Research Article

# Voice Onset Time in Children With and Without Vocal Fold Nodules

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ARTICLE INFO

Article History:
Received August 10, 2022
Revision received November 21, 2022
Accepted January 16, 2023

Editor: Susan L. Thibeault

https://doi.org/10.1044/2023_JSLHR-22-00463

ABSTRACT

**Purpose:** Voice onset time (VOT) of voiceless consonants provides information on the coordination of the vocal and articulatory systems. This study examined whether vocal–articulatory coordination is affected by the presence of vocal fold nodules (VFNs) in children.

**Method:** The voices of children with VFNs (6–12 years) and age- and gender-matched vocally healthy controls were examined. VOT was calculated as the time between the voiceless stop consonant burst and the vocal onset of the vowel. Measures of the average VOT and VOT variability, defined as the coefficient of variation, were calculated. The acoustic measure of dysphonia, cepstral peak prominence (CPP), was also calculated. CPP provides information about the overall periodicity of the signal, with more dysphonic voices having lower CPP values.

**Results:** There were no significant differences in either average VOT or VOT variability between the VFN and control groups. VOT variability and average VOT were both significantly predicted by the interaction between Group and CPP. There was a significant negative correlation between CPP and VOT variability in the VFN group, but no significant relationship was found in the control group.

**Conclusions:** Unlike previous studies with adults, there were no group differences in average VOT or VOT variability in this study. However, children with VFNs who were more dysphonic had increased VOT variability, suggestive of a relationship between dysphonia severity and control of vocal onset during speech production.

Vocal fold nodules (VFNs) are the most common cause of dysphonia in children (Akif Kiliç et al., 2004; Ongkasuwan & Friedman, 2013; Shah et al., 2005; Shearer, 1972; Tavares et al., 2011). Children with VFNs may exhibit phonotraumatic vocal behaviors that can occur in situations conducive to yelling, such as participating in sports or speaking in noisy environments. Additionally, they may also demonstrate inefficient or inappropriate vocal use (i.e., misuse), such as speaking at a pitch that is too high or too low or using increased vocal strain (Hillman et al., 1989, 2020). The etiology of VFN can also be exacerbated by conditions such as laryngopharyngeal reflux, allergies, and nasal obstruction, which are all common in children (Bhattacharyya, 2015; Block & Brodsky, 2007; De Bodt et al., 2007; Martins et al., 2012; Özçelik Korkmaz & Tüzüner, 2020). Treatment for dysphonia is essential as chronic dysphonia can negatively impact a child's voice use, behaviors, school performance, social participation, and other aspects of health and daily life (Carroll et al., 2013; Connor et al., 2008; Verduyckt et al., 2011).

Although children and adults both develop VFN, previous research has pointed to significant differences in VFN presentation between children and adults. Unlike VFN in adults, which are more commonly found in women, VFN in children are more commonly found in male children, especially in those around school age (6–12 years; Akif Kiliç et al., 2004; Coyle et al., 2001; De Bodt et al., 2007; Dobres et al., 1990). Children with VFNs have differences in respiratory and laryngeal functions compared to adults with VFNs (Lohscheller & Eysholdt, 2008; Patel et al., 2016; Sapienza & Stathopoulos, 1994; Yamauchi et al., 2016).

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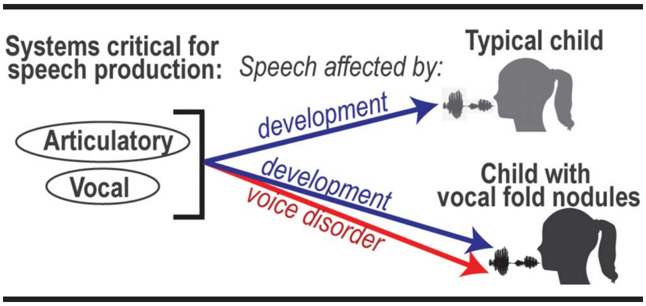
Acoustic measures of fundamental frequency ($f_o$) transitions into and out of voiceless consonants are significantly different in adults with and without phonotraumatic (e.g., VFNs) voice disorders (Heller Murray et al., 2017; Stepp et al., 2010), yet these same measures are not different in children with and without phonotraumatic voice disorders (Heller Murray et al., 2020). Furthermore, adults with voice disorders have reduced auditory discrimination abilities compared to adults without voice disorders (Abur et al., 2021), whereas children with and without voice disorders have comparable auditory discrimination abilities (Heller Murray et al., 2019). The differences between children with VFNs and adults may be partially attributed to the significant structural differences in the laryngeal mechanism between children and adults. The vocal folds of children are smaller than those of adults, with differences in their microstructure, and an approximately equal membranous-to-cartilaginous ratio in infancy that changes over development so the membranous portion becomes more dominant (Boseley & Hartnick, 2006; Hammond et al., 1998, 2000; Hirano et al., 1983; Rogers et al., 2014; Sato et al., 2001, 2006; Schweinfurth & Thibeault, 2008). Furthermore, the mature three-layer vocal fold structure does not fully emerge until around 7 years, with differentiation initially occurring between 1 and 4 years of age (Hartnick et al., 2005; Hirano et al., 1983; Ishii et al., 2000; Sato et al., 2001). These structural changes contribute to the differences in vibratory motions as well as abduction and adduction behavior in children compared to adults (Döllinger et al., 2012; Patel et al., 2012, 2014a, 2014b, 2015), further providing evidence of differences in the vocal system between adults and children. In addition to these changes in the vocal system, children also undergo significant changes in their articulatory systems (Kent, 1976; Koenig, 2000; Vorperian & Kent, 2007; Vorperian et al., 2009). In typical children, maintaining intelligible speech requires adapting to the developmental changes in both systems (see Figure 1, blue arrow). Children with VFNs also adapt to these typical developmental changes; however, they also have an additional task of adapting to any changes that occur in either system due to the presence of a voice disorder (see Figure 1, red arrow). Thus, to fully understand the impact of VFN in children, changes in both the developing vocal and articulatory systems must be considered.

One method of examining the coordination of the vocal and articulatory systems during speech is the measurement of voice onset time (VOT). VOT is the time between the release of the stop consonant and the initiation of the subsequent vowel (Lisker & Abramson, 1964, 1967). Coordination between these two systems is especially crucial for producing voiceless stops, which require the vocal folds to remain open during the stop production with subsequent closure to support phonation during the vowel. In English-speaking adults, VOT is an acoustic temporal cue used by listeners to determine whether a consonant is voiced or voiceless, as voiced productions have a shorter VOT than voiceless productions (Lisker & Abramson, 1964, 1967). However, this clear distinction between voiced and voiceless productions is not always present in children. For example, in children 9–18 months old, there is minimal to no distinction between the VOTs of voiced and voiceless cognates. This distinction emerges around 18–28 months of age when production accuracy increases and production range decreases (Barton & Macken, 1980; Hitchcock & Koenig, 2013). Children's VOTs reach adultlike averages around 6 years of age, although increased production variability is present until 8–11 years of age when this variability reaches adultlike levels (Eguchi & Hirsh, 1969; Kent, 1976; Kewley-Port & Preston, 1974; S. Whiteside et al., 2003; Yu et al., 2014). A key factor that remains unknown is whether a structural difference in the developing vocal system (i.e., the presence of VFN) impacts the relationship between the vocal and articulatory systems during development.

**Figure 1.** A schematic depicting that both development (blue arrow) and a voice disorder (red arrow) impact speech production in children with vocal fold nodules.



Only a few studies have examined VOT in individuals with dysphonia. McKenna et al. (2020) found that adults with vocal hyperfunction exhibited more variable VOTs than a cohort of age- and gender-matched vocally healthy individuals. Furthermore, VOT variability was related to dysphonia severity, with increased dysphonia severity associated with increased VOT variability (McKenna et al., 2020). Heller Murray and Chao (2021) examined the relationship between VOT variability and dysphonia in children. Although no relationship was found between VOT variability and dysphonia, there was a correlation between dysphonia severity and $f_o$ variability (Heller Murray & Chao, 2021). Importantly, this work did not know the voice disorder status of the children, and additional work is needed to examine this relationship in children diagnosed with voice disorders. This study was a secondary analysis of data collected from age- and gender-matched children with and without VFN between 6 and 12 years of age. These data were initially collected for another study examining voice in children with and without VFN (Heller Murray et al., 2020) in which vocalic onset and offset $f_o$ were examined. The previous study was designed to examine a more commonly used measure of vocal hyperfunction in individuals with voice disorders (Heller Murray et al., 2016, 2017; Kapsner-Smith et al., 2022; Roy et al., 2016; Stepp et al., 2010, 2011). The current work utilized speech samples from the same participants to examine a distinct measurement, VOT. This temporal measurement allows a novel look at the coordination of the voice and speech system in children with VFNs.

The following research questions examined group differences in the measures of interest, average VOT, and VOT variability.

> Q1: Does average VOT or VOT variability vary between children with and without VFN?
>
> Q2: Does the relationship between VOT variability and CPP or the relationship between average VOT and CPP vary between children with and without VFN?

## Method

### Participants

Twenty-eight children with VFNs (average 9.1 years, 13 girls, 15 boys) were selected from a clinical database at Boston Children's Hospital Data for the original study (Heller Murray et al., 2020); the same participants were examined for the current analysis. Participants with VFNs were retrospectively selected from the clinical database with the following inclusion criteria: (a) between 6.0 and 12.5 years of age; (b) had a primary diagnosis of bilateral VFNs made during a flexible laryngoscopic evaluation by an otolaryngologist at Boston Children's Hospital who received specialized fellowship training in pediatrics; (c) no prior voice therapy history; (d) received an overall voice severity score greater than or equal to 25 rated on the Consensus Auditory-Perceptual Evaluation of Voice (CAPE-V; Kempster et al., 2009) determined by a certified speech-language pathologist during the initial clinical evaluation; (e) no history of other speech, language, or hearing concerns noted during evaluation; (f) usable, high-quality voice recordings were obtained during the initial clinical evaluation; and (g) accents were representative of a fluent English speaker from the northeast region. Boston Children's Hospital Institutional Review Board approved the retrospective search for the original study and permitted reliance on the Boston University Institutional Review Board for the full study review (Heller Murray et al., 2020).

A control group of 28 children without VFN (average 8.9 years, 13 girls, 15 boys) were recruited from Boston and its surrounding communities for the original study. Children without VFN were recruited after selecting children with VFNs from the Boston Children's Hospital clinical database. Thus, the children without VFN were recruited to be age- and gender-matched to the children with VFNs. Participants spoke English as their primary language, had no history of a voice disorder per parental report, and had not received speech or language therapy within the previous year. A speech-language pathologist confirmed that vocal quality was within the normal range for all children without VFN. Children aged 7;0 (years;months) and older provided verbal assent and dissent from children under 7;0 was respected, while guardians provided written consent. The original study was approved by Boston University Institutional Review Board (Heller Murray et al., 2020).

### Recording Procedures

All recordings were completed in a sound-treated room. Recordings from children with VFNs were completed during clinical evaluation with the Computerized Speech Lab (Pentax Medical), with a 32.0-kHz sampling rate and a 16-bit resolution. Information about the microphone used during recordings was not available. Recordings from the control group were conducted with a dynamic headset microphone (model WH20XLR) and acquired with a MOTU UltraLite-mk3 hybrid soundcard (MOTU), sampled at 44.1 kHz with a 16-bit resolution. An independent sample $t$ test indicated that there was no significant difference in signal-to-noise ratio of the background noise to the speech production between speech samples collected from the children with VFNs ($M$ = 28.14 dB) or the control group ($M$ = 28.34 dB; $t[53] = -0.11$, $p = .91$).

Children repeated each of the six CAPE-V sentences 1–3 times. The number of repetitions varied based on clinician preference during the initial recording, primarily due to reasons such as audible mistakes or confusion by the child on the speech task. Four voiceless consonants were selected for VOT analysis; only correct productions of the voiceless consonants were analyzed (see Table 1). Consistent with previous studies that optimized the identification of the first vocalic cycle (e.g., Heller Murray et al., 2020; Lien & Stepp, 2014), the acoustic samples were low-pass filtered using a fifth-order Butterworth filter. A cutoff value of 680 Hz was selected for the filter, as it was 100 Hz higher than the highest $f_o$ measured in the sample. This filtering aimed to reduce extraneous noise

**Table 1.** Stimuli selected for VOT analysis.

| CAPE-V sentences | Word | Vocal onset analyzed |
|---|---|---|
| The blue spot is on the key again. | key | /ki/ |
| Peter will keep at the peak. | Peter | /pi/ |
| | keep | /ki/ |
| | peak | /pi/ |

*Note.* VOT = voice onset time; CAPE-V = Consensus Auditory-Perceptual Evaluation of Voice.

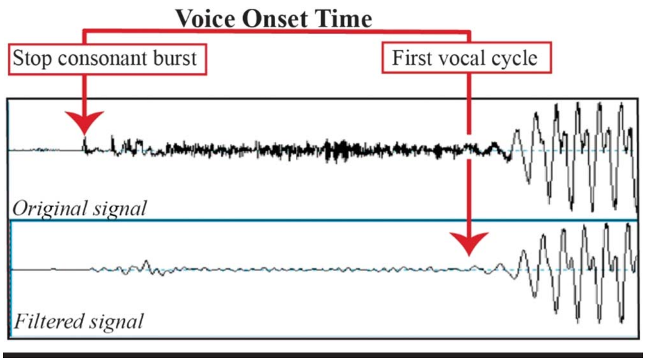
from the vocal tract and environment, thus making the vocal cycles easier to identify.

## *Data Processing and Acoustic Analysis*

The burst of the stop consonant (VOT start) and the first vocalic cycle (VOT end) were manually identified in Praat for each VOT instance (Boersma & Weenick, 2019; see Figure 2). The stop consonant burst was identified in the unfiltered signal and marked at the zero-crossing directly before a large change in the waveform. This selection was confirmed by the presence of a dark vertical band in the spectrogram. The first vocal cycle was identified in the filtered waveform, using the voicing bar in the spectrogram to support the selection. Finally, the onset and offset of the target sentence were marked to determine the total sentence length. All marked boundaries were exported for analysis to excel and JMP (SAS Institute, 2019).

Cepstral peak prominence (CPP) was calculated in Praat (Boersma & Weenick, 2019). CPP is the current recommendation for acoustic measurement of dysphonia (Patel et al., 2018), and relationships between CPP and dysphonia have been found in both adult and pediatric populations (e.g., Esen Aydinli et al., 2019; Heman-Ackah et al., 2002; Murton et al., 2020; Sauder et al., 2017). The measure of CPP is calculated in the cepstral domain and provides a measure of how high the cepstral peak (associated with the fundamental period) emerges from the cepstral noise (Hillenbrand et al., 1994; Hillenbrand & Houde, 1996). A signal with a low CPP value, as seen in dysphonic voices, is less differentiated from the remainder of the vocal noise. The current work calculated CPP using a Praat plugin that measured CPP after removing the unvoiced and silent periods. Full details of this open-source plugin can be found here (Heller Murray et al., 2022). The current article used a silence threshold of 0.03 and a voicing threshold of 0.3 to find voiced periods of speech and found CPP within the peak search range of 60–500 Hz using a "Straight" trendline and a "Robust" fit method (Boersma & Weenick, 2019).

**Figure 2.** Example of the original signal (top) and filtered signal (bottom). Red arrows indicate the start of the voice onset time (stop consonant burst) and the end of the voice onset time (first vocal cycle).



## *Data Analysis*

Prior to data analysis, instances were removed if the VOT was greater than 200 ms ($n$ = 4 instances) or if there was an audible elongation consistent with vocal play ($n$ = 1 instance). We were interested in examining variation in typical speech production patterns without examining edge cases more indicative of extreme productions; therefore, these instances were considered outliers. Furthermore, four participants with VFNs were removed from the analyses because they had less than four usable VOT values, resulting in a final grouping of 24 included participants with VFNs and 28 included control participants. As VOT identification was a manual process, reliability measures were calculated first to ensure the results of VOT analyses could be interpretable. The first author (L.C.) repeated VOT analysis on 15% of the samples, and the senior author (E.H.M.) completed VOT analysis on the same samples. Intraclass correlation coefficients (ICC) were calculated for interrater and intrarater reliability metrics (Koo & Li, 2016). Excellent reliability was found for both interrater (ICC = .94) and intrarater (ICC = .98) reliability measures.

Prior to all analyses, the distribution of each variable was tested for normality with a Shapiro–Wilk test. Variables that were not normally distributed were subsequently log-transformed before analysis. To confirm that the different intentions behind the data collection (clinical evaluations vs. research study) did not impact the number of VOTs used for analysis, an independent-samples $t$ test examined the number of usable VOT instances in each group. Since CPP was a factor of interest in our research question, we wanted to confirm that other confounding variables did not significantly impact CPP. We specifically focused on vocal pitch and age, as previous work has shown they can be related to CPP (Brockmann-Bauser et al., 2021; Demirci et al., 2021; Infusino et al., 2015; Kent et al., 2021; Sampaio et al., 2020). A linear regression was conducted to examine whether Pitch or Age had a significant effect on the outcome of CPP. We did not anticipate that this linear regression would be significant, as CPP is primarily impacted by these factors in studies with wider age ranges with more extreme changes in pitch (Brockmann-Bauser et al., 2021; Demirci et al., 2021; Infusino et al., 2015; Kent et al., 2021; Sampaio et al., 2020).

The statistical analyses were selected to examine the two primary research questions: (a) Does average VOT or VOT variability vary between children with and without VFN? (b) Does the relationship between average VOT and CPP or the relationship between VOT variability and CPP vary between children with and without VFN? Two linear regressions were calculated, one with the outcome of average VOT (Model 1) and one with the outcome of VOT variability (Model 2). Predictors of each model included Group, Age, CPP, Sentence Length, and Gender, as well the interaction of Group × CPP and Group × Sentence Length. The primary predictor of interest for the first research question was the main effect Group (VFN, control), whereas the interaction of Group × CPP was of primary interest for the second research question. Age and Sentence Length were also included as covariates in the models, as both variables can significantly impact VOT (Hitchcock & Koenig, 2013; Kent, 1976; Kessinger & Blumstein, 1998; Koenig, 2001; Macken & Barton, 1980; Volaitis & Miller, 1992; S. Whiteside & Marshall, 2001; S. P. Whiteside et al., 2004; Yu et al., 2014, 2015; Zlatin & Koenigsknecht, 1976). The interaction of Group × Sentence Length was also included to account for any potential group differences (e.g., if one group always spoke faster). Any significant Group × CPP interactions were examined further with Pearson's correlations to evaluate the relationship between CPP and the outcome variable within each group.

## Results

Descriptive statistics for each group are outlined in Table 2 for the 28 included control subjects and the 24 included VFN subjects. There were no significant group differences in number of usable VOT instances ($t[50] = 1.62$, $p = .11$). Additionally, there was no significant main effect of pitch ($\beta = -.009$, $p = .56$) or Age ($\beta = -.102$, $p = .55$) on CPP.

Shapiro–Wilk tests indicated that distributions for VOT variability (W = 0.93, $p = .005$) and average sentence length (W = 0.87, $p < .001$) deviated from normal and thus were log-transformed. The first linear regression examining the outcome of the average VOT model was significant ($R^2 = .35$, $p = .006$), with average VOT significantly predicted by the main effect of sentence length ($\beta = .06$, $p = .002$) and the interaction of Group × CPP ($\beta = -.003$, $p = .02$). The second linear regression examining the outcome of VOT variability was also significant ($R^2 = .30$, $p = .02$), with VOT variability significantly predicted by the main effect of CPP ($\beta = -.07$, $p = .04$) and the interaction between Group × CPP ($\beta = .07$, $p = .02$).

To further examine the interaction between Group × CPP for both VOT average and VOT variability, correlational analyses were conducted within each group. There was a significant negative correlation ($r = -.60$, $p = .002$) between CPP and VOT variability within the VFN group, yet no correlation was noted for the control group ($r = .04$, $p = .85$; see Figure 3). There was no significant correlation between CPP and average VOT for either group (both $p > .05$; see Figure 3).

## Discussion

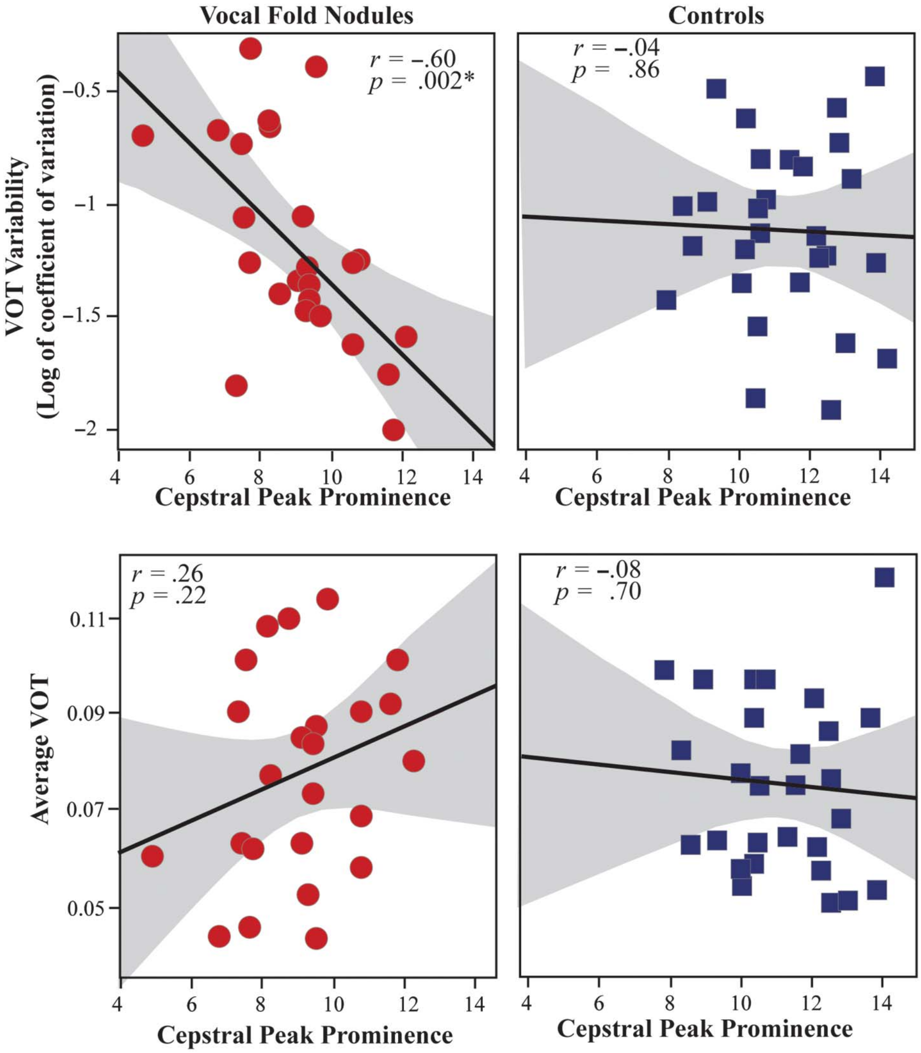
Research on children with VFNs primarily focuses on voice and vocal outcomes. However, children do not use their voices in isolation during speech production. Rather, intelligible speech production requires children to coordinate their developing vocal and articulatory systems. Therefore, this study examined a naturally occurring segment of speech production that relies on vocal and articulatory coordination, VOTs of voiceless stop productions.

**Table 2.** Descriptive statistics for included participants with usable VOT values.

| Variable | Control<br>*M* (*SD*) | VFN<br>*M* (*SD*) |
|---|---|---|
| VOT average (milliseconds) | 75.41 (17.0) | 77.44 (21.17) |
| VOT variability (coefficient of variation) | 0.35 (0.13) | 0.34 (0.17) |
| CPP (decibels) | 11.19 (1.71) | 9.02 (1.74) |
| Number of usable VOTs | 7.29 (1.41) | 6.41 (2.39) |
| Sentence length (seconds) | 2.07 (0.47) | 2.18 (0.36) |
| Pitch (hertz) | 267.95 (25.36) | 262.95 (31.09) |

*Note.* VOT = voice onset time; VFN = vocal fold nodule; CPP = cepstral peak prominence.

**Figure 3.** Relationships between voice onset time (VOT) variability and cepstral peak prominence (top row) and average VOT and cepstral peak prominence (bottom row). Children with vocal fold nodules had a significant negative correlation between cepstral peak prominence and VOT variability (top left, red circles). Asterisk indicates a significant correlation at $p < .05$. No other significant relationships were found. Solid black lines and gray shaded area indicate fit and 95% confidence intervals.



## *VOT Variability*

There was no significant difference in VOT variability between the VFN and control groups. However, VOT variability was significantly predicted by the interaction of Group and CPP. Further analysis within each group was conducted. A significant relationship was found in the VFN group, with increased dysphonia associated with increased VOT variability. No relationship was found between VOT variability and CPP in the control group. The current work suggests that children with VFNs who display decreased periodicity (e.g., decreased CPP) also have increased variability of vocal control during speech production. We propose that one potential explanation for this relationship is that the presence of VFNs interrupts the typical development of the vocal motor control system. This could make vocal fold movements less reliable, resulting in children with VFNs being less likely to monitor them auditorily during speech (e.g., less likely to focus on changes in pitch and pitch variability). If vocal motor control is related to the severity of the vocal deviation, this reduced reliability of vocal fold movements and decreased auditory monitoring during speech production could be more severe in children with greater dysphonia. However, this proposed idea requires additional studies designed to more directly address whether there are differences in vocal motor control in children with VFNs and whether these potential differences are impacted by factors such as the size of the VFN or the age of VFN onset.

Another potential explanation is that decreased motor control (e.g., increased VOT variability) is one of the factors causing phonotraumatic vocal behaviors to persist. The presence of the VFN can increase breathiness, as the VFN becomes the initial point of contact during phonation, leading to anterior and posterior escape of air (Simpson & Rosen, 2008; Sodersten & Lindestad, 1990). Children may also find it difficult to build up adequate subglottic pressure, leading to the implementation of phonotraumatic behaviors (e.g., strain, increased muscle tension) to phonate. This vocal behavior leads to additional vocal misuse, further exacerbating the already present VFN (Galindo et al., 2017; Hillman et al., 1989, 2020). These maladaptive compensatory strategies children might employ may be more severe in children with increased dysphonia. Thus, the increased use of these phonotraumatic strategies may make all vocal production more variable, including the vocal control required for speech. Whether the changes in vocal motor control are in response to VFN or contribute to their persistence, it would be beneficial for clinicians to know if children are less attuned to their vocal motor system. Learning to control the vocal system is a key component in many direct therapy tasks (Van Stan et al., 2015; Verdolini Abbott, 2013) and thus understanding any potential deficits in vocal motor control could influence task selection. Additional work is needed explore this relationship between voice and speech motor control in children with VFNs.

Findings from this study on the relationship between dysphonia and VOT variability are consistent with those of a previous study examining adults with hyperfunctional voice disorders (McKenna et al., 2020). However, unlike this study, McKenna et al. noted that adults with voice disorders had increased VOT variability compared with gender- and age-matched vocally healthy peers (McKenna et al., 2020). The authors suggested this group difference may be related to the disordered vocal motor control hypothesized to be one of the causes of vocal hyperfunction development (Hillman et al., 2020; McKenna et al., 2020; Stepp et al., 2017). One key element of this hypothesis is that accurate auditory perception is needed to detect and correct vocal feedback errors, which is a key element of vocal motor control. Abur et al. found that adults with vocal hyperfunction have decreased auditory discrimination abilities (Abur et al., 2021), which may result in larger auditory target ranges and contribute to increased VOT variability in adults (McKenna et al., 2020). However, prior research suggests that children with VFNs have comparable vocal discrimination abilities to age- and gender-matched peers with typical voices (Heller Murray et al., 2019). As auditory-discrimination deficits do not appear to be present in children with VFNs, this may explain why this study did not find a group difference in VOT variability. Heller Murray et al. did note that younger children had poorer pitch discrimination abilities than older children. Moreover, older children continued to have poorer pitch discrimination abilities than adults (Heller Murray et al., 2019). Further exploration into auditory discrimination deficits and vocal variability within the dysphonic pediatric population across different ages may be warranted. Additional work is also needed to examine if children with VFNs perceive their vocal differences as “errors” that require correction. Most adults who are their own primary caretakers will seek a professional evaluation if a change in their voice occurs. However, children are not their main caretakers and rely heavily on external sources to monitor changes in their behavior, health, and safety. Children referred to a professional for dysphonia are frequently brought in because someone external, such as a caregiver, has noticed a change in their vocal quality (Braden et al., 2018). Although research has shown that children are generally aware of their voice (Connor et al., 2008), further work is needed to determine children’s abilities to detect smaller changes in their own vocal quality.

### *Average VOT*

There was no significant difference in average VOT values between children with and without VFN. Values for both groups were within the ranges found in previous work with typical children, with an average VOT range of 65–90 ms and coefficient of variation values between 0.18 and 0.34 (Kent, 1976; Koenig, 2001; S. Whiteside & Marshall, 2001; S. P. Whiteside et al., 2004; Yu et al., 2014, 2015; Zlatin & Koenigsknecht, 1976). Ideally, VOT measurements should be analyzed within phonemes, as normative data for VOT measurements differ by phoneme (Abramson & Whalen, 2017). However, this was not possible with this study design; therefore, this work focused on two voiceless phonemes (/p/, /k/). Although there were not enough instances to examine any potential average or variability differences between these phonemes, both groups examined produced the same stimuli. Therefore, phoneme differences are unlikely to contribute to any group differences. Future work should include prospective data collection with a larger number of phonemes to examine nuances not captured in the current work.

Although there was no group difference in average VOT, there was a significant interaction between Group and CPP. The interaction suggested that individuals in the VFN group with decreased CPP had shorter average VOTs. However, further examination of this relationship in each group did not reach significance. Upon initial visual evaluation of this relationship, the VFN group appears to have greater between-subjects variability. Therefore, the current sample size may have been underpowered to examine this relationship. Subsequent work should examine a larger group to elucidate this relationship fully. Another possible explanation is that the strong relationship between average VOT and sentence length may have masked other findings. Sentence length measurements provide information about speech rate, which has been shown to influence VOT values of voiceless productions (Kessinger & Blumstein, 1998; Volaitis & Miller, 1992). Similar to these earlier studies, this study demonstrated that shorter sentences (ostensibly spoken at a faster rate) were associated with decreased VOT. As speech rate was not controlled or experimentally tested in this retrospective design, future studies with controlled speech rates are needed to fully determine the relationship between average VOT and CPP in this population.

### *CPP*

Increased dysphonia was measured using the acoustic measure of CPP, which provides information on the harmonic structure related to the periodicity of the vocal folds during phonation (Awan et al., 2009; Heman-Ackah et al., 2003; Watts & Awan, 2011). CPP was significantly different between the control and VFN groups, with lower CPP values (corresponding to a more dysphonic voice) found in children with VFNs. These results support prior research examining the reliability of CPP values in indicating the presence of dysphonia in a pediatric population (Esen Aydinli et al., 2019). Although CPP is now a recommended clinical tool for examining dysphonic voices for patients of all ages (Patel et al., 2018), ongoing work is needed to determine the appropriate normative values. CPP has been shown to vary as a function of age (Demirci et al., 2021; Infusino et al., 2015; Kent et al., 2021; Spazzapan et al., 2022), and Infusino et al. created a normative reference for CPP values in children (Infusino et al., 2015). However, it is important to note that this normative database used the Analysis of Dysphonia in Speech and Voice (ADSV) program to calculate CPP. In contrast, this study used the Praat program (Boersma & Weenick, 2019) to calculate CPP. CPP values can be reliably calculated using the ADSV program or Praat software; however, these individual programs use different algorithms to calculate CPP and thus cannot be directly compared (Watts et al., 2017). Continued work is needed to understand the impact of development and VFN on CPP in children, independent of the program selected for calculation.

## Limitations and Future Directions

This study has several limitations that may have impacted the outcome. First, this study had a reduced age range, examining children between 6 and 12 years of age. This may have contributed to the lack of group differences in VOT averages. As VOT averages become adultlike around 6 years old (Kent, 1976; S. Whiteside & Marshall, 2001), it is possible that children in this study already had mature VOT productions that were not impacted by structural vocal changes. Second, additional information about the VFN participants was unknown, including the size of the VFN for each child or whether the child had further speech concerns that the parent did not note. It is possible that the majority of the participants had small VFN that did not impact vocal fold movement as much as larger VFN might have. Future work is needed to expand the age range to examine younger children and to include VFN characteristics that may impact phonation. Third, although formalized articulation testing was not completed in this study, the analysis of VOT was completed manually. Thus, a trained analyst listened to every instance before the VOT calculation and would have noted any instances of inaccurate articulation in the speech sections of interest. It is possible that unforeseen differences in speech may have impacted the results, and future work would need to include formalized articulation testing to confirm these findings. Fourth, the retrospective nature of the design resulted in limited control of the recording environment, as data were collected at two locations. The analyses were structured to minimize these potential limitations, including evaluating only the voiced segments for CPP analysis and filtering the speech signals to help with vocalic onset identification; however, future work is needed to examine these potential confounds fully.

## Author Contributions

**Lauren Colletti:** Conceptualization (Equal), Data curation (Supporting), Formal analysis (Equal), Investigation (Lead), Methodology (Equal), Writing – original draft (Lead), Writing – review & editing (Equal). **Elizabeth Heller Murray:** Conceptualization (Equal), Data curation (Lead), Formal analysis (Equal), Funding acquisition (Lead), Investigation (Supporting), Methodology (Equal), Resources (Lead), Software (Lead). Supervision (Lead), Writing – original draft (supporting), Writing – review & editing (Equal).

## Data Availability Statement

Data available upon request to the corresponding author.

## Acknowledgments

This project was originally written and presented by Lauren Colletti as part of a master's thesis at Temple

University. Acquisition of this original data for this project was supported by the National Institute on Deafness and Other Communication Disorders Grants DC016197 (Elizabeth Heller Murray), DC015570 (Cara Stepp), and DC015446 (Robert Hillman). The authors would like to thank Edwin Maas and Susan Caspari for their helpful contributions throughout all stages of this project. Additional thanks to Andie Chao for her assistance with this project.

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