Klatt & Klatt, 1990; Kreiman & Gerratt, 2012; Stevens, 1977; Zhang, 2016). The TD group had higher H1*–A2* values than the CP group for [ɑ], but the opposite pattern emerged for [i], and there were no group differences for [u]. As noted above, [a] appears to be produced with the least amount of constriction and the most regularity of vocal fold vibration. Potentially, this feature most facilitates vocal fold closing velocity and symmetry for the TD group, whereas having more constriction and less regularity of vocal fold vibration facilitates vocal fold closing velocity and symmetry for the CP group. Further investigation is required to determine why there is a differential effect of vocal tract configuration on H1*–A2* between these two groups.

Similarly, the CPP indicated that the CP group had more noise (i.e., lower CPP values) than their TD peers. CPP relates to vocal qualities of breathiness, roughness, and voicing irregularity at the level of the vocal folds (Blankenship, 2002; Fraile & Godino-Llorente, 2014; Garellek, 2019; Hillenbrand et al., 1994). Taken together with the findings for H1*–H2* and H1*–A2*, the current results indicate that we can quantify the irregular creaky (perhaps also pressed) phonation observed clinically in this population (e.g., Nordberg et al., 2014).

Task Differences Between Vowels in Isolation and Story Retell

Furthermore, previous studies using acoustic measures of the voice source suggest that voice quality may not differ for vowels produced in isolation or connected speech. For example, Gerratt et al. (2016) noted that vowels produced in isolation did not differ from vowels produced during a story retell task in adults. However, the current findings suggest that task differences exist for children with CP and their TD peers. CPP had significantly lower values for isolated vowels as compared to the story retell task for [ɑ] and [u], suggesting that isolated vowels are produced with more noisy vocal fold vibration for both groups. A potential explanation for the difference between the current study and the Gerratt et al. study may be due to the younger age group in the current study. Speech motor control is known to be prolonged into adolescence for the oral articulators (Kleinow et al., 2001; Nip & Green, 2013), and this may also be true for laryngeal control. From a clinical perspective, this suggests that psychoacoustic assessment of voice quality of children should include sampling the voice source in vowels produced in isolation and in connected speech.

Another explanation for the presence of task effects may be that one task is more habitual and preferred (e.g., words) than the other task. Previous studies in this population have demonstrated that preferred habitual tasks such as simple sentences are produced with more coordination in both children with CP and their TD peers (Nip, 2017). In a dynamic systems perspective (Thelen, 1991), simple sentences may be the preferred attractor state (Nip, 2017). In articulatory studies, speechlike tasks such as diadochokinetic repetition of syllables (e.g., "papapapa") will differ in movement characteristics, such interarticulator coordination, from more habitual speech tasks such as sentence repetition (Nip, 2017).

A similar reason may explain why the isolated vowels differed from the story retell task. In speech, vowels are produced in utterances where both vowels and consonants are produced and without prolonged vowel durations. Potentially holding a specific articulatory and laryngeal posture may impact vocal fold articulation, resulting in less efficient laryngeal movements and greater noise at the glottis.

Finally, the findings that noisier vocal quality is associated with vowel singletons as compared to story retell also contrast recent studies demonstrating that voice quality in children is worse in longer utterances (e.g., sentences vs. words; Allison & Hustad, 2014). Part of the reason for the difference in findings are likely due to methodological issues. Allison and Hustad (2014) used a hybrid acoustic–perceptual method to identify the proportion of an utterance where dysphonic qualities were present. This study examined the voice source during vowels produced as a singleton or as part of a word. This finding suggests that these vocal fold articulation differences may not always be perceptible to even a trained listener.

Clinical Implications and Limitations

Previous findings examining clinical judgments supplemented with acoustic analyses have demonstrated that children with CP are more likely to have changes to their voice quality when producing sentences rather than single words (Allison & Hustad, 2014). As Allison and Hustad (2014) note, this finding demonstrates that voice quality is significantly different in children with CP than their TD peers, but this does not provide information about vocal fold functioning during speech production in these children. Other studies that have evaluated variables associated with laryngeal dysfunction, such as shimmer and jitter, have not found significant differences between these groups of children (Lee et al., 2014). A reason for this finding may be that although shimmer and jitter are sometimes associated with the severity of the voice disorders (e.g., Parsa & Jamieson, 2001; Wolfe et al., 1995), these variables can be difficult to extract reliably during irregular vocal fold vibration (Kreiman & Gerratt, 2005) and therefore may not be the best acoustical variables to quantify voice quality. A possible confounding factor might be the higher nasality that could be observed for the CP group. If there was hypernasality in the CP group overall, then a higher F1 for both [i, u] compared to TD would be expected, because both vowels' low F1 would be affected by the first nasal pole, which in adults occurs between 250 and 450 Hz. However, the findings do not reflect this pattern so there is likely no main effect of nasality by group. Furthermore, increased nasality would be expected to raise H1 because the first nasal pole would have a similar frequency to H1. This effect would raise spectral tilt for the CP group compared to the TD group. However, the CP group has lower H1*–H2* and H1*–A2* for some vowels.

The current study is an initial attempt to quantify voice quality and identify vocal fold articulation patterns in children with CP and their TD peers. Although it provides valuable information about these patterns, the sample size of the current study is small and only includes children with spastic CP, which limits the generalizability of the findings. Future studies examining larger groups of children and inclusion of other types of CP, such as dyskinetic CP, should be conducted to determine if the patterns found in this study are replicated in larger studies.

Author Contributions

Ignatius S. B. Nip: Conceptualization (Lead), Formal analysis (Lead), Investigation (Lead), Writing – original draft (Lead), Writing – review & editing (Lead). **Marc Garellek:** Formal analysis (Supporting), Writing – original draft (Supporting), Writing – review & editing (Supporting).

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