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Research Article

Relative Fundamental Frequency in Children With and Without Vocal Fold Nodules

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Purpose: Relative fundamental frequency (RFF) is an acoustic measure that is sensitive to functional voice differences in adults. The aim of the current study was to evaluate RFF in children, as there are known structural and functional differences between the pediatric and adult vocal mechanisms.

Method: RFF was analyzed in 28 children with vocal fold nodules (CwVN, M = 9.0 years) and 28 children with typical voices (CwTV, M = 8.9 years). RFF is the instantaneous fundamental frequency (f_0) of the 10 vocalic cycles during devoicing (vocal offset) and 10 vocalic cycles during the revoicing (vocal onset) of the vowels that surround a voiceless consonant. Each cycle's f_0 was normalized to a steady-state portion of the vowel. RFF values for the cycles closest to the voiceless consonant, that is, Offset Cycle 10 and Onset Cycle 1, were examined.

Results: Average RFF values for Offset Cycle 10 and Onset Cycle 1 did not differ between CwVN and CwTV; however, within-subject variability of Offset Cycle 10 was decreased in CwVN. Across both groups, male children had lower Offset Cycle 10 RFF values as compared to female children. Additionally, Onset Cycle 1 values were decreased in younger children as compared to those of older children.

Conclusions: Unlike previous work with adults, CwVN did not have significantly different RFF values than CwTV. Younger children had lower RFF values for Onset Cycle 1 than older children, suggesting that vocal onset f_0 may provide information on the maturity of the laryngeal motor system.

The presence of dysphonic vocal quality in a child can have significant negative functional, physical, emotional, and social impacts (Carroll, Mudd, & Zur, 2013; Connor et al., 2008; Verduyckt, Remacle, Jamart, Benderitter, & Morsomme, 2011). Whereas there is a previously held belief that children with voice disorders are not aware of changes in their own voice (e.g., Andrews, 1986), studies have shown that children with voice disorders have negative feelings about their vocal quality (Connor et al., 2008; De Nil & Brutten, 1990). Furthermore, the voices of dysphonic children are judged negatively by others on aspects unrelated to voice, such as personality and physical traits (Lass, Ruscello, Bradshaw, & Blankenship, 1991; Lass, Ruscello, Stout, & Hoffman, 1991; Ruscello, Lass, & Podbesek, 1988). This is particularly troublesome from an educational viewpoint, as these negative attitudes toward children with dysphonic voice were found with teachers (Ma & Yu, 2013; Zacharias, Kelchner, & Creaghead, 2013). Coupled with the finding that many children with dysphonia are fearful or hesitant to participate in class (Connor et al., 2008), the presence of dysphonic voice quality in a child can have a detrimental effect on academic outcomes. Overall, dysphonia in children can have significant educational, psychological, physical, and social negative consequences and thus requires attention and treatment.

The most common cause of dysphonia in children is vocal fold nodules, benign lesions that typically occur at the junction of the anterior and medial portions of the vocal folds (Angelillo, Di Costanzo, Costa, Barillari, & Barillari, 2008; Kiliç, Okur, Yildirim, & Güzelsoy, 2004; Leeper, Leonard, & Iverson, 1980; McMurray, 2010; Miller & Madison, 1984; Mortensen, Schaberg, & Woo, 2010; Shah, Harvey Woodnorth, Glynn, & Nuss, 2005; Shearer, 1972). While the exact etiology of vocal fold nodules is unknown

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(Pedersen & McGlashan, 2012), patterns have emerged in both children and adults with vocal fold nodules that provide insights into underlying developmental factors. In adults, vocal fold nodules are thought to occur due to hyperfunctional voicing patterns, which include increased vocal fold tension and increased collision forces of the vocal folds during phonation (Hillman, Holmberg, Perkell, Walsh, & Vaughan, 1989). However, there are differences between children and adults in both the structure and functional movements of the vocal folds, which preclude the assumption that the development of vocal fold nodules in children is the same as in adults. In addition to the obvious size differences between the pediatric and adult larynx (Hirano, Kurita, & Nakashima, 1983), there are also differences in the tissue properties and microstructure of vocal folds in children versus adults (Gray, 2000; Gray, Alipour, Titze, & Hammond, 2000; Hammond, Gray, & Butler, 2000; Hartnick, Rehbar, & Prasad, 2005; Hirano et al., 1983). Functional repercussions of these structural differences are evident in the speech acoustics (Bennett, 1983; Glaze, Bless, Milenkovic, & Susser, 1988; Glaze, Bless, & Susser, 1990; Kent, 1976; Nicollas et al., 2008; Stathopoulos & Sapienza, 1993; Sussman & Sapienza, 1994; Wilson, 1987), aerodynamics (Keilmann & Bader, 1995; McAllister, Sederholm, Sundberg, & Gramming, 1994; Stathopoulos & Sapienza, 1997), as well as both vibrational and articulatory features of the vocal folds (Döllinger, Dubrovskiy, & Patel, 2012; Patel, Donohue, Unnikrishnan, & Kryscio, 2015; Patel, Dubrovskiy, & Döllinger, 2014). For these reasons, information on children with vocal fold nodules (CwVN) should not be extrapolated from previous work focused on adults with vocal fold nodules. Independent work on the mechanisms for the development and persistence of vocal fold nodules in children is necessary.

The historical perspective on voice therapy in children has placed significant focus on the elimination of "vocal abuse" patterns, such as constant yelling, as this was thought to be one of the primary causes of voice disorder development in children (Andrews & Summers, 2002; Boone, 1993). Although these behaviors may play a contributory role, it is now widely accepted that children benefit from a direct behavioral voice therapy approach (Braden & Verdolini Abbott, 2018; Hartnick et al., 2018; Lee & Son, 2005; McMurray, 2010; Reynolds, Meldrum, Simmer, Vijayasekaran, & French, 2017; Tezcaner, Ozgursoy, Sati, & Dursun, 2009; Trani, Ghidini, Bergamini, & Presutti, 2007; Valadez et al., 2012; Verdolini Abbott, Yee-Key Li, Hersan, & Kessler, 2010), suggesting that there is a hyperfunctional component that can be successfully targeted. Descriptors used in the clinical and research literature of hyperfunctional voicing patterns in CwVN include increased supraglottic compression (Lee & Son, 2005; Shah et al., 2005), use of a "pressed voice" (McMurray, 2010; Verdolini Abbott et al., 2010), increased tension inferred from increased fundamental frequency (f_0) of the vocal production (Hufnagle, 1982), increased vocal strain (Lee & Son, 2005), and increased speed of vocal fold closure during vibration (Patel, Unnikrishnan, & Donohue, 2016). Hyperfunctional voicing patterns are seen both in children with large and small vocal fold nodules. Some have suggested that supraglottic compression may be employed as a compensatory strategy to overcome the glottal gap caused by the presence of the large vocal fold nodules (Nuss, Ward, Huang, Volk, & Woodnorth, 2010; Shah et al., 2005; Woodnorth & Nuss, 2009). However, significant supraglottic compression has also been noted in children with small vocal fold nodules (Shah et al., 2005; Woodnorth & Nuss, 2009). Overall, it is difficult to discern whether a hyperfunctional voicing pattern in CwVN is a necessary compensatory strategy to achieve voicing or if it is unnecessary and characteristic of vocal misuse, making it an appropriate target of voice therapy. Difficulty in classifying hyperfunctional voicing patterns may contribute to the varied levels of success noted in voice therapy practices for CwVN (Deal, McClain, & Sudderth, 1976; Hartnick et al., 2018; Lee & Son, 2005; Mori, 1999; Şenkal & Çiyiltepe, 2013; Tezcaner et al., 2009; Trani et al., 2007; Valadez et al., 2012), and it highlights the need for defining, objectively measuring, and tracking hyperfunctional voicing behaviors. Thus, an ideal objective measurement would capture the functional voice changes that occur during voice therapy but would not depend on structural changes (i.e., resolution of nodules), which may take years to achieve (Nardone, Recko, Huang, & Nuss, 2014).

An acoustic measure that shows promise in detecting functional voice changes in adults is relative fundamental frequency (RFF; Heller Murray et al., 2017; Lien, Calabrese, et al., 2015; Roy, Fetrow, Merrill, & Dromey, 2016; Stepp, Hillman, & Heaton, 2010). RFF examines the instantaneous f_0 of the vocalic devoicing and voicing gestures preceding and following a voiceless consonant. Discussed in detail in previous works (Heller Murray et al., 2017; Stepp, Merchant, Heaton, & Hillman, 2011), f_0 changes during the phonetically governed vocal onsets and offsets. Vocal onsets and offsets are thought to be impacted by a combination of factors, including the pressure changes across the glottis (Ladefoged, 1967; Löfqvist, Koenig, & McGowan, 1995; Löfqvist & McGowan, 1992) and changes in laryngeal tension (Halle & Stevens, 1971; Stevens, 1977). The modulation of laryngeal tension is necessary to both start and cease vocal fold vibrations. Compared to vocally healthy adults, adults with hyperfunctional voice disorders have a lower relative f_0 for both the vocal onset and offset cycles closest to the voiceless consonant as compared to the center of the onset and offset vowels (Heller Murray et al., 2017; Lien, Calabrese, et al., 2015; Stepp et al., 2010). The hypothesized primary pathophysiological difference in adults with hyperfunctional voices is the presence of increased baseline laryngeal tension, and this increase in baseline tension is thought to allow for less use of laryngeal tension during vocal onset and offset (Heller Murray et al., 2017). This is further supported by the sensitivity of RFF to (a) voice disorders that are hypothesized to have functionally different etiologies (Heller Murray et al., 2017; Stepp et al., 2010; Stepp, Sawin, & Eadie, 2012), (b) functional changes in voice that occur after a successful course of voice therapy (Roy et al., 2016;

Stepp, Merchant, et al., 2011), (c) periods of high voice use (Heller Murray, Hands, Calabrese, & Stepp, 2016), and (d) experimental manipulations of increased vocal effort in adults with healthy voices (Lien, Michener, Eadie, & Stepp, 2015; McKenna, Heller Murray, Lien, & Stepp, 2016). Additionally, RFF has been shown to correlate with auditory-perceptual ratings of vocal strain and vocal effort (Eadie & Stepp, 2013; McKenna & Stepp, 2018; Roy et al., 2016; Stepp et al., 2012). Conversely, RFF remains unchanged after surgical removal of vocal lesions (Stepp et al., 2010), suggesting that RFF values are not significantly impacted by purely structural laryngeal changes. RFF shows promise in its usability to detect functional vocal changes in adults, yet no study to date has used RFF to examine whether CwVN demonstrate similar hyperfunctional voicing patterns.

In children without voice disorders, a few studies have examined instantaneous f_0 changes during devoicing and voicing onset gestures in relation to development. Evaluation of vocal offsets indicates that patterns of decreased f_0 are seen in children as young as 2–3 years of age (Arenas, Zebrowski, & Moon, 2012) and that average vocal offset f_0 values do not vary as a function of development (Robb & Smith, 2002). For vocal onset, however, f_0 values do vary as a function of development. In children 1–2 years of age, the f_0 of the first onset cycle was not significantly different than the remaining onset cycles (Robb & Saxman, 1985), with the expected pattern of decreasing f_0 during vocal onset emerging around 2–3 years of age (Arenas et al., 2012; Robb & Smith, 2002). Additionally, average vocal onset f_0 values are different between children and adults; 4-year-olds have lower vocal onset f_0 values than adults (Robb & Smith, 2002), and adultlike onset f_0 values emerge around 8–9 years of age (Ohde, 1985; Robb & Smith, 2002). The between-token (within-subject) variability of vocal onset and vocal offset f_0 shows developmental trends. Younger children demonstrate increased variability as compared to older children and adults (Arenas et al., 2012; Ohde, 1985; Robb & Smith, 2002), potentially suggesting an immature vocal mechanism.

The current study sought to examine whether RFF varied based on age, voice disorder status, and sex in a group of school-age CwVN and age- and sex-matched children with typical voices (CwTV). We hypothesized that, similar to previous works (Ohde, 1985; Robb & Smith, 2002), children under the age of 9 years would have lower vocal onset RFF values, no difference in vocal offset RFF values, and more variable vocal onset and offset values as compared to older children. Additionally, we hypothesized that CwVN would have lower RFF values for both vocal onset and vocal offset values, similar to what is seen in adults with vocal fold nodules (Heller Murray et al., 2017; Lien, Calabrese, et al., 2015; Stepp et al., 2010). Finally, we hypothesize that sex will not have a significant effect on RFF values, as previous works suggest f_0 is relatively similar between male and female children prior to puberty (Bennett, 1983; Kent, 1976).

Method

Participants

CwVN

Twenty-eight CwVN (15 boys, 13 girls) were retrospectively selected from a clinical database at Boston Children's Hospital. Inclusion criteria for the CwVN group included participants who (a) were between 6.0 and 12.5 years of age; (b) had a primary diagnosis of vocal fold nodules by a board-certified laryngologist; (c) did not have a previous history of voice therapy; (d) had a score of 25 or greater for overall severity of voice, rated on the Consensus Auditory-Perceptual Evaluation of Voice (Kempster, Gerratt, Abbott, Barkmeier-Kraemer, & Hillman, 2009) by a certified speech-language pathologist during the initial clinical evaluation; (e) did not have other speech, language, or hearing concerns noted in their voice evaluation report; (f) had usable high-quality voice recordings from their initial clinical evaluation as determined by the first author (E. H. M.); and (g) had accents that were representative of a fluent English speaker from the northeast region, as judged by the first author. Clinical voice recordings were reviewed chronologically from 2007 to 2015 for selection of participants, with similar sex[1] distributions selected for the current study. Boston Children's Hospital Institutional Review Board approved the retrospective search for the current study and permitted reliance on the Boston University Institutional Review Board for the full study review. At Boston Children's Hospital, more boys than girls are seen in the voice clinic for vocal fold nodules (Shah et al., 2005); however, similar group sizes were selected for the current study in order to allow examination of any potential effects of sex. Following the selection of all participants, the CwVN group was subdivided by age for all analyses into younger (N = 14; M = 7.6 years; range: 6.2–8.7 years; seven boys, seven girls) and older (N = 14; M = 10.4 years; range: 9.2–12.3 years; eight boys, six girls) age groups. All recordings were acquired in a sound-treated room by certified speech-language pathologists using the Computerized Speech Lab (Pentax Medical), with a 32.0-kHz sampling rate and a 16-bit resolution. Information on microphones used during recordings was not available.

CwTV

Twenty-eight CwTV (15 boys, 13 girls) were prospectively collected as age- and sex-matched controls for CwVN. The CwTV group was subdivided by age for analyses into younger (N = 14; M = 7.6 years; range: 6.4–8.7 years; six boys, eight girls) and older (N = 14; M = 10.3 years; range: 9.0–12.0 years; nine boys, five girls) age groups. All children aged 7.0 years or older provided verbal assent, dissent was respected for all children under 7.0 years of age, and all guardians provided written consent. Consent and assent were in compliance with the Boston University Institutional

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[1] Information on gender identity was not available for the current study. We acknowledge that using sex only is a limitation.

Review Board. Data were recorded in a sound-treated room at Boston University using a dynamic headset microphone (model WH20XLR) sampled at 44.1 kHz with a 16-bit resolution. CwTV were recruited from the greater Boston community and spoke English as their primary language. Participants had no history of a voice disorder and had not received speech or language therapy within the past year. All participants passed an audiometric hearing screening at 25 dB HL or better at the frequencies 0.25, 0.5, 1, 2, 4, 6, and 8 kHz.

RFF Stimuli Selection and Analysis

Speech samples, shown in Table 1, were four sentences from the Consensus Auditory-Perceptual Evaluation of Voice (Kempster et al., 2009), with each participant repeating each sentence between one and three times. Previous work has indicated that RFF measures in adults are more valid when analyzed from at least six instances (Eadie & Stepp, 2013); therefore, speech segments chosen for RFF analysis included eight vocal onset and eight vocal offset instances (see Table 1). Acoustic samples were low-pass filtered using a fifth-order Butterworth filter, similar to previous works (Lien & Stepp, 2014; Watson, 1998), to remove excessive noise from the vocal tract and any background noise during the recording. Preliminary analyses prior to filtering indicated that the highest cycle f_0 was 580 Hz; therefore, a cutoff frequency of 100 Hz higher (i.e., 680 Hz) was selected for the low-pass filter.

Consistent with previous work (e.g., Heller Murray et al., 2016; Lien, Gattuccio, & Stepp, 2014; Lien & Stepp, 2014; Stepp, 2013; Stepp, Heaton, et al., 2011; Stepp et al., 2010), RFF values were calculated from the 10 cycles preceding the voiceless consonant (vocal offset) and the 10 cycles following the voiceless consonant (vocal onset). RFF was manually calculated using Praat (Boersma & Weenink, 2014) by two trained technicians (see Figure 1). An RFF instance was not included in the final analysis if the production was glottalized, had less than 10 vocal cycles, or if the consonant was inappropriately voiced. To obtain measures of reliability, each technician repeated the analysis for 40% of the total participants, allowing for interrater reliability calculations between the two technicians. Additionally, half of these participants (i.e., 20% of the total participants) were originally analyzed by one technician and half by the other, thus allowing for intrarater reliability calculations for each technician. Reliability analysis was conducted at least 2 months following the original analysis. Pearson correlation coefficient was calculated for both intrarater reliability (Technician 1: $r = .90$; Technician 2: $r = .92$) and interrater reliability ($r = .86$).

To calculate the RFF values of the offset vowel, the experimenter visually identified the cycle closest to the voiceless consonant (Offset Cycle 10) and used the *pulse* feature in Praat (Boersma & Weenink, 2014) to acquire the timing of Offset Cycle 10 as well as the nine cycles preceding it (Offset Cycles 1–9). Instantaneous f_0 values for each cycle (f_{cycle}) were calculated from the inverse of the periods, computed from the timing of each cycle. In order to compare across individuals with different baseline f_0 values, all cycles were converted to semitones (ST) using a reference cycle (f_{ref}), calculated during a steady-state portion of the vowel (Offset Cycle 1) using Equation 1. A similar procedure was completed to calculate RFF values for the onset vowel: The cycle closest to the voiceless consonant was identified (Onset Cycle 1), the timing of the following nine cycles (Onset Cycles 2–10) was calculated, and the instantaneous f_0 of each cycle was converted to ST in reference to Onset Cycle 10 with Equation 1. If the cycle closest to one of the reference cycles (i.e., either Offset Cycle 9 or Onset Cycle 2) had a value of ± 0.8 ST, the vowel was determined not to be at steady state and was removed (Heller Murray et al., 2016; Lien et al., 2014; Stepp, Merchant, et al., 2011; Stepp et al., 2012).

$$RFF\ value\ (ST) = \frac{12\log_{10}\frac{f_{cycle}}{f_{ref}}}{\log_{10^2}} \qquad (1)$$

Data Analysis

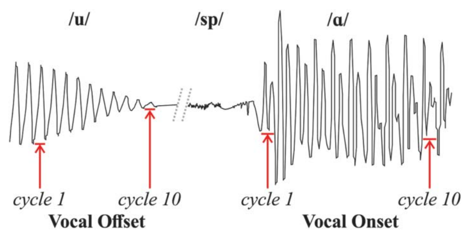
Number of Usable RFF Instances

Previous work has discussed the importance of understanding the impact that the number of usable instances has on calculation and interpretation of RFF values (Roy et al., 2016); accordingly, the number of usable instances was examined in the current data set. To quantify whether the number of usable instances was related to any additional factors, two three-way analyses of variance (ANOVAs) examined whether group (CwTV, CwVN), age (young, old),

Table 1. Sentences chosen for analysis from the Consensus Auditory-Perceptual Evaluation of Voice.

Sentence	Analysis section	Vocal offsets	Vocal onsets
The blue spot is on the key again.	blue spot	/u sp/	/spɑ/
	the key	/ʌ k/	/ki/
We eat eggs every Easter.	Easter	/ist/	/stər/
My mama makes lemon muffins.	makes	/eɪk/	
	muffins	/ʌf/	/fɪ/
Peter will keep at the peak.	Peter		/pi/
	keep at	/ip/	/ki/ /p æ/
	the peak	/ʌ p/ /ik/	/pi/

Figure 1. Filtered waveform showing the vocal offset and vocal onset of /u/ and /ɑ/ from the phrase "blue spot." The center of the voiceless blend /sp/ is removed in this figure, indicated by the dashed lines. The cycles closest to the voiceless /sp/ (Offset Cycle 10, Onset Cycle 1) and the reference cycles from the steady point of the vowels (Offset Cycle 1, Onset Cycle 10) are indicated with a red arrow.



sex (male, female), or any of the two- or three-way interactions had an effect on the number of usable instances for offset and onset, respectively.

Offset Cycle 10 and Onset Cycle 1 RFF

Offset Cycle 10 and Onset Cycle 1 are known to be significantly different between adults with and without voice disorders (Heller Murray et al., 2017; Lien, Calabrese, et al., 2015; Stepp et al., 2010, 2012), as well as significantly different between adults with vocal fold nodules and adults with voice disorders such as muscle tension dysphonia (Heller Murray et al., 2017; Stepp et al., 2010). Therefore, these two cycles were used for the remainder of the analyses. Two three-way ANOVAs examined the effect of group (CwTV, CwVN), age (young, old), sex (male, female), and all two- and three-way interactions on average Offset Cycle 10 and Onset Cycle 1 RFF values. To examine the variability of RFF values, two additional three-way ANOVAs examined the effect of participant group (CwTV, CwVN), age (young, old), sex (male, female), and all two- and three-way interactions on the within-subject standard deviations of Offset Cycle 10 and Onset Cycle 1 RFF across instances. Effect sizes for the ANOVA factors were calculated using a squared partial curvilinear correlation (η_p^2), designated as either a small (~.01), medium (~.09), or large (> .25) effect size. For all ANOVAs, Tukey's post hoc analyses were conducted with a corrected alpha level of 0.05. Cohen's *d* effect sizes were calculated to further assess statistically significant pairwise group differences. Cohen's *d* values were designated as either small (0.2–0.3), medium (~0.5), or large (> 0.8; Witte & Witte, 2010).

Results

Number of Usable RFF Instances

The average number of usable instances was comparable between groups (CwTV: offset = 8.9, onset = 8.7; CwVN: offset = 8.7, onset = 8.0). There were no significant effects of either group (CwTV, CwVN), age (young, old), sex (male, female), or interaction among these factors for either offset or onset cycles (all $p > .05$).

Offset Cycle 10 and Onset Cycle 1 RFF

Average RFF Values

Results of the three-way ANOVAs examining Onset Cycle 1 and Offset Cycle 10 average RFF values are displayed in Figure 2. There was a main effect of sex ($p = .02$) on Offset Cycle 10 RFF values (see Table 2). Post hoc testing indicated that males had significantly lower average Offset Cycle 10 RFF values as compared to females, with a medium-to-large effect size (see Table 3). There were no significant effects of either age or group on average Offset Cycle 10 RFF values. There was a main effect of age ($p = .02$) on Onset Cycle 1 RFF values (see Table 2). Post hoc testing indicated that younger children had significantly lower average RFF values for Onset Cycle 1 than older children with a medium-to-large effect size (see Table 3). There were no significant effects of sex or group on average Onset Cycle 1 RFF values.

RFF Variability

Results of the three-way ANOVAs examining the standard deviation of Onset Cycle 1 and Offset Cycle 10 RFF values (used as a metric of RFF variability) are displayed in Figure 3. There was a main effect of group ($p = .02$) on Offset Cycle 10 RFF variability (see Table 2). Post hoc testing indicated there was significantly less variability in Offset Cycle 10 RFF in CwVN (as compared to CwTV, with a medium effect size; see Table 3). There were no significant effects of either age or sex on Offset Cycle 10 RFF variability. There was a significant interaction of age and group on the variability of Onset Cycle 1 RFF values ($p = .01$; see Table 2); however, paired comparisons with post hoc Tukey's tests did not reach significance. Qualitatively, there was a trend indicating that the younger CwTV group ($M = 2.13$ ST) had increased variability compared to the

Figure 2. Mean and 95% confidence intervals for average relative fundamental frequency (in semitones [ST]) values for children with typical voices (CwTV; open blue circles) and children with vocal fold nodules (CwVN; solid green circles).

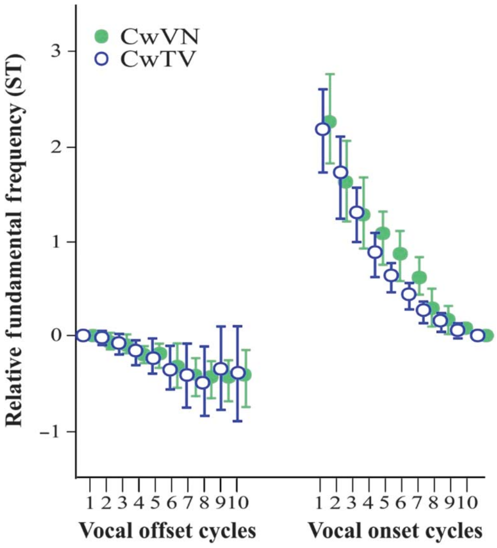


Table 2. Results of a three-way analysis of variance on relative fundamental frequency (RFF) average and variability.

Effect	RFF average				RFF variability			
	Offset Cycle 10		Onset Cycle 1		Offset Cycle 10		Onset Cycle 1	
	F	η_p^2	F	η_p^2	F	η_p^2	F	η_p^2
Age (young, old)	0.49	—	5.64*	.12	0.06	—	0.82	—
Group (CwTV, CwVN)	0.04	—	0.19	—	5.42*	.09	0.14	—
Sex (male, female)	6.32*	.12	0.57	—	2.23	—	0.94	—
Age × Group	0.00	—	0.47	—	2.49	—	7.29*	.16
Age × Sex	1.72	—	0.59	—	1.00	—	1.37	—
Group × Sex	1.22	—	0.06	—	0.00	—	3.86	—
Age × Group × Sex	0.01	—	0.75	—	0.39	—	0.23	—

Note. Em dashes indicate effect size is not reported if effect was not significant. CwTV = children with typical voices; CwVN = children with vocal fold nodules.

*Significant at $p < .05$.

older CwTV group (M = 1.52 ST), whereas for CwVN, the opposite effect was observed; the younger CwVN group (M = 1.78 ST) showed decreased variability compared to the older CwVN group (M = 2.23 ST).

Discussion

Vocal Onset

Onset Cycle 1 RFF values were lower in younger children (< 9 years of age) as compared to those of older children ($\geq$ 9 years of age). These age differences are consistent with previous work, which suggest that vocal onset values change during maturation and that similar vocal onset values are seen between 8- and 9-year-olds and adults (Arenas et al., 2012; Ohde, 1985; Robb & Smith, 2002). The difference in vocal onset f_0 as a function of age may be attributed to the maturity of the laryngeal structure, improved laryngeal control, or a combination of both of these structural and functional changes. Evidence points to the mature three-layer vocal fold structure emerging between age 7 years and puberty (Hartnick et al., 2005; Hirano et al., 1983). The timing of this structural change suggests that there may be a larger percentage of children in the older group who each have a mature laryngeal structure, thereby resulting in more adultlike RFF values.

In addition to these structural changes, speech motor control is developing during maturation, with reduced speech variability observed between 8 and 12 years of age (Kent, 1976). One feature of speech motor control related to laryngeal function is voice onset time (VOT), defined as the time between the release of the burst in a stop consonant and the voicing of the next vowel (Lisker & Abramson, 1964). In the mature system, VOT is shorter after voiced consonants as compared to voiceless consonants; however, this differentiation is not as clear in younger children (Eguchi & Hirsh, 1969; Kent, 1976). Previous work has indicated that younger children have increased variability and decreased differentiation between their VOTs for voiced and voiceless stops, with both of these factors reaching adultlike levels around 8 years of age (Eguchi & Hirsh, 1969). The current work adds continued support to the idea that phonetically governed vocal onsets vary throughout development, suggesting that reduced variability may be partially attributable to the maturation of the laryngeal motor control system.

Vocal Offset

Sex differences were noted for average Offset Cycle 10, with male participants showing lower RFF values than

Table 3. Average (mean) values for relative fundamental frequency (RFF) average and variability by group, age, and sex.

Variable	Cohort	RFF average				RFF variability			
		Offset Cycle 10		Onset Cycle 1		Offset Cycle 10		Onset Cycle 1	
		M	d	M	d	M	d	M	d
Group	CwTV	–0.36	—	2.08	—	1.91	0.59	1.92	—
	CwVN	–0.42		2.22		1.50		1.97	
Age	Younger	–0.43	—	1.80	0.72	1.67	—	2.02	—
	Older	–0.35		2.51		1.74		1.86	
Sex	Male	–0.66	0.69	2.29	—	1.83	—	2.00	—
	Female	–0.08		2.00		1.56		1.87	

Note. Cohen's d values are shown for variables that were significantly different in post hoc analyses ($p < .05$). Em dashes indicate Cohen's d is not reported if variables were not significantly different. CwTV = children with typical voices; CwVN = children with vocal fold nodules.

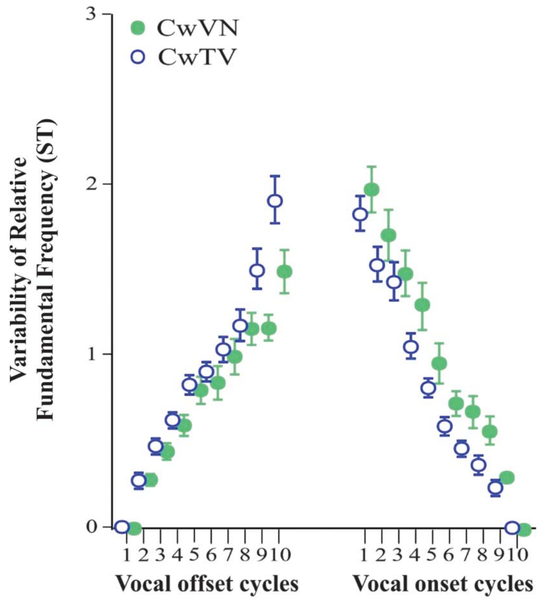


Figure 3. Mean and 95% confidence intervals for variability of relative fundamental frequency (in semitones [ST]) values for children with typical voices (CwTV; open blue circles) and children with vocal fold nodules (CwVN; solid green circles).

female participants. Previous acoustic examination of sex differences in children has shown a primary differentiation after puberty, with little difference noted before that time period in measures such as f_0 (e.g., Kent, 1976), vocal fold size, composition, and general laryngeal size (Hartnick et al., 2005; Hirano et al., 1983). During puberty, the male larynx undergoes larger changes in physical size and weight than the female larynx (Kahane, 1978), potentially leading to a period of functional misuse as the child adapts to the large structural changes. However, the absence of a significant interaction of age, group, and sex indicates pubertal change alone does explain the sex effects in Offset Cycle 10 RFF values. Previous work examining vocal fold vibrations found that male children (ages 5–11 years) were more likely to display an hourglass closure pattern than female children, male adults, and female adults (Patel, Dixon, Richmond, & Donohue, 2012). Authors suggested the presence of this high-impact phonatory pattern could increase the risk for male children to develop vocal fold nodules (Patel et al., 2012), consistent with the higher incidence of vocal fold nodules in male children as compared to that of female children (Dobres, Lee, Stemple, Kummer, & Kretschmer, 1990; Shah et al., 2005). Additionally, Wuyts et al. (2003) examined ranges of produced f_0 and sound pressure level in children 6–11 years of age and found a widening of these ranges in children between 7 and 8 years of age. Authors suggest this may be attributable to hormone changes that occur around 7 years of age, potentially impacting the structure of the vocal folds during this time period (Wuyts et al., 2003). Findings from the current study support that differences in the male and female larynx prior to puberty may significantly impact vocal production.

Comparing CwTV to CwVN

There were no group differences between CwVN and CwTV in mean RFF values for either Offset Cycle 10 or Onset Cycle 1. This is markedly different than previous findings of RFF differences between adults with and without voice disorders (Heller Murray et al., 2017; Lien, Calabrese, et al., 2015; Stepp et al., 2010). The current study had relatively small groups of CwVN and CwTV, potentially resulting in an underpowered design. However, given the large effect size seen in adults with and without voice disorders (Heller Murray et al., 2017; Lien, Calabrese, et al., 2015; Stepp et al., 2010), it is likely that, if a similar effect was present in children, this study would have enough power to detect any potential differences. One potential explanation for the lack of a group effect is that CwVN may not have hyperfunctional voicing patterns. However, this argument is unlikely, since reducing hyperfunctional voicing is often a target of voice therapy (Lee & Son, 2005; Verdolini Abbott, 2013; Verdolini Abbott et al., 2010; Wilson, 1987; Woodnorth & Nuss, 2009) and is the preferred treatment for vocal fold nodules in children (Allen, Pettit, & Sherblom, 1991; Connelly, Clement, & Kubba, 2009; Moran & Pentz, 1987; Signorelli, Madill, & McCabe, 2011). Although it is unlikely that children do not use hyperfunctional voicing patterns, it is possible that the manner in which their voices are hyperfunctional is different from adults and not appropriately measured by RFF. Children with and without vocal fold nodules may be developing hyperfunctional voicing as a natural pattern during development. Previous work examining the voices of children with and without voice disorders shows similar ratings for vocal strain (Simões-Zenari, Nemr, & Behlau, 2012), with one explanation being that both children with and without vocal fold nodules are producing a hyperfunctional voice. Additionally, vocal fold vibration patterns in male children may put them at higher risk for developing voice disorders (Patel et al., 2012). Additional work is needed to examine the voicing patterns in CwTV as compared to adults and examine potential changes that occur throughout development with regard to hyperfunctional voicing patterns.

Unlike average RFF values, the variability of RFF differed between CwTV and CwVN. CwVN had less variable Offset Cycle 10 RFF values as compared to CwTV. This may appear contradictory to current clinical practice, as clinicians often define a deviant voice as one with increased variability and aperiodicity in the acoustic signal measured during steady-state phonation (Gramuglia, Tavares, Rodrigues, & Martins, 2014; Infusino et al., 2015). Yet, measurements of steady-state phonation may not accurately reflect onset and offset of vocal fold vibration. Previous work has indicated that CwVN may have decreased the flexibility of their vocal mechanisms (Wuyts et al., 2003). Thus, pliability limitations imposed by the vocal fold nodules may explain the decreased variability of Offset Cycle 10. Continued work is needed to further evaluate whether variability in vocal offset is similar in a phonetically unconstrained production in this population. Onset Cycle 1 RFF variability also differed between groups in this study, with a significant interaction between age and group found. However, direct paired comparisons did not reach significance after statistical correction. Therefore, although there was a qualitative difference between the groups, the lack of significance after statistical corrections and the lack of main effects of age or group suggest that there may not be a strong interaction between age and group. Rather, it is likely that, in order to examine a measure of variability, a larger group size may be necessary to examine potential group differences.

Limitations and Future Directions

Though this study was an initial examination of vocal onsets and vocal offsets in CwTV and CwVN, certain limitations should be considered when interpreting the findings of the study. In the current study, data from the CwVN group, with overall severity scores that were moderately dysphonic or greater, were collected retrospectively. It is possible that instructions on how to produce the sentences may have varied across data collection sites, and subsequently, any potential acquisition differences may have affected the results. All CwTV repeated the sentences after the experimenter. It is likely that CwVN similarly repeated the sentences, as repetition is common practice at the clinic these data were collected; however, this cannot be confirmed due to the retrospective design. Additionally, although there were no significant hearing concerns noted by either the parent or the treating physician at the time of voice evaluations of CwVN, a hearing screening was not completed. Therefore, it is unknown whether hearing status differed between the CwVN and CwTV groups. Finally, stimuli were obtained from standard clinical protocols. Previous work has indicated that consistent stimuli (Lien et al., 2014) produced with even stress (Park & Stepp, 2018) provide the most stable RFF measures; thus, the stress patterns used could have influenced variability measures. Future work on this topic should be prospective in nature, allowing for all of the above limitations to be addressed and controlled for during data collection.

Conclusions

This study adds to the growing body of literature suggesting that a pediatric-specific framework is needed for examining children with voice disorders. In contrast to the effects observed in previous studies in adults, RFF means did not differ between children with and without vocal fold nodules. Age differences in Onset Cycle 1 RFF were noted and consistent with previous work, suggesting that vocal onset may be related to the maturation of laryngeal motor control. Sex differences were observed for Offset Cycle 10, in which boys had lower RFF values than girls. Future work should continue to examine whether these sex differences noted in Offset Cycle 10 are related to the greater incidence of voice disorders in male children compared to female children.

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