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Research Article

The Effects of Syntactic Complexity and Sentence Length on the Speech Motor Control of School-Age Children Who Stutter

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Purpose: Early childhood stuttering is associated with atypical speech motor development. Compared with children who do not stutter (CWNS), the speech motor systems of school-age children who stutter (CWS) may also be particularly susceptible to breakdown under increased processing demands. The effects of increased syntactic complexity and sentence length on articulatory coordination were investigated.
Method: Kinematic, temporal, and behavioral indices of articulatory coordination were quantified for school-age CWS (n = 19) and CWNS (n = 18). Participants produced 4 sentences varying in syntactic complexity (simple declarative/complex declarative with a relative clause) and sentence length (short/long). Lip aperture variability (LAVar) served as a kinematic measure of interarticulatory consistency over repeated productions. Articulation rate (syllables per second) was also calculated as a related temporal measure. Finally, we computed accuracy and stuttering frequency percentages for each sentence to assess task performance.
Results: Increased sentence length, but not syntactic complexity, increased LAVar in both groups. This effect was disproportionately greater for CWS compared with CWNS. No group differences were observed for articulation rate. CWS were also less accurate in their sentence productions than fluent peers and exhibited more instances of stuttering when processing demands associated with length and syntactic complexity increases.
Conclusions: The speech motor systems of school-age CWS appear to be particularly vulnerable to processing demands associated with increased sentence length, as evidenced by increased LAVar. Increasing the length and complexity of the sentence stimuli also resulted in reduced production accuracy and increased stuttering frequency. We discuss these findings within a motor control framework of speech production.

Childhood stuttering, also known as childhood-onset fluency disorder (American Psychiatric Association, 2013), is characterized by the presence of involuntary stuttering-like disfluencies (SLDs) that likely arise because of disruptions in the sequencing of motor commands to speech muscles (Guenther, 2016; Smith, 1989). According to Smith and Weber (2017), children who stutter (CWS) exhibit speech motor systems more vulnerable to disruption compared with children who do not stutter (CWNS), particularly when neural resources facilitating cognitive, emotional, linguistic, and speech motor processes are taxed. Identification and quantification of processing demands affecting the fluency of CWS are of great value both theoretically and clinically, with implications toward more effective therapeutic interventions. Behavioral, kinematic, and temporal indices of articulatory coordination during sentence production reveal the impact that linguistic demands have on speech output and identify vulnerabilities in speech motor control associated with childhood stuttering.

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Production Accuracy as a Behavioral Index of Articulatory Coordination

A number of behavioral studies have consistently found that increasing linguistic and motoric demands (such as

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syntactic complexity and utterance length) increased the frequency of SLDs and other types of disfluencies (for reviews, see Bernstein Ratner, 1997; Bloodstein & Ratner, 2008). Syntactic complexity has been a salient variable regarding stuttering characteristics, particularly for young CWS (Bernstein Ratner & Sih, 1987; Brundage & Ratner, 1989). Longer utterance length, independent or in conjunction with increased syntactic complexity, also elicits SLDs of greater frequency compared with shorter utterances (Buhr & Zebrowski, 2009; Gaines, Runyan, & Meyers, 1991; Richels, Buhr, Conture, & Ntourou, 2010; Sawyer, Chon, & Ambrose, 2008; Yaruss, 1999; Zackheim & Conture, 2003). Logan and Conture (1995) categorized utterance length as a "macro-variable" reflecting the influence of numerous cognitive and linguistic processes on speech motor control. Unlike analysis of spontaneous speech, the use of imitation paradigms allows confounding variables to be controlled (e.g., semantic and phonological processing demands) and for the isolation and standardization of syntactic structure and utterance length (Bernstein Ratner & Sih, 1987). The negative effects of processing demands on the speech performance of CWS are also evident from kinematic studies of perceptually fluent, imitated productions (e.g., MacPherson & Smith, 2013; Usler, Smith, & Weber, 2017). In these studies, the number of production inaccuracies (such as articulation errors and typical disfluencies) and SLDs by young CWS increased when imitating more complex and longer sentences to a degree not characteristic of their fluent peers. This is evidence that, for at least some CWS, increased processing demands disproportionately affect their articulatory coordination, sometimes to the degree that repeated fluent and accurate sentence productions were not attainable for kinematic analysis.

Lip Aperture Variability as a Kinematic Index of Articulatory Coordination

In previous kinematic analyses, we have used a spatiotemporal index (STI) to capture the consistency of articulatory patterns for a single effector, such as the lower lip, across repeated productions (Smith, Johnson, McGillem, & Goffman, 2000). The lip aperture variability (LAVar) index is an STI that assesses interarticulatory coordination of the upper and lower lips to control oral aperture during speech production (Smith & Zelaznik, 2004). Studies using these measures to index neuromotor maturation for speech in typically developing speakers aged 4 years through young adulthood revealed a protracted development of speech motor control, with speakers not reaching adultlike articulatory consistency until late adolescence (Smith & Zelaznik, 2004; Walsh & Smith, 2002).

STI has also been used to document destabilizing effects of linguistic demands on speech motor coordination in young CWS and adults who stutter. Kleinow and Smith (2000) found that adults who stutter demonstrated increased variability in lower lip movement with increased syntactic complexity compared with typical adults. CWS also exhibit atypical speech motor control processes during fluent speech, including immature speech motor dynamics characterized by decreased displacement amplitudes and velocities and higher articulatory coordination variability compared with typically developing children (MacPherson & Smith, 2013; Smith, Goffman, Sasisekaran, & Weber-Fox, 2012; Usler et al., 2017; Walsh, Mettel, & Smith, 2015). MacPherson and Smith (2013) found increased LAVar in 4- to 6-year-old CWS and CWNS with increased sentence length, but their results did not reveal CWS to be more vulnerable than their fluent peers to increasing syntactic complexity. Higher LAVar was also characteristic of 5- to 7-year-old children for sentence production regardless of length and complexity compared with their previously recovered peers and fluent controls—evidence that articulatory coordination variability may be a marker of stuttering chronicity (Usler et al., 2017). The above kinematic studies in young CWS suggest that their articulatory coordination is more variable than their fluent peers but have not revealed that increased processing demands may impact speech motor control to a disproportionate degree compared with CWNS.

Articulation Rate as a Temporal Index of Articulatory Coordination

Articulation rate, indexed as the number of fluent syllables produced per second excluding pauses and disfluencies, is a temporal measure of articulatory coordination and development (Amster & Starkweather, 1987; Kowal, O'Connell, & Sabin, 1975; Turner & Weismer, 1993). With the development of speech motor skills, the ability to efficiently and rapidly articulate speech increases (Smith & Zelaznik, 2004; Tsao & Weismer, 1997; Walsh & Smith, 2002). Many studies have not found differences in articulation rate between CWS and CWNS (e.g., Kelly & Conture, 1992; Logan, Byrd, Mazzocchi, & Gillam, 2011; Yaruss, 1997). Previous kinematic studies also have not reported group differences in the related measure, movement duration, for sentence production (e.g., MacPherson & Smith, 2013; Usler et al., 2017). However, others suggest that articulation rate is slower in CWS compared with CWNS, particularly for those children with more severe stuttering (e.g., de Andrade, Cervone, & Sassi, 2003; Chang, Ohde, & Conture, 2002; Chon, Sawyer, & Ambrose, 2012; Hall, Amir, & Yairi, 1999; Meyers & Freeman, 1985; Tumanova, Zebrowski, Throneburg, & Kulak Kayikci, 2011; Zebrowski, 1994).

Purpose of the Study

The purpose of this study was to gain insight into the development of speech motor control processes in older children who have persisted in stuttering. Whereas previous studies from our laboratory have focused on the distal ends of the developmental spectrum, in young children near onset or, alternatively, in adults who stutter, the current study investigated the impact of increased processing demands on speech production in CWS and CWNS in the school-age years. Specifically, we assessed the effects of increased syntactic complexity and sentence length on behavioral, kinematic, and temporal indices of speech motor performance. We used an imitation paradigm similar to that of previous studies with younger children and adults (e.g., Kleinow & Smith, 2000; MacPherson & Smith, 2013; Usler et al., 2017). Given that processing demands may affect the speech motor systems of individuals who stutter differently across development from early childhood through adulthood (Silverman & Ratner, 1997), further investigation of the articulatory coordination abilities of older CWS and CWNS is warranted and may reveal divergences in speech motor development between CWS and CWNS in the school-age years. Our earlier studies with preschool CWS revealed less consistent articulatory coordination across the speech stimuli regardless of length or linguistic complexity but that adults who stutter were disproportionately affected by these demands. Given these findings, we hypothesized that CWS and CWNS may show comparable performance for the less demanding conditions (e.g., short, simple sentences) but may produce the more demanding sentences with decreased accuracy and/or greater coordinative variability. Finally, we investigated possible associations between participant indices of LAVar and articulation rate with age and stuttering severity (indexed by Stuttering Severity Instrument for Children and Adults–Third Edition [SSI-3] scores) to further explore the potential impact of sentence length and syntactic complexity on speech motor performance.

Method

Participants

Our participants were native English-speaking children between the ages of 7;3 and 12;7 years;months assigned to one of two groups: CWS (n = 19, four girls, 15 boys) and CWNS (n = 18, five girls, 13 boys). Mean age (in months) was similar between groups: CWS (M = 120.21, SE = 4.02, range = 91–151) and CWNS (M = 120.06, SE = 4.09, range = 87–149). Per parent reporting, all participants had no history of cognitive, developmental, neurological, speech, or language disorders other than stuttering in the group of CWS. Children were also screened for medications expected to affect performance (e.g., caffeine, muscle relaxants, antidepressants). Participants scored within normal limits on the Clinical Evaluation of Language Fundamentals–Fourth Edition (Semel, Wiig, & Secord, 2003) and the Oral Speech Mechanism Screening Examination–Third Edition (St. Louis & Ruscello, 1987) and passed a bilateral pure-tone hearing screening at 500, 1000, 2000, 4000, and 6000 Hz at 20 dB. CWS and CWNS groups also had comparable socioeconomic status (SES) determined by maternal level of education (Hollingshead, 1975). SES was evaluated on a 7-point scale (5 = *some college,* 6 = *college degree,* and 7 = *graduate or professional degree*). The medians for CWS (range = 4–7) and CWNS (range = 5–7) were 6 and 7, respectively. To elucidate possible group differences in maternal education, which were not normally distributed, a nonparametric independent-samples median test was performed (Siegel & Castellan, 1988). No group differences in SES (p = .07) were observed.

Inclusion criteria for the CWS included (a) evidence of at least 3% stuttered syllables during conversational and reading tasks; (b) score of at least "very mild" (an overall score ≥ 6) on the SSI-3 (Riley, 1994); and (c) being considered as persons who stutter by both the child's parent(s)/legal guardian and by a speech-language pathologist (SLP) using an 8-point severity scale (0–1 = *normal,* 2–3 = *mild stuttering,* 4–5 = *moderate stuttering*, and 6–7 = *severe stuttering*). In two cases, the speech sample collected on the day of the experiment resulted in only 2% of syllables stuttered. In these cases, we relied upon caregiver ratings and the clinical judgment of the SLP during interactions that occurred with her over the course of the experiment and during clinical testing to confirm stuttering. CWS ranged in severity from very mild to moderate on the SSI-3. Stuttering severity for CWS participants was measured by SSI-3 scores (M = 16.63, SE = 1.61). The mean duration of stuttering (i.e., time since onset) was 6.59 years (SE = 0.33 years) per parent report. Finally, CWS were eligible to participate in the study regardless of whether they had received or were currently receiving speech therapy. We documented that approximately 63% of CWS participants (12/19) had received or were currently receiving therapy for stuttering. Participant characteristics are displayed in Table 1.

Stimuli

Participants were told they would hear sentences about birds and butterflies through a speaker and to repeat the sentences exactly as they were heard. Imitative tasks have been used to study the effects of syntactic complexity and utterance length in behavioral (e.g., Bernstein Ratner & Sih, 1987) and kinematic (e.g., MacPherson & Smith, 2013) studies of CWS. These types of paradigm standardize the demands of interest, such as syntactic complexity or length of an utterance, while controlling for confounds such as semantic or phonological variables. Pictures of birds and butterflies were displayed on a computer monitor in front of the participants to accompany the audio presentations. Four declarative sentences containing predominantly bilabial consonants (so that lip aperture was a dynamically controlled articulatory target) and varying in length and syntactic complexity were presented. As shown in Table 2, short sentences contained six words (eight syllables) and long sentences contained 11 words (15 syllables). Syntactically complex sentences included a subject relative clause (the main-clause subject is modified by an embedded clause through the complementizer "that"), which was shown to influence variability in speech motor coordination (e.g., Kleinow & Smith, 2006). The complexity and frequency of subject relative clause use increase as a function of age throughout the preschool years (Diessel & Tomasello, 2001). The long sentences differed from their short counterparts through the addition of a nonobligatory adjunct.

Table 1. Participant characteristics.

Participant	Gender	Age	SES	SSI-3	Tx
CWS-1	M	8;1	7	9	No
CWS-2	F	9;5	6	23	Yes
CWS-3[a]	M	11;6	4	22	No
CWS-4	M	10;0	6	19	Yes
CWS-5	M	11;6	7	9	No
CWS-6	M	11;2	6	18	Yes
CWS-7[a]	F	10;1	5	16	Yes
CWS-8	M	9;0	7	23	No
CWS-9[a]	M	7;7	7	27	Yes
CWS-10	M	12;7	6	20	Yes
CWS-11[a]	M	8;3	5	18	No
CWS-12	F	11;1	6	11	Yes
CWS-13	M	11;0	7	7	Yes
CWS-14[a]	M	9;0	6	21	Yes
CWS-15	F	11:2	6	9	No
CWS-16	M	9;1	6	8	Yes
CWS-17	M	8;3	5	7	No
CWS-18	M	9;9	6	20	Yes
CWS-19	M	11;10	6	29	Yes
CWNS-1	M	11;8	7	N/A	N/A
CWNS-2	M	9;2	7	N/A	N/A
CWNS-3	M	10;10	7	N/A	N/A
CWNS-4	M	7;7	7	N/A	N/A
CWNS-5	M	11;7	7	N/A	N/A
CWNS-6	M	7;3	7	N/A	N/A
CWNS-7	M	9;10	7	N/A	N/A
CWNS-8	F	11;4	7	N/A	N/A
CWNS-9	M	9;3	6	N/A	N/A
CWNS-10	F	9;2	7	N/A	N/A
CWNS-11	F	11;4	7	N/A	N/A
CWNS-12	F	10;1	6	N/A	N/A
CWNS-13	F	8;9	6	N/A	N/A
CWNS-14	M	8;9	6	N/A	N/A
CWNS-15	M	10;6	7	N/A	N/A
CWNS-16	M	12;5	6	N/A	N/A
CWNS-17	M	11;1	5	N/A	N/A
CWNS-18	M	9;6	6	N/A	N/A

Note. SES = socioeconomic status (Hollingshead, 1975); SSI-3 = Stuttering Severity Instrument for Children and Adults–Third Edition (Riley, 1994); Tx = exposure to stuttering therapy; CWS = children who stutter; M = male; F = female; CWNS = children who do not stutter. N/A = not applicable.

[a]Did not complete the required number of accurate trials and thus not included in kinematic or rate analyses.

Procedure

At the beginning of the task, participants were told, "For this part of the experiment, you will hear some sentences about birds and butterflies. Listen to each sentence carefully then repeat it back exactly as you hear it. Let's try them." The participants practiced each sentence approximately two times during which modeling and feedback were provided. After this, stimuli were presented in blocks of eight quasirandomized sentences. The paradigm consisted of 12 production trials; however, more attempts were given to the participant if needed. After the participant's production of a sentence, a 2- to 3-s pause occurred before the next stimulus. After the experiment, during offline analysis, the first production was omitted and the next 8–10 error-free and fluent productions of each sentence type were analyzed from each participant. To reduce boredom and fatigue during the experiment, we provided breaks at regular intervals, allowing the children to take several turns at a game before initiating the next block. To maintain participants' attention throughout the task, the experimenters guided the children to focus their attention to the computer monitor in front of them.

Data Measurement and Analysis

During the repeated sentence productions, superior–inferior movements of the upper and lower lips were recorded using a Northern Digital Optotrak Certus 3020 system (Northern Digital, Waterloo, Ontario, Canada). Previous studies from our laboratory have used similar kinematic measurement and analysis methods (e.g., Smith & Zelaznik, 2004; Walsh, Smith, & Weber-Fox, 2006). The Optotrak system recorded the motions of eight infrared light-emitting diodes (IREDs), each sampled at 250 samples per second, in three dimensions with an accuracy of 0.1 mm. IREDs were attached to the midline vermillion borders of each participant's upper and lower lips to track lip motion. Participants also wore modified sports goggles with four attached IREDs. A fifth IRED was placed on the center of the forehead. These five markers were used to create a three-dimensional coordinate system to track head motion. Head movement artifact was removed from superior–inferior lip motions. The Optotrak system also recorded the acoustic signal from a condenser microphone so that the acoustic and kinematic recordings were synchronized. The audio signal was digitized at 16,000 samples per second after low-pass filtering with a cutoff frequency of 7500 Hz.

Measurement of LAVar

Articulatory movements were measured using a custom, interactive MATLAB program that displayed lip displacement and velocity signals for each production. The recording of upper and lower lips began with the release

Table 2. Sentence stimuli.

Condition	Sentence	Number of words/syllables	Relative clause
Short simple	The birds and the butterflies played.	6/8	Absent
Short complex	The birds that saw butterflies played.	6/8	Present
Long simple	The baby birds and the many butterflies played by the pond.	11/15	Absent
Long complex	The baby birds that saw many butterflies played by the pond.	11/15	Present

of the /b/ in "birds" in all sentences and ended with the release of the /p/ in "played" for the short sentences and in "pond" for the long sentences. Upper and lower lip displacement signals, verified with the acoustic signal, were segmented into analysis records from the points of peak velocity of these first and last bilabial movements of each sentence production. The LAVar index assesses the degree to which repeated utterances converge on an underlying pattern. Therefore, only accurate and fluent productions (e.g., not containing SLDs, typical disfluencies, aberrant prosody or pauses, substitutions, or omissions) were used in the kinematic analysis. The LAVar index, derived by subtracting upper lip from lower lip movement, measures spatial and temporal variability in the coordination of upper and lower lip coupling across multiple productions. Each set of 8–10 lip aperture signals for each sentence was then time and amplitude normalized. As described in earlier studies, time normalization was achieved by linearly interpolating all records to 1,000 points (e.g., Smith et al., 2000). Amplitude normalization was achieved by subtracting the mean and dividing by the standard deviation of each record. These standard deviations were calculated at 2% intervals in relative time and summed to create a LAVar index score. Figure 1 illustrates the steps in kinematic data processing, including the displacement signals (top), time-normalized signals (center), and LAVar indices (bottom) for a single participant from each group.

Measurement of Articulation Rate

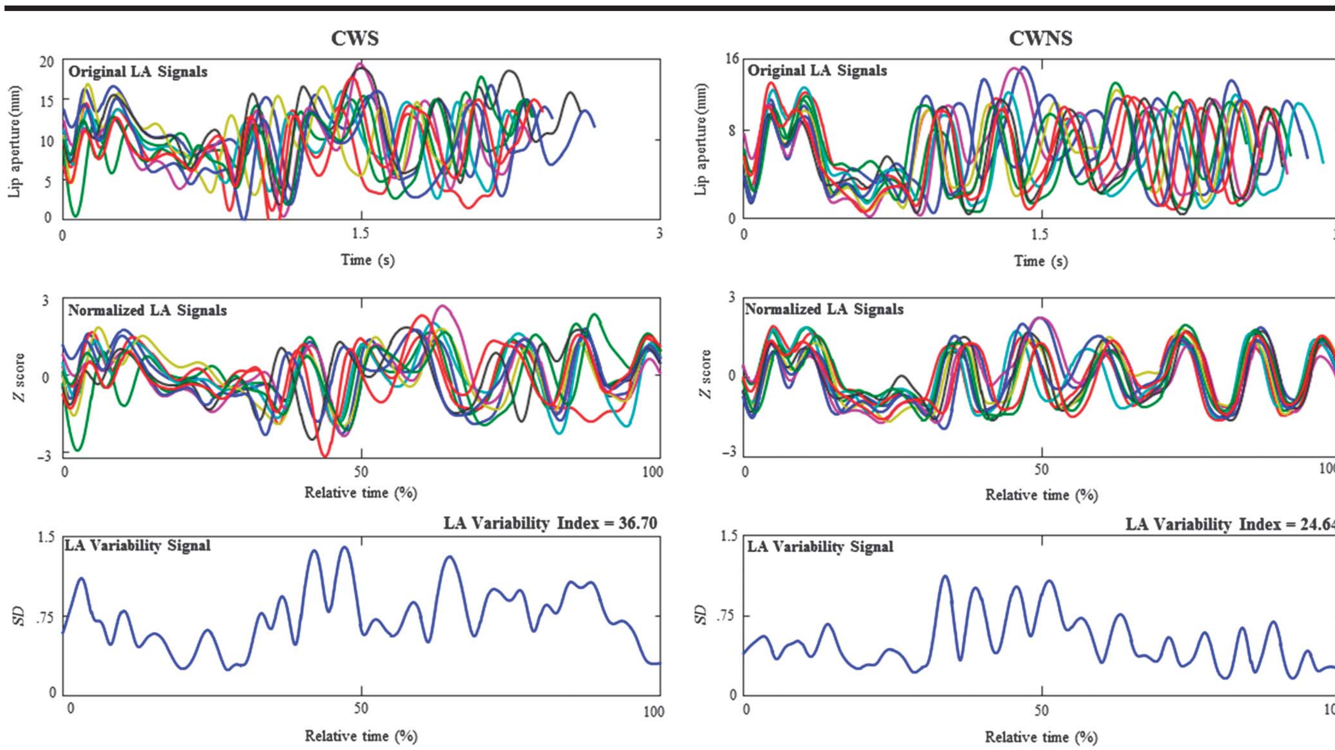
Movement duration was computed as the time (in seconds) of each original, nonnormalized sentence (see Figure 1, top), starting at the release of the /b/ in "birds" and ending at the release of the /p/ in "played" for the short sentences or in "pond" for the long sentences. The mean duration of repeated productions of each sentence type was averaged for every participant before statistical comparisons were performed. Mean articulatory rate (syllables per second) was then calculated by dividing the number of syllables by the movement duration. Significant differences in articulation rate and LAVar were considered using an alpha level of $p < .05$. Repeated-measures analyses of variance were used to determine main and interaction effects. Partial eta squared (η_p^2) was used to determine the size of significant effects.

Results

Production Accuracy

We calculated accuracy percentage in CWS and CWNS by comparing the number of fluent and accurate productions with the number of attempts for each sentence type to obtain complementary behavioral analyses of articulatory performance. Trials that included SLDs or production inaccuracies (such as typical disfluencies, articulation errors,

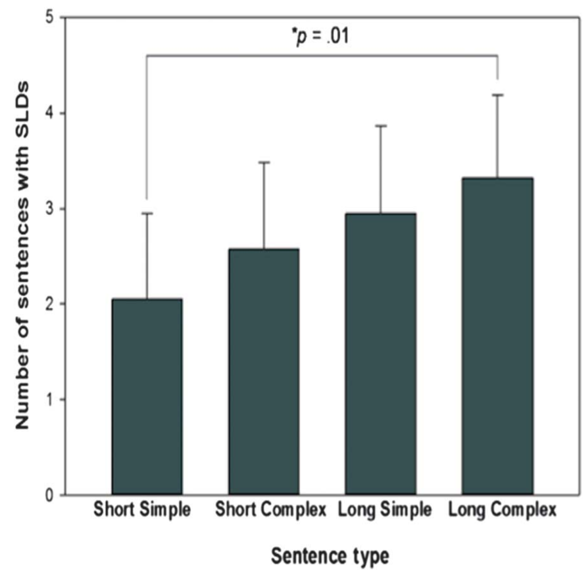
Figure 1. Kinematic data processing steps. Original lip aperture signals (top), normalized lip aperture signals (center), and lip aperture variability indices (bottom) for long, complex sentence productions by one CWS participant (left) and one CWNS participant (right). Different colors distinguish individual trials. CWS = children who stutter; CWNS = children who do not stutter.



mistaken word order, etc.) were not included in the later kinematic analysis. As shown in Table 3, CWS had significantly lower accuracy percentages compared with CWNS across the four sentence types, suggesting that school-age CWS overall exhibited greater difficulty with the sentence production task. A multivariate analysis of variance confirmed significant group differences (*p*s < .05) in the accuracy percentages for all sentence types; effect sizes were largest for the long and short complex sentence conditions (see Table 3). The number of production attempts with SLDs by CWS for each sentence type is also provided (see Figure 2) because these data have relevance with respect to earlier behavioral studies looking at effects of syntactic complexity or length on fluency (e.g., Bernstein Ratner, 1997). We found a significant effect of sentence type on the number of stuttered trials within the group of CWS, $F(3, 54) = 3.86$, $p = .01$, $\eta_p^2 = .18$. Post hoc analysis revealed that CWS stuttered more frequently on the long complex condition compared with the short simple condition (Tukey's honestly significant difference, $p = .01$). The other comparisons were not significantly different (all *p*s = .11–.78).

Finally, it is notable that of the 19 CWS participants originally recruited for this study, five (26.3%) could not successfully produce the minimum eight accurate and fluent trials per sentence type necessary for kinematic analysis. Analysis of individual data of accurate versus inaccurate and stuttered versus fluent trials revealed that the inability to complete the paradigm was due to the presence of SLDs for three CWS participants and production inaccuracies in the other two. On the other hand, all CWNS participants successfully completed the paradigm. This suggests that the task requirements pertaining to sentence imitation were overly challenging for a subset of our school-age CWS.

Figure 2. Number of production attempts by children who stutter with SLDs (with standard errors) for each of the four sentence types. SLDs = stuttering-like disfluencies.



LAVar

Fourteen participants from the original group of 19 CWS completed the requisite 8–10 repetitions of each sentence. Data from these 14 children were used for subsequent kinematic analyses. Figure 3 shows the mean LAVar indices for CWS and CWNS across the four sentence types. A condition effect was observed for sentence length, with higher LAVar for the long sentences (M = 30.73, SE = 0.75) compared with the short sentences (M = 24.67, SE = 0.88), $F(1, 30) = 67.82$, $p < .001$, $\eta_p^2 = .69$. A condition effect was not observed for syntactic complexity, with LAVar not differing between the simple and complex conditions, $F(1, 30) = 0.07$, $p = .80$. As illustrated in Figure 4, LAVar increased for long sentences regardless of complexity in both groups; however, this effect was more pronounced for CWS. This was supported by a significant Group × Sentence Length interaction, $F(1, 30) = 12.84$, $p = .001$, $\eta_p^2 = .30$. This large effect revealed that CWS exhibited a higher LAVar (M = 33.20, SE = 1.12) than CWNS (M = 28.26, SE = 0.99) for the production of long sentences. We did not observe a significant interaction between Group and Syntactic Complexity, $F(1, 30) = 0.63$, $p = .43$. Finally, a significant Group × Sentence Length × Syntactic Complexity interaction was not observed, $F(1, 30) = 0.08$, $p = .78$, suggesting that the effect of these increasing demands was not cumulative but strictly pertaining to the length of the utterance.

Articulation Rate

Articulation rate (syllables per second) was slower for short sentences (M = 4.73, SE = 0.10) compared with

Table 3. Percentages of production accuracy (standard errors) for each of the four sentence types.

Group	Short simple sentence	Short complex sentence	Long simple sentence	Long complex sentence
CWS	82.20 (7.24)	75.89 (7.39)	55.04 (6.85)	54.91 (7.10)
CWNS	98.57 (.80)	98.22 (1.00)	89.91 (1.9)	90.47 (2.60)
Statistical analysis	$F(1, 35) = 4.79$, $p = .04$, $\eta_p^2 = .12$	$F(1, 35) = 8.50$, $p = .006$, $\eta_p^2 = .36$	$F(1, 35) = 22.95$, $p < .001$, $\eta_p^2 = .20$	$F(1, 35) = 21.25$, $p < .001$, $\eta_p^2 = .36$

Note. CWS = children who stutter; CWNS = children who do not stutter.

Figure 3. Lip aperture variability indices for CWS and CWNS across all sentence types. Symbols represent means. Error bars indicate standard error. CWS = children who stutter; CWNS = children who do not stutter.

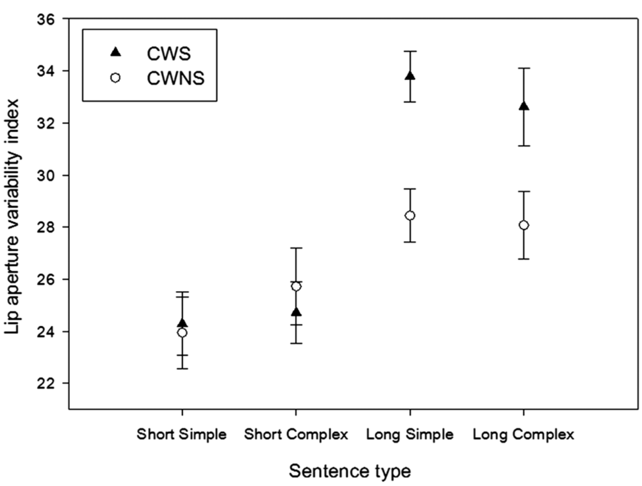
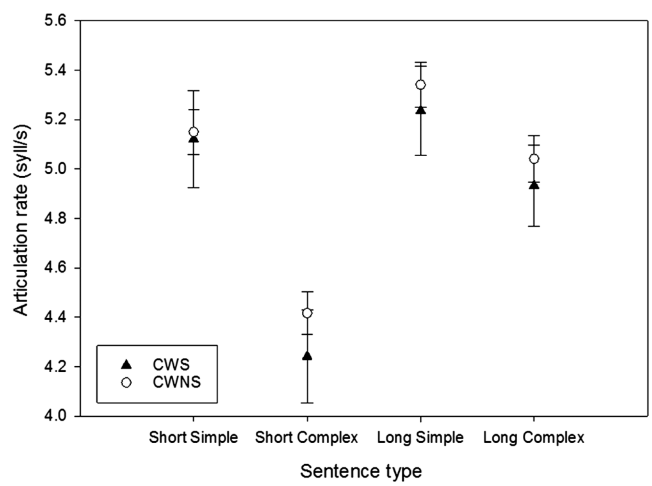


Figure 5. Articulation rates for CWS and CWNS across all sentence types. Symbols represent means. Error bars indicate standard error. CWS = children who stutter; CWNS = children who do not stutter; syll/s = syllables per second.

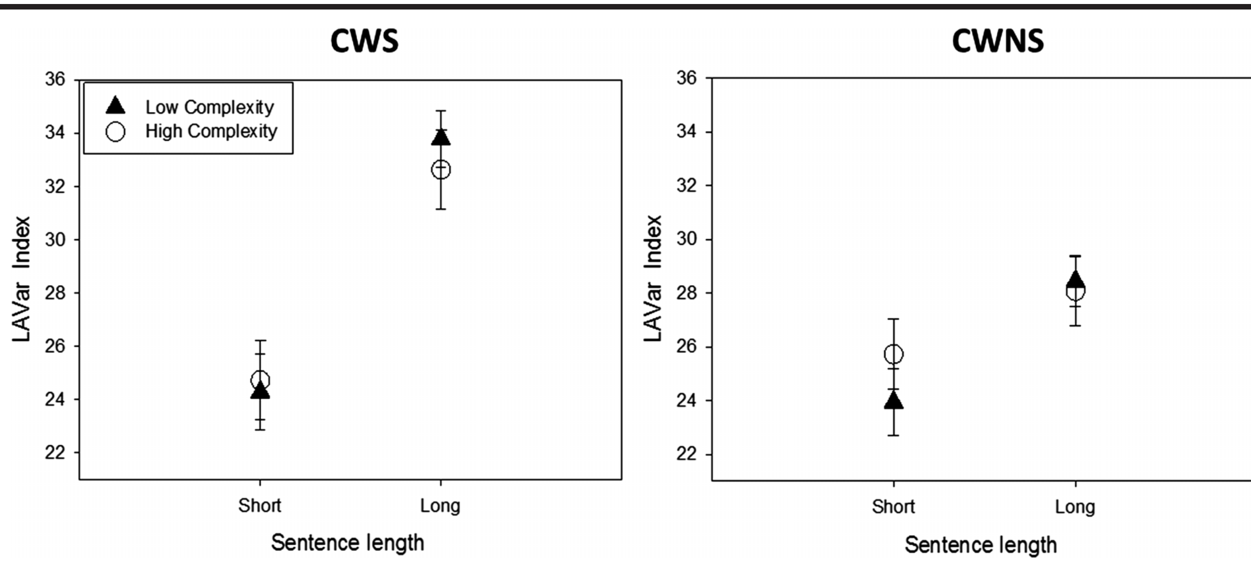


long sentences (M = 5.14, SE = 0.09), $F(1, 30) = 126.37$, $p < .001$, $\eta_p^2 = .81$. Syntactic complexity also influenced articulation rate, with the simple sentences (M = 5.21, SE = 0.09) articulated faster than complex sentences (M = 4.66, SE = 0.09), $F(1, 30) = 284.66$, $p < .001$, $\eta_p^2 = .91$. A Sentence Length × Syntactic Complexity interaction was also significant, $F(1, 30) = 86.69$, $p < .001$, $\eta_p^2 = .74$. Short complex sentences were articulated at a slower rate compared with the other three sentence types (see Figure 5). No group interactions with Syntactic Complexity or Sentence Length were observed ($ps > .05$). Articulation rates across the sentence types were similar between CWS (M = 4.88, SE = 0.14) and CWNS (M = 4.99, SE = 0.12). A Group × Sentence Length × Syntactic Complexity interaction was also not significant, $F(1, 30) = 1.67$, $p = .21$. These findings indicate that articulation rates for the groups were comparable across the sentence types.

Correlational Analyses and Individual Differences

Pearson correlations were performed to explore possible associations between participant indices of LAVar and articulation rate and characteristics such as age and stuttering severity (indexed by SSI-3 scores). Across the sentence

Figure 4. Lip aperture variability (LAVar) indices for low and high syntactic complexity across short and long sentences for CWS and CWNS. CWS = children who stutter; CWNS = children who do not stutter.



types, age was not significantly correlated with LAVar ($-.17 < r$s $< .28$) or articulation rate ($.16 < r$s $< .37$) for CWS. Similarly for CWNS, age was not associated with LAVar ($-.17 < r$s $< .29$) or articulation rate ($-.13 < r$s $< .09$). This lack of an age effect is consistent with developmental studies showing a plateau in the development of LAVar between the ages of 8 and 12 years (e.g., Smith & Zelaznik, 2004). Stuttering severity for CWS also did not significantly correlate with LAVar ($-.01 < r$s $< .52$) or articulation rate ($-.21 < r$s $< -.09$).

Consistent with multifactorial theories of stuttering (Smith & Weber, 2017), we saw a range in speech motor performance in the group of CWS and overlapping LAVar index scores between the two groups of children. Individual data points for LAVar and rate across the sentence types are displayed in Figures 6 and 7, respectively. In Figure 6, we see overlapping LAVar index scores between the two groups of children for the shorter sentences; however, a significant proportion of CWS have higher LAVar indices for the two longer sentences, denoting greater variability. Finally, although we did not find a significant difference in articulation rate between the groups of children, we observed a wider range of articulation rates in the group of CWS compared with CWNS, with CWS demonstrating either the fastest or slowest articulation rates (see Figure 7).

Discussion

In this study, we assessed the effects of increased processing demands on the behavioral, kinematic, and temporal indices of speech production in school-age CWS to contribute to a cohesive account of speech motor development in stuttering. This study was motivated by our lack

Figure 6. Individual LAVar for CWS and CWNS across the sentence. Please note that the number of visible data points may be less than the actual number because of the overlap of multiple symbols. CWS = children who stutter; CWNS = children who do not stutter; LAVar = lip aperture variability.

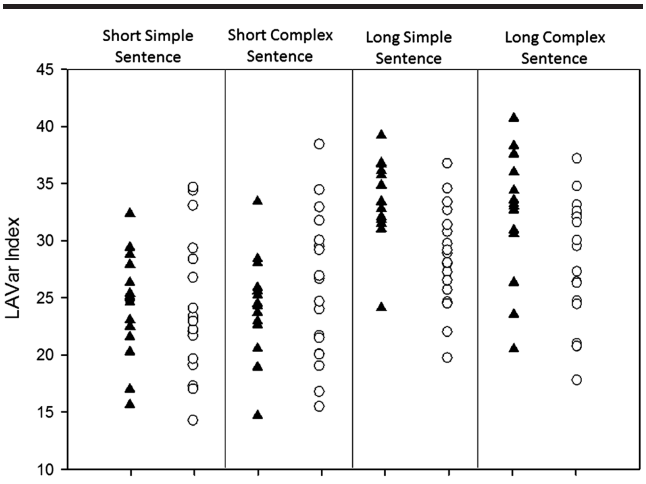
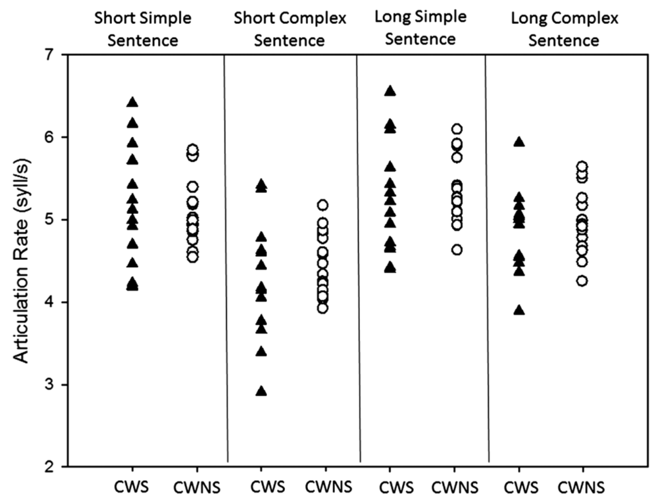


Figure 7. Individual articulation rates for CWS and CWNS across the sentence types. Please note that the number of visible data points may be less than the actual number because of the overlap of multiple symbols. CWS = children who stutter; CWNS = children who do not stutter; syll/s = syllables per second.



of knowledge pertaining to the speech motor control processes of older CWS and early adolescents who stutter—a population less frequently investigated compared with preschool-age CWS and adults who stutter. The LAVar index measured the degree of consistency of upper and lower lip coupling to control oral aperture over repeated productions. Increasing sentence length, but not syntactic complexity, resulted in greater articulatory variability in both groups—an evidence that processing demands associated with longer utterances resulted in less stable speech motor coordination in school-age children. However, this effect was seen to a significantly greater degree in those who stutter. Behaviorally, the frequency of stuttering in CWS increased with increased processing demands. These behavioral findings are consistent with earlier work from our laboratory with preschool-age CWS and CWNS (MacPherson & Smith, 2013; Usler et al., 2017) that also revealed decreased accuracy with increased length and linguistic complexity. The task requirements pertaining to sentence imitation were too demanding for five of our original (N = 19) cohort of school-age CWS, and thus we were not able to obtain complete data sets from these participants. With the removal of these participants, most of whom exhibited severe stuttering, our kinematic findings were likely biased toward less significant group differences between CWS and CWNS. This may have influenced the lack of significant correlations between kinematic indices and stuttering severity. It should also be noted that some CWS participants needed more trials to successfully produce the target number of sentences, and this may have exerted an influence over LAVar indices. However, this limitation actually introduced a bias against finding differences because LAVar in school-age children decreases with practice (Walsh et al., 2006). Despite these biases, group differences in LAVar were still observed for long sentence productions.

Contrary to our hypothesis, we did not find an effect by syntactic complexity on LAVar. It is possible that the insertion of a relative clause was not syntactically demanding enough to increase LAVar in our school-age children as it was for groups of preschool-age children (e.g., MacPherson & Smith, 2013; Usler et al., 2017). The use of relative clauses has been mastered by English-speaking children by middle and late childhood (Diessel & Tomasello, 2001). Although complex syntactic tasks that elicit high processing demands affect stuttering frequency in adults (Tsiamtsiouris & Cairns, 2013), our finding is consistent with the point made by Silverman and Ratner (1997) that the negative effects of syntactic complexity on the speech motor systems of CWS may reduce with increasing age. For example, Walsh et al. (2015) found that 4- to 5-year-old CWS produced short simple sentences with significantly greater articulatory variability compared with CWNS. Usler et al. (2017) also found that LAVar for short simple sentences was significantly higher in 5- to 7-year-old children with persistent stuttering compared with age-matched recovered and fluent peers. The average LAVar for this same short simple sentence in our current cohort of 7- to 12-year-old CWS was not different from that of CWNS, which suggests that CWS make up this initial lag in the speech motor coordination for short simple sentences when they reach the school-age years.

Articulation rate in both groups was also slower during production of the short complex sentences compared with the other sentence types. This finding is consistent with earlier studies that found that articulation rate increases with utterance length (e.g., Fónagy & Magdics, 1960). No group differences were observed for articulation rate across the sentences, although it is interesting to note that CWS typically demonstrated the fastest and slowest rates. This trend may explain the inconsistencies in the literature regarding articulation rate in CWS. Our finding of no appreciable differences in articulation rate between CWS and CWNS reveals that the effect of length on LAVar was not driven by increased articulation rates.

A final point to consider is that, although we did not find a syntactic complexity effect on articulatory kinematics during fluent speech production, our behavioral results indicated that speech motor performance in many CWS was affected by the demands of increased length and linguistic complexity. Five CWS from the original group were unable to accurately and fluently complete the experimental task, particularly for the longer and more complex conditions. Moreover, accuracy decreased while stuttering increased in CWS for the most demanding sentences.

Taken together, the kinematic and behavioral findings support the view that childhood stuttering is a neurodevelopmental, multifactorial disorder involving atypical speech motor control processes and that the speech motor output of those who stutter is clearly vulnerable to increases in task demands (Smith & Weber, 2017). The speech motor control processes in school-age CWS may be susceptible to destabilization from processing demands associated with difficulties in speech motor planning and execution. This interpretation does not appear to be supported by the findings of Kleinow and Smith (2000), who found STI values of lower lip movement in eight adults who stutter to be significantly higher for long complex, but not long simple, utterances (relative to a baseline short simple sentence). The apparent contradiction between our findings and that of Kleinow and Smith may be explained by the use of different sentence stimuli and kinematic index. The longest utterance in the Kleinow and Smith study (14 syllables) was a nonsentence, unlike the 15-syllable sentences produced by our participants. Production of this utterance resulted in a higher STI compared with a slightly shorter (13-syllable) utterance in adults who stutter, but not in fluent controls. Regarding the kinematic index, we measured the variability of the interarticulation between the upper and lower lips, whereas Kleinow and Smith measured the variability in trajectory of a single effector, the lower lip. These considerations indicate that length is likely a destabilizing processing demand on the articulatory coordination of individuals who stutter. However, length remains a macrovariable (Logan & Conture, 1995) whose effect on speech motor stability is influenced by the degree of interaction with linguistic factors and the degree of articulation measured by the kinematic index.

From a motor programming perspective, the negative effect of sentence length on the articulatory spatiotemporal variability of CWS may be an epiphenomenon of deficiencies in speech motor planning. If individuals who stutter exhibit aberrant sensorimotor integration (i.e., feedforward and feedback control) to correct execution errors during articulation (Civier, Bullock, Max, & Guenther, 2013; Civier, Tasko, & Guenther, 2010), the stability of articulatory coordination may decrease as a function of increasing utterance length. The processing demands that encompass sentence length likely include speech motor sequencing and related working memory processes (Guenther, 2016). Increasingly complex sequencing of phonemes/syllables is facilitated by an increased load on verbal working memory (Bohland & Guenther, 2006; Guenther, 2016). Subvocal rehearsal is critical for the accurate recall and production of imitated sentences (Baddeley, Chincotta, Stafford, & Turk, 2002). Cowan et al. (2010) showed that older children and young adults can recall approximately three to four chunks (e.g., words or short phrases) of verbal information. Given that imitation of the long sentences (11 words/15 syllables) required longer subvocal rehearsal before speech onset, the load on phonological working memory in both groups could have had a negative effect on their articulatory stability. This demand may have been particularly salient for CWS, as childhood stuttering has been associated with subclinical differences in phonological working memory (Pelczarski & Yaruss, 2016). Moreover, evidence suggests that the subvocal rehearsal abilities of adults who stutter may not be as robust as those of controls (Bosshardt, 1990, 1993; Byrd, McGill, & Usler, 2015; Byrd, Vallely, Anderson, & Sussman, 2012).

In summary, the demands of speech motor planning elicited by increasingly long utterances may have a disproportionately negative effect on the speech of school-age CWS relative to their fluent peers.

Regarding clinical practice, understanding how particular processing demands affect the speech production of school-age CWS is of great value. The developmental period between the ages of 7 and 12 years is critical not only in terms of stuttering persistence versus recovery but also as a period of protracted refinement of linguistic and articulatory capabilities as children enter more demanding social environments (Nippold, 2000; Smith & Zelaznik, 2004). Determining the clinical validity and appropriateness of different therapeutic approaches for older children can be supported by a better understanding of the underlying mechanisms that induced successful outcomes, including increased measures of fluency. Therapeutic interventions for young CWS, such as the Demands and Capacities approach for preschool-age CWS (de Sonneville-Koedoot, Stolk, Rietveld, & Franken, 2015), have simplified speech production including the reduction of utterance length and syntactic complexity. Although our findings regarding LAVar were derived from fluent productions that were imitated within a controlled paradigm, our behavioral findings are consistent with previous work that found utterance length to be an important processing demand for the elicitation of stuttering behaviors (for a review, see Zackheim & Conture, 2003). However, it should also be noted that some CWS performed comparably in LAVar with their CWNS peers. The speech motor control processes of school-age CWS, as in adults who stutter, are quite heterogeneous, and kinematic measures of articulation are only a single measure that cannot encompass or explain the situational variability and wide spectrum of behavior that stuttering entails.

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