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Influences of Sentence Length and Syntactic Complexity on the Speech Motor Control of Children Who Stutter

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Abstract

Purpose—To investigate the potential effects of increased sentence length and syntactic complexity on the speech motor control of children who stutter (CWS).

Method—Participants repeated sentences of varied length and syntactic complexity. Kinematic measures of articulatory coordination variability and movement duration during perceptually fluent speech were analyzed for 16 CWS and 16 typically developing children (CTD) between 4 and 6 years of age. Behavioral data from a larger pool of children were also examined.

Results—For both groups, articulatory coordination variability increased with sentence length. For syntactically simple sentences, CWS had higher coordination variability than CTD. There was no group difference in coordination variability for complex sentences. Coordination variability increased significantly with complexity for CTD, while that of CWS remained at the high levels seen for simple sentences. There was a trend for higher overall coordination variability in CWS, compared to CTD. For both groups, movement duration was greater for syntactically complex, as compared to simple, sentences.

Conclusions—Results indicate more variable speech motor coordination during fluent speech production in many CWS, as compared to CTD. Disproportionate effects of sentence length and syntactic complexity on articulatory coordination variability and movement duration were not found for CWS. Considerable individual differences in performance were observed.

Introduction

Multifactorial theories of stuttering posit that many variables—such as language, motor, cognitive, emotional, and genetic factors—interact in complex ways in both the development of stuttering and in the overt breakdowns in speech motor control that are perceived as stuttering-like disfluencies (Conture, 2001; Smith, 1999; Smith & Kelly, 1997; Van Riper, 1982). The importance of the interactions of two of these factors, language and speech motor processes, is supported by a wealth of data including behavioral findings that increases in utterance length and/or syntactic complexity are associated with the increased occurrence of disfluency in children and adults who stutter (Bernstein Ratner & Costa Sih, 1987; Buhr & Zebrowski, 2009; Gains, Runyan, & Meyers, 1991; Logan & Conture, 1995; Sawyer, Chon, & Ambrose, 2008; Tornick & Bloodstein, 1976; Wells, 1979; Yaruss, 1999).

In the dynamic, multifactorial model of stuttering (Smith, 1999; Smith & Kelly, 1997), effects of the interactions of language and speech motor processes are not limited to perceptible disfluencies. Rather, these disfluencies are salient manifestations of the

continuous, dynamic, nonlinear interaction of many variables (including language and motor factors) that affect speech motor planning and execution. Accordingly, perceptible disfluencies are hypothesized to reflect underlying instabilities in the speech motor systems of individuals who stutter, which are present even during perceptually fluent speech. Empirical support for this view is provided by articulatory kinematic evidence of reduced speech motor stability in adults who stutter (Kleinow & Smith, 2000), as well as by findings that adults who stutter differ from normally fluent adults in aspects of speech motor dynamics (Max, Caruso, & Gracco, 2003; Smith & Kleinow, 2000; Zimmermann, 1980) and neuromuscular activation (Smith, Denny, Shaffer, Kelly, & Hirano, 1996; van Lieshout, Hulstijn, & Peters, 1996; van Lieshout, Peters, Starkweather, & Hulstijn, 1993) during perceptually fluent speech production.

The relationship between overt breakdowns in speech motor control and the linguistic properties of spoken utterances indicates that the speech motor systems of many individuals who stutter are particularly vulnerable to heightened linguistic demands. In our laboratory, we have utilized composite measures of the spatiotemporal variability of single-articulator movement and of inter-articulator coordination to examine the interactions of language and motor processes during perceptually fluent speech production. We have found that the speech motor instability (as reflected by an index of articulatory variability) of individuals who stutter, compared to that of their typically fluent peers, is disproportionately increased by heightened linguistic complexity, including the phonological complexity of novel nonwords (Smith, Sadagopan, Walsh, & Weber-Fox, 2010) and the syntactic complexity of meaningful utterances (Kleinow & Smith, 2000).

In an examination of the effects of utterance length and syntactic complexity on lower lip stability (Kleinow & Smith, 2000), participants produced multiple repetitions of a baseline phrase (“Buy Bobby a puppy.”), of this phrase embedded in utterances of increased syntactic complexity (and length) according to Brown’s Linguistic Stages (Brown, 1973; Miller, 1981; e.g., “You buy Bobby a puppy now if he wants one.”), and of this phrase embedded in utterances of increased length (e.g., “Sunday Sunday buy Bobby a puppy Sunday Sunday.”). For adults who stutter, the spatiotemporal stability of the lower lip over repeated productions was significantly reduced for some syntactically complex utterances compared to the baseline utterance. Increased utterance length did not significantly affect the lower lip stability of adults who stutter. However, as noted in the study, this may have been related to the method used to increase utterance length, which did not allow for the independent assessment of the effects of length and complexity. These findings demonstrate that language processes, although sometimes considered remote from speech motor processes (e.g., Levelt, 1989), can affect the speech motor systems of adults who stutter and likely play a role, for some individuals, in the disturbances of speech fluency characteristic of stuttering. Additionally, they substantiate the view that the speech motor systems of some adults who stutter are particularly susceptible to destabilization by increased linguistic demands.

The above-mentioned findings in adults who stutter (Kleinow & Smith, 2000)—along with additional kinematic (Kleinow & Smith, 2006; Maner, Smith, & Grayson, 2000; Sadagopan & Smith, 2008) and electromyographic evidence (van Lieshout et al., 1993) that the speech motor systems of normally fluent children and adults are sensitive to increased linguistic demands—provide a strong impetus to examine the effects of linguistic demands on the speech motor control of children who stutter. Such an examination is important for several reasons. First, the performance of children who stutter cannot be directly extrapolated from that of adults who stutter due to the maturation of the speech motor system from childhood to adulthood, which has clear effects on speech motor dynamics and variability (Kleinow & Smith, 2006; Maner et al., 2000; Sadagopan & Smith, 2008; Sharkey & Folkins, 1985; B.

Smith & McLean-Muse, 1986; Smith & Goffman, 1998; Walsh & Smith, 2002). Therefore, it cannot be assumed that language and speech motor processes will interact in the same manner in children who stutter and adults who stutter. Second, it is particularly critical to characterize these potential interactions in young children who are relatively close to the onset of stuttering since the nature of the interactions may be altered by a number of factors that change as children move further from stuttering onset, such as expressive language abilities (Silverman & Bernstein Ratner, 1997; Watkins & Yairi, 1997). Finally, examining the effects of linguistic demands on the speech motor control of young children near the onset of stuttering is especially relevant due to the temporal proximity of the onset of stuttering and the acquisition of more advanced linguistic structures (Brown, 1973; Wells, 1985), many of which can affect speech fluency (Bernstein Ratner, 1997; Colburn & Mysak, 1982a, 1982b). Thus, examining the effects of sentence length and syntactic complexity on the speech motor control of young children who stutter will provide a unique and crucially needed window onto the role of language and speech motor interactions in the development of stuttering and the state of the speech motor system in this young population.

In the present study, we examined the effects of sentence length and syntactic complexity on the speech motor control (as reflected by measures of articulatory movement coordination variability and duration) of a group of 4- to 6-year-old children who stutter, as compared to a group of their typically developing peers. Following the practice of Kleinow and Smith (2006), we utilized sentence stimuli in which length and syntactic complexity were systematically manipulated, both in concert with and independently of one another. This resulted in better control of length and complexity than in previous work (e.g., Kleinow & Smith, 2000; Maner et al., 2000) and is an important step in disambiguating the effects of length and syntactic complexity on speech motor control. In addition, because prior work suggests that alterations in speech motor control may become evident only when the system is sufficiently taxed (Kleinow & Smith, 2000; Smith & Kleinow, 2000), we intentionally designed challenging stimuli.

We predicted that increased sentence length and syntactic complexity would result in more variable articulatory coordination in both children who stutter and typically developing children, but that the effects of length and complexity on coordination variability would be significantly greater in children who stutter, compared to their typically developing peers. An increase in coordination variability would reflect more variable neuromotor commands to achieve movement goals (Wohlert & Smith, 2002) and, therefore, decreased stability in the speech motor system. We also predicted that increased sentence length and syntactic complexity would be associated with increased movement duration, particularly for children who stutter. Findings consistent with these predictions would indicate that the speech motor systems of children who stutter are particularly susceptible to increased linguistic demands, which may contribute to the development of stuttering and to disruptions of speech fluency characteristic of stuttering.

Method

The data reported in the present study were collected as part of a large-scale, ongoing, longitudinal study (the Purdue Stuttering Project) of the speech motor and language skills of children who stutter and their typically developing peers. Data were collected at two sites, Purdue University, West Lafayette, Indiana and the University of Iowa, Iowa City, Iowa.

Participants

Participants for this study were 16 children who stutter (CWS) and 16 typically developing children (CTD) between 4 years; 0 months and 6 years; 11 months of age. There were 4 females and 12 males in each group. All participants were native speakers of North

American English, had normal or corrected-to-normal vision, and passed a hearing screening at 20 dB HL at 500, 1000, 2000, 4000, and 6000 Hz. In addition, all participants demonstrated age-appropriate (standard score = 85) articulation skills, as assessed with the consonant inventory of the Bankson – Bernthal Test of Phonology (BBTOP-CI; Bankson & Bernthal, 1990), expressive language skills, as assessed with the Structured Photographic Expression of Language Test-Edition 3 (SPELT-3; Dawson, Stout, & Eyer, 2003), and nonverbal intelligence, as assessed with the Columbia Mental Maturity Scale (CMMS; Burgemeister, Blum, & Lorge, 1972). None of the participants demonstrated symptoms of impaired reciprocal social interaction or restriction of activities, as assessed with the Childhood Autism Rating Scale (Schopler, Reichler, & Renner, 1988), and none had a history of neurological disorders, treatment for emotional issues, or the use of medication that could affect cognitive or motor function. The education level of each participant's mother, which ranged from the completion of the 9th grade (SES score of 2 on a 7-point scale) to the completion of a graduate or professional degree (SES score of 7) was used as an index of the child's socioeconomic status (SES; Hollingshead, 1975). The two groups of 16 children did not significantly differ in age; performance on the BBTOP-CI, SPELT-3, or CMMS; or SES (2-tailed independent samples *t*-tests and Mann-Whitney *U* test). Table 1 provides a summary of the participant characteristics for the CWS and CTD groups.

Participants were classified as CWS according to the criteria of Ambrose and Yairi (1999) and Yairi and Ambrose (1999). Each CWS: (1) was considered to have a stuttering problem by an experienced speech-language pathologist involved in this project, (2) had a stuttering severity that was rated as 2 or higher on an 8-point scale by his/her parents and/or a speech-language pathologist, and (3) exhibited a minimum of three stuttering-like disfluencies (SLDs) per 100 syllables of spontaneous speech. Spontaneous speech samples from parent-child and clinician-child interactions were analyzed by research assistants who were trained to code the type (stuttering-like or normal, as defined by Ambrose & Yairi, 1999) and number of disfluencies. The coding of the research assistants reached a minimum reliability of 85% with that of a speech-language pathologist experienced in fluency and childhood language disorders, who trained the research assistants.

According to parent report, 25.0% of the CWS in the experimental group were currently receiving treatment for stuttering. An additional 6.25% and 12.5% had previously received treatment for stuttering or language, respectively, but were not receiving any treatment at the time of participation in this study. Over half (56.25%) of the CWS in the experimental group had never received any speech or language treatment. Individual characteristics of the 16 CWS are provided in Table 2. As noted in the Appendix, the participants for this study were drawn from a larger pool of children who participated in the Purdue Stuttering Project.

Experimental Protocol

Sentence stimuli—Stimuli were four declarative sentences designed to systematically vary in length and syntactic complexity. As shown in Table 3, short sentences consisted of 6 words (8 syllables), while long sentences consisted of 9 words (11 syllables). Syntactic complexity was manipulated via the absence (simple sentences) or presence (complex sentences) of a subject relative clause. This is a relatively late developing syntactic structure (Bloom, Lahey, Hood, Lifter, & Fiess, 1980) that has been shown to affect speech motor variability (Kleinow & Smith, 2006). These stimuli were adapted from those of Kleinow and Smith (2006), in which both the length and syntactic complexity of the stimuli decreased trial-to-trial oral motor coordination consistency during fluent sentence production. All sentence stimuli contained a large proportion of bilabial consonants in order to constrain superior-inferior movements of the upper lip, lower lip, and jaw during speech production.

Experimental task—Participants repeated the sentence stimuli in response to recorded auditory models, which were produced by an adult female who was a native speaker of North American English. Each participant completed two to three practice trials of each sentence. Children were told they would hear sentences about birds and butterflies through a speaker, and they were instructed to be a “copy cat” and say exactly what they heard. Modeling and feedback were provided during practice, as appropriate and according to preset guidelines.

After the completion of the practice trials and prior to the beginning of experimental data collection, participants were told they would hear the same sentences that they had practiced. They were reminded to listen carefully and repeat each sentence exactly as they heard it. Concurrent with the presentation of each auditory model, a picture of birds and butterflies was displayed on a computer monitor located in front of the participant. Participants were told to look at these pictures in order maintain their focus and orientation in the proper direction for the motion capture cameras to track the movement of markers on the lips and jaw.

Data collection then commenced with the presentation of each sentence, which was followed by the child’s attempted production of that sentence. Each production was followed by a two- to three-second pause before the next stimulus was presented. The experimenter controlled the presentation rate of the stimuli, which were presented in blocks of eight sentences each, with sentence order quasi-randomized within each block. Short breaks and reinforcement were provided between blocks. For each sentence, an attempt was made to collect ten error-free and fluent productions with normal prosody from each participant. Data collection continued until these productions were obtained, or until it became evident that the participant was unable to adequately complete the remainder of the experimental task. The recording session lasted approximately 30 minutes for each participant, including both practice and experimental trials.

Recording Apparatus

Articulatory kinematic data were recorded with an Optotrak 3020 system (Northern Digital), which tracks the movements of active markers in three dimensions with an accuracy of 0.1 mm. Participants were seated in front of the Optotrak cameras, which were located above the computer monitor on which the birds and butterflies pictures were displayed. Movements of the upper lip, lower lip, jaw, and head were tracked with eight small (7 mm) active markers (infrared light emitting diodes, IREDs). Lip motion was tracked via IREDs attached with adhesive collars to the vermilion borders of the upper lip and lower lip at midline. The motion of the lower lip marker represents the combined actions of the lower lip and jaw. An additional IRED was affixed to a lightweight splint attached to the skin under the chin at midline. Data from this IRED were not analyzed. Head motion was tracked via one IRED placed on the center of the forehead and four IREDs attached to modified sports goggles. These five IREDs were used to create a three-dimensional head coordinate system. The superior-inferior movements of the upper lip and lower lip (plus jaw) were calculated relative to the head coordinate system, resulting in articulatory movement data that were corrected for head motion artifact (Smith, Johnson, McGillem, & Goffman, 2000). The position of each IRED was sampled at 250 samples/s.

The speech acoustic signal was transduced with a condenser microphone and digitized on an A/D channel of the Optotrak system, resulting in synchronized kinematic and acoustic signals. The acoustic signal was digitized at 16,000 samples/s and low-pass filtered with a cut-off frequency of 7,500 Hz. In addition, audiovisual DVD recordings were made of each session.

Kinematic Data Analysis

Consistent with established methods (Kleinow & Smith, 2006; Smith & Zelaznik, 2004; Walsh, Smith, & Weber-Fox, 2006), only accurate and fluent productions with normal prosody were used in the kinematic analysis because the movement goals must be consistent across trials for this particular analysis. The 32 participants included in the present analysis each had a minimum of six repetitions per sentence that met movement data criteria. It should be noted that, in previously published work that employed the same analysis method, 8-10 trials per sentence were utilized (Kleinow & Smith, 2006; Smith & Zelaznik, 2004; Walsh et al., 2006). In the present study, in a minority of cases, 6-7 trials of a sentence were used for a given participant. This occurred for two sentences for one CWS and for all four sentences for another CWS, representing 9.4% of the data from the group of CWS. Preliminary analysis indicated that the inclusion of these data was not problematic, as results based on 6-10 trials did not significantly differ from those based on 8-10 trials. Additionally, this practice reduced the amount of data lost.

Kinematic dependent measures—Kinematic measurements were completed using a custom, interactive Matlab (MathWorks, Inc.) program. The lower lip displacement and velocity signals for each production were displayed. The lower lip velocity signal was used to segment the upper and lower lip kinematic records (as well as the acoustic record) from the points of peak velocity of the first and last opening movements of each sentence production (Smith et al., 2000). The first point corresponded to the release of the /b/ in “birds” for all sentences. The last point corresponded to the release of the /p/ in “played” for the short sentences and in “pond” for the long sentences. All kinematic measures were computed on the segments between these points. Appropriate segmentation was verified with the acoustic signal.

Lip Aperture Variability Index: Figure 1 illustrates the steps in kinematic data processing, which resulted in the lip aperture (LA) variability index. The LA signal for each sentence production was obtained by the point-by-point subtraction of the upper lip displacement signal from the lower lip displacement signal (Figure 1, top panel). As LA results from the combined actions of the upper lip, lower lip, and jaw, the LA signal reflects the coordination of all three effectors to control oral opening (in the superior-inferior dimension) as a function of time. The LA variability index for each sentence for each participant was computed according to the methods outlined in Kleinow and Smith (2006), Smith and Zelaznik (2004), and Walsh et al. (2006). Briefly, the set of LA signals for each sentence for each participant (6-10 trials per sentence per participant) were linearly time- and amplitude-normalized (Figure 1, middle panel). Time normalization was achieved by linearly interpolating all records to 1000 points. Amplitude normalization was achieved by subtracting the mean and dividing by the standard deviation (*SD*) of each record. For each set of 6-10 normalized LA signals, *SD*s were calculated at 2% intervals in relative time (Figure 1, bottom panel). These 50 *SD*s were then summed to yield the LA variability index, which reflects the extent of dispersion of the LA signals associated with multiple repetitions of each sentence. This index reflects the degree of variability in upper lip, lower lip, and jaw coordination to control oral opening over repeated productions of an utterance. A higher LA variability index indicates greater articulatory coordination variability and reduced speech motor stability.

Movement Duration: Movement duration was computed as the time, in seconds, of each original, non-normalized sentence segment (Figure 1, top panel). Again, the segments began at the release of the /b/ in “birds” and ended at either the release of the /p/ in “played” (short sentences) or the /p/ in “pond” (long sentences). The duration values for each sentence were

averaged for each participant, and these averages were used in the statistical analysis of movement duration.

Results

Behavioral Results

For a participant to be included in the present kinematic study, he or she had to complete 6-10 accurate and fluent productions of each of the four sentence stimuli. Therefore, all of the 16 CWS and 16 CTD whose articulatory kinematic data are reported here completed the full experimental task. It is important to note that these 32 children were drawn from a much larger pool of CWS and CTD, many of whom could not complete the full experimental task. As noted in the introduction, the high level of difficulty of the stimuli was intentional, as we are investigating the children's improvement in performance over five years. As the children's behavioral performance on the sentence repetition task provides relevant information about their speech production abilities, behavioral data are summarized in the Appendix. It is clear that as a group, fewer CWS, as compared to CTD, were able to perform the sentence repetition task, particularly for the longer and more syntactically complex sentences.

Kinematic Dependent Measures

Lip Aperture Variability Index—Effects of group, sentence length, and syntactic complexity on the LA variability index were examined with a repeated measures ANOVA. Partial Eta squared (η_p^2) measures of effect size were also computed. When appropriate, post hoc Fisher LSD tests were performed for significant main and interaction effects. The α -level for all tests was set at $p < .05$.

As shown in Figure 2, there was a significant main effect of sentence length, $F(1, 30) = 69.61$, $p < .001$, $\eta_p^2 = .70$, on the LA variability index. The LA variability index was significantly higher for long sentences than for short sentences. The main effect of group approached significance, $F(1, 30) = 3.82$, $p = .06$, $\eta_p^2 = .11$. There was no significant interaction of sentence length with group or syntactic complexity.

Figure 3 illustrates the significant Group $\times$ Syntactic Complexity interaction, $F(1, 30) = 4.53$, $p = .04$, $\eta_p^2 = .13$. Pairwise contrasts revealed that, for syntactically simple sentences, the LA variability index of the CWS was significantly higher than that of the CTD ($p = .04$). In addition, for the CTD, the LA variability index was significantly higher for syntactically complex sentences than for syntactically simple sentences ($p = .03$). No other post hoc comparisons reached statistical significance.

Movement duration—Statistical procedures for the analysis of the effects of group, sentence length, and syntactic complexity on movement duration were consistent with those reported above for the LA variability index. There were significant main effects of sentence length, $F(1, 30) = 1181.79$, $p < .001$, $\eta_p^2 = .98$, and syntactic complexity, $F(1, 30) = 258.31$, $p < .001$, $\eta_p^2 = .90$, on movement duration. As expected, movement duration for long sentences ($M = 2.43$ s, $SE = 0.05$ s) was significantly greater than for short sentences ($M = 1.70$ s, $SE = 0.03$ s). Duration was also significantly greater for syntactically complex sentences ($M = 2.23$ s, $SE = 0.46$ s) than for syntactically simple sentences ($M = 1.90$ s, $SE = 0.04$ s). There was no significant effect of group on movement duration, nor was there any interaction between group, sentence length, and syntactic complexity. Further, movement duration was not significantly correlated with the LA variability indices of either group on any of the sentences ($p > .05$, CWS r range = .14 - .25, CTD r range = -.23 - .20).

Measures of Correlation

Pearson correlations were calculated in order to examine any potential relationships among stuttering severity, age of stuttering onset, and kinematic performance of the CWS. There was no significant correlation between stuttering severity, as indexed by the number of SLDs per 100 syllables of spontaneous speech, and age of onset; nor were there any significant correlations between stuttering severity and the LA variability index or movement duration for any of the sentences. Age of stuttering onset was significantly negatively correlated with the LA variability index for the short simple sentence only ($r = -.65, p = .006$). In addition, there were no significant relationships between the articulation and language scores of the CWS and their performance on the dependent measures, and no relationship between therapy status and kinematic performance was detected.

Individual Data

Because stuttering is a highly heterogeneous disorder and the performance of some children who stutter may fall within the normal range, it is prudent to consider the performance of individual participants, in addition to averaged group data. LA variability index and movement duration data for each participant on each sentence length and syntactic complexity are plotted in Figures 4 and 5, respectively. As is evident in these figures, there was considerable overlap in individual participant performance between the two groups, with the LA variability indices and movement durations of many CWS comparable to those of CTD.

To quantify this overlap in performance on the LA variability index, we calculated the number of CWS whose LA variability indices exceeded ± 1 SD of the CTD group mean for each sentence length and syntactic complexity. For short sentences, the LA variability indices of 7 out of 16 CWS fell more than 1 SD above the CTD group mean, while that of 1 CWS fell more than 1 SD below the CTD mean. For long sentences, the indices of 4 CWS were more than 1 SD above the CTD mean, while that of 1 CWS fell more than 1 SD below the CTD mean. For syntactically simple sentences, the indices of 8 CWS were more than 1 SD above the CTD mean, while none were below 1 SD of the CTD mean. Lastly, for syntactically complex sentences, the LA variability indices of 3 CWS fell more than 1 SD above the CTD group mean and that of 1 CWS fell more than 1 SD below the CTD mean. In spite of this overlap, the highest levels of articulatory coordination variability for all sentence lengths and complexities were produced by CWS, and the lowest levels of articulatory coordination variability were produced by CTD. Some individuals in both groups had relatively high (or low) values of coordination variability across the four sentences. However, this was not always the case, as some participants with relatively high or low values for one sentence had average values for other sentences. Further, inspection of the data indicated that the effects of sentence length and syntactic complexity varied considerably across individuals.

Discussion

The purpose of the present study was to examine the effects of sentence length and syntactic complexity on the speech motor control of young children who stutter (CWS), as compared to their typically developing peers (CTD). To the best of our knowledge, this is the first kinematic study to examine the effects of these linguistic variables on the lip aperture (LA) variability index of children who stutter. We utilized strict inclusion criteria, and we required that all participants pass the SPELT-3 (Dawson et al., 2003), an assessment that taps expressive morphosyntactic abilities, as well as the BBTOP-CI (Bankson & Bernthal, 1990) and the CMMS (Burgemeister et al., 1972). We carefully equated the groups on demographic characteristics as well as on speech, language, and nonverbal intelligence

scores. In addition, we employed stimuli that were designed to provide better disambiguation of sentence length and syntactic complexity than in earlier work. Hence, this study provides novel findings that contribute to the experimental and theoretical literature on language and motor factors in developmental stuttering.

Our overarching hypothesis was that, while the speech motor control of both children who stutter and their typically developing peers would be negatively affected by increased sentence length and syntactic complexity, the effects of these linguistic demands would be greater in the children who stutter. Overall, the findings provide mixed support for this hypothesis and paint a complicated picture that reflects the multifaceted, heterogeneous, and dynamic nature of developmental stuttering.

Sentence Length

Sentence length strongly influenced the speech motor control of both children who stutter and typically developing children. Consistent with our hypothesis, increased sentence length resulted in significantly more variable articulatory coordination over repeated productions for both groups of children (Figure 2). This inverse relationship between sentence length and articulatory coordination variability mirrors that previously documented in typically developing older children (9-10 years of age) and adults by Kleinow and Smith (2006), who utilized similar stimuli. Longer utterances likely place greater demands on both speech motor planning and execution processes (Brennan & Cullinan, 1976; Maner et al., 2000; Yaruss, 1999). In the present context, higher coordination variability can be interpreted as reflecting more variable neuromotor commands for the control of lip aperture (Wohlert & Smith, 2002) when speech motor planning and/or execution abilities are taxed by the production requirements of longer sentences. Therefore, increased sentence length appears to be a destabilizing factor for the developing speech motor system.

While we predicted that the speech motor coordination of children who stutter would be more affected by increased sentence length than that of typically developing children, this was not borne out by the results. However, this does not exclude the possibility that sentence length does differentially affect the speech motor coordination of some children who stutter in a manner that was not reflected by the LA variability index. As it is the only other study of this particular nature in individuals who stutter, it is important to note that Kleinow and Smith (2000) found no significant effect of utterance length on lower lip spatiotemporal variability in either adults who stutter or typically fluent adults. However, unlike the present study, length was increased by the addition of words that were not meaningfully related to the remainder of the sentence.

Finally, before turning to a discussion of the effects of syntactic complexity, a caveat is needed. Many attempts have been made, including our own, to disambiguate sentence length from syntactic complexity. While the current stimuli were designed to better disambiguate these linguistic properties relative to earlier work (e.g., Kleinow & Smith, 2000; Maner et al., 2000; Sadagopan & Smith, 2008), sentence length and syntactic complexity are tightly linked in grammatical sentences and, therefore, complete dissociation is extremely difficult. Hence, this remains a methodological challenge for any work of this nature. Nonetheless, the present data strongly suggest independent influences of sentence length and syntactic complexity on speech motor control.

Syntactic Complexity

Children who stutter and typically developing children showed different patterns of LA variability in response to increased syntactic complexity (Figure 3). For syntactically simple sentences, children who stutter had significantly more variable articulatory coordination than

typically developing children. For syntactically complex sentences, both groups had high levels of variability. However, variability increased with syntactic complexity for typically developing children only. For both groups, movement duration significantly increased with increased syntactic complexity.

The lack of a significant effect of syntactic complexity on the LA variability index of the children who stutter was unexpected. This result initially seems surprising given that the articulatory movements of typically developing children (in the present study and in prior work), adults who stutter, and, in some cases, typically fluent adults become more variable when syntactic complexity is increased (Kleinow & Smith, 2000, 2006). However, the observed performance pattern of the children who stutter is not necessarily incongruous with the supposition that syntactic complexity can affect their speech motor control. In fact, additional evidence suggests that the speech motor control of many children who stutter is compromised when challenged by heightened syntactic demands.

The data presented in the Appendix (see table) point to a potentially key reason why an effect of syntactic complexity on the speech motor coordination of the children who stutter was not reflected by the LA variability index results. When the behavioral performance of the larger pool of children who stutter who attempted the experimental task is considered (total $n = 38$), it is evident that the ability of children who stutter to complete the experimental task was highly affected by the syntactic complexity of the stimuli. Of the 38 children who stutter who attempted the task, only 18 (47.4%) and 17 (44.7%) produced at least six accurate and fluent repetitions of the short complex and the long complex sentences, respectively. Production of syntactically complex sentences was significantly lower than production of syntactically simple sentences of the same length, as 34 of 38 (89.5%) and 30 of 38 (78.9%) children who stutter produced the required number of accurate and fluent repetitions of the short simple and the long simple sentences, respectively. Additionally, considerably fewer children who stutter (16 of 38, 42.1%), as compared to typically developing children (24 of 39, 61.5%), successfully completed the entire set of four sentences. This differential is made even more striking by the fact that all of these children demonstrated age-appropriate articulation and expressive language skills.

Thus, an effect of syntactic complexity on the speech motor systems of many children who stutter is clearly indicated by their behavioral performance (see table in Appendix). For a large proportion of the children who stutter who attempted the experimental task (total $n = 38$), their speech motor systems broke down to the point that the complex sentences could not be accurately and fluently produced. That is, their speech production systems were pushed past the point at which increased syntactic complexity resulted in increased coordination variability with perceptually intact production, to the point of overt breakdown in speech production abilities—which necessarily excluded them from the kinematic analysis. For these children who stutter, the demands imposed by increased syntactic complexity exceeded their functional abilities for accurate and fluent speech production. Therefore, the children who stutter included in the experimental analysis were those whose speech production systems were least affected by heightened linguistic demands, particularly syntactic complexity, potentially skewing the LA variability results.

Finally, while the average LA variability index of this group of children who stutter was not significantly affected by syntactic complexity, their movement duration was significantly longer for syntactically complex sentences than for syntactically simple sentences, regardless of sentence length. This indicates that, like the typically developing children, the children who stutter slowed their speech rate as syntactic complexity increased. In other words, even during perceptually fluent speech production, the speech motor performance of

the children who stutter was affected (but not disproportionately so) by syntactic complexity.

Individual Differences in the Effects of Sentence Length and Syntactic Complexity

As shown in Figures 4 and 5, there was a range of performance on the LA variability index and movement duration measures across the individual participants, and the performance of many of the children who stutter overlapped with that of the typically developing children. These findings are consistent with a large body of experimental and theoretical literature which finds that there are large differences in various abilities across individuals who stutter and that some individuals who stutter operate within the normal range on some language and motor measures (Smith & Kleinow, 2000; Smith et al., 2010; Watkins & Yairi, 1997; Watkins, Yairi, & Ambrose, 1999). The impact of any factor—including sentence length and syntactic complexity—will vary not only across individuals, but also over time within individuals. Accordingly, experimental results, which provide one snapshot of performance, will vary depending on the particular sample of children studied and the point in time when they are studied. It is quite possible that different results, including disproportionate effects of sentence length and syntactic complexity on articulatory coordination variability and movement duration, would be evident in a different sample of children who stutter, or in the same sample if studied at a different time. Clearly, our results and others show that stuttering is a highly heterogeneous disorder, and this heterogeneity will influence experimental results.

As suggested by Yairi (2007), Hubbard Seery, Watkins, Mangelsdorf, and Shigeto (2007), and others, within our sample of children who stutter there are likely many potential subtypes or subgroups, which may be differently affected by various factors, including linguistic and motoric demands. A significant impetus behind the search for stuttering subtypes has been to increase the ability to predict which children will recover and which will persist in stuttering. The implication of this is that there may be some commonalities across the profiles of some children who stutter which affect the probability of spontaneous recovery. Differences in both expressive language and general motor abilities have been implicated (Howell, Davis, & Williams, 2008; Watkins & Yairi, 1997). At this time, we cannot know the eventual fluency status of our participants nor how this may have affected their performance on our experimental task. Given the age at which the participants were originally recruited into our longitudinal study (4-6 years), approximately 50-75% should recover. It is possible that this is a source of the heterogeneity in our data. Perhaps responses to sentence length and syntactic complexity differ between children who will persist in stuttering and children who will recover. This important issue is a focus of ongoing, longitudinal research in our laboratory.

Overall Articulatory Coordination

Many of the children who stutter demonstrated more variable overall articulatory coordination than their typically developing peers. There was a strong group trend for the overall LA variability index, with the variability of the CWS greater than that of the CTD ($p = .06$, see Figure 2). In addition, the children who stutter had significantly higher articulatory coordination variability than their peers on syntactically simple sentences (Figure 3). These results indicate compromised speech motor stability in many of these children who were relatively close to stuttering onset, whose articulation and expressive language abilities were within the normal range, and who were comparable to their typically developing peers on a variety of measured dimensions (e.g., BBTOP-CI and SPELT-3 scores, nonverbal intelligence, and SES), with the exception of speech fluency. These results are also consistent with previous findings of reduced speech motor stability in individuals who stutter (Kleinow & Smith, 2000; Namasivayam, van Lieshout, & De Nil, 2008; Smith

et al., 2010). Thus, reduced coordinative stability within the speech motor system is likely a significant component of developmental stuttering for many individuals, a premise that is supported by evidence of structural and functional abnormalities in the neural speech motor networks of individuals who stutter (Chang, Erickson, Ambrose, Hasegawa-Johnson, & Ludlow, 2008; Chang, Kenny, Loucks, & Ludlow, 2009; Howell, 2010; Salmelin, Schnitzler, Schmitz, & Freund, 2000).

Conclusions

The study reported here provides an initial examination of the effects of sentence length and syntactic complexity on the speech motor control (as reflected by measures of articulatory coordination variability and movement duration) of a group of children who stutter, relative to a group of their typically developing peers. As such, it is one thread of evidence that seems to tell a complicated story befitting the complexity and heterogeneity of the disorder.

The findings suggest that, even during perceptually fluent speech production, the speech motor systems of some children who stutter are functioning with a reduced level of coordinative stability. Both children who stutter and typically developing children demonstrated increased articulatory coordination variability with increased sentence length. Unlike typically developing children, syntactic complexity did not significantly affect the average LA variability index of this group of children who stutter. Therefore, the predicted disproportionate effects of sentence length and syntactic complexity on the speech motor coordination of children who stutter were not confirmed. We posit that there are several factors that may have obscured an effect of syntactic complexity on this measure of speech motor coordination variability. For both groups of children, movement duration was significantly greater for syntactically complex sentences, as compared to syntactically simple sentences. Considerable individual differences were noted, and the performance of some of the children who stutter overlapped with that of the typically developing children.

The current study is not without limitations, which we hope will be addressed in future work from our laboratory and others. For example, many of the children simply could not complete the experimental task, which may have excluded those with the most vulnerable speech motor systems from the kinematic analysis. In addition, the inclusion of children who stutter with concomitant speech and language disorders in future studies may provide valuable information about the nature of language-motor interactions in this heterogeneous population. Finally, eventual stuttering status (i.e., persistence versus recovery) may be a significant source of the observed individual differences in performance. Longitudinal data will be fundamental in improving our understanding of these and many other issues.

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Appendix

Behavioral performance and inclusion in the kinematic analysis.

The 32 participants (16 CWS and 16 CTD) included in the present kinematic analysis were drawn from a larger pool of 77 children (38 CWS and 39 CTD) with age-appropriate articulation and expressive language skills. All of the children in the larger pool attempted the experimental task for the articulatory kinematic study. However, only 16 CWS and 24

CTD successfully completed the task (i.e., produced at least six accurate and fluent productions of all four sentences). From these 24 CTD, the 16 who were most similar to the 16 CWS in age, articulation and language scores, nonverbal intelligence, and SES were selected for the kinematic analysis. This insured that the groups of 16 CWS and 16 CTD were equated on these potentially confounding factors.

The table below summarizes the overall behavioral performance of the original pool of 77 children on the sentence repetition task used in the kinematic study. It shows the percentage of children (out of the 38 CWS and 39 CTD who attempted the task) who successfully completed the repetition task for each sentence, as well as the percentage who successfully completed all four sentences. As is evident in the table, fewer children were able to produce the sentences as length and syntactic complexity increased. In particular, task completion was significantly affected by syntactic complexity, across sentence lengths (related-samples McNemar change tests based on the binomial distribution, $p < .001$). Additionally, significantly fewer CWS, as compared to CTD, produced an adequate number of repetitions of each sentence and of all four sentences (1-tailed proportion difference tests, $p < .05$).

Finally, it should be noted that, for syntactically complex sentences, the CWS included in the kinematic analysis and the CWS excluded from the kinematic analysis due to insufficient data differed in both production accuracy and fluency. However, the included and excluded subgroups of CWS did not significantly differ in the number of SLDs per 100 syllables of spontaneous speech (2-tailed independent samples t -test, $p > .05$).

Table
Percentage of children, by group, from the larger pool
($n = 77$) with at least six accurate and fluent
productions of each sentence and of all four sentences

Group	Sentence				All 4 sentences
	Short simple	Long simple	Short complex	Long complex	
CWS (total $n = 38$)	89.5 [†]	78.9 [*]	47.4	44.7	42.1
CTD (total $n = 39$)	100.0 [†]	97.4 [*]	66.7	69.2	61.5
Difference between groups	- 10.5 ^{**}	- 18.4 ^{**}	- 19.3 ^{**}	- 24.5 ^{**}	- 19.4 ^{**}

[†]Note. = short simple significantly greater than short complex (within group).

^{*} = long simple significantly greater than long complex (within group). Difference between groups = % of CWS – % of CTD for each column.

^{**} = significant difference between groups.

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Figure 1. Kinematic data processing steps. Original LA signals (top plot), normalized LA signals (middle plot), and the LA variability signal from productions of the long complex sentence by one CTD (left column) and one CWS (right column). The bottom plot displays standard deviations (*SDs*) computed at each 2% point in relative time. The sum of these *SDs* yields the LA variability index for each participant.

Figure 2. LA variability index: Sentence length effect (shown for each group). Symbols represent means. Error bars indicate standard error.

Figure 3.
LA variability index: Group $\times$ Syntactic Complexity interaction. Symbols represent means.
Error bars indicate standard error.

Figure 4.

LA variability index: Individual data. Each symbol represents an individual participant's performance on each sentence length and syntactic complexity. Horizontal bars mark the CTD group mean, and upper and lower brackets mark ± 1 SD of the CTD mean for each sentence length and syntactic complexity. Please note that, in some cases, the number of visible datapoints per group is less than 16 due to the overlap of multiple symbols.

Figure 5.

Movement duration: Individual data. Each symbol represents an individual participant's performance on each sentence length and syntactic complexity. Horizontal bars mark the CTD group mean, and upper and lower brackets mark ± 1 SD of the CTD mean for each sentence length and syntactic complexity. Please note that, in some cases, the number of visible datapoints per group is less than 16 due to the overlap of multiple symbols.

Table 1
Summary of participant characteristics, by group, for the 32 children included in the kinematic analysis

Characteristic		Group	
		CWS (<i>n</i> = 16)	CTD (<i>n</i> = 16)
Age (months)	Range	49 – 83	48 – 83
	Median	59.00	60.50
	Mean (<i>SD</i>)	62.88 (10.31)	62.25 (9.63)
CMMS	Range	90 – 137	95 – 126
	Median	112.00	117.00
	Mean (<i>SD</i>)	111.94 (11.62)	115.19 (9.25)
SES	Range	4 – 7	5 – 7
	Median	6.00	6.00
	Mean (<i>SD</i>)	5.75 (0.93)	6.13 (0.72)
BBTOP-CI	Range	87 – 115	88 – 115
	Median	98.50	100.00
	Mean (<i>SD</i>)	97.63 (7.29)	99.44 (7.28)
SPELT-3	Range	92 – 122	93 – 123
	Median	107.00	113.50
	Mean (<i>SD</i>)	106.50 (9.53)	111.38 (8.97)
Age of stuttering onset (months)	Range	22 – 54	
	Median	39.50	
	Mean (<i>SD</i>)	38.69 (9.94)	
SLDs per 100 syllables*	Range	1.86 – 12.73	
	Median	4.73	
	Mean (<i>SD</i>)	6.01 (3.66)	

* *Note.* As indicated by the range of SLDs per 100 syllables, a value of less than 3 was calculated for some CWS. This occurred because the SLD measure reflects the average of multiple 100-syllable speech segments from two conversational settings. However, the criterion number of SLDs per 100 syllables for classification as a CWS was met if the child demonstrated 3 or more SLDs in any one of these 100-syllable segments (Yairi & Ambrose, 1999). Therefore, all CWS still met this criterion for stuttering classification.

Table 2
Individual characteristics of the children who stutter included in the kinematic analysis

Participant	Sex	Age (months)	CMMS	SES	BBTOP-CI	SPELT-3	Age of stuttering onset (months)	SLDs per 100 syllables	Therapy*
CWS-1	M	55	111	6	104	100	42	5.05	None
CWS-2	F	83	137	6	100	100	36	4.01	Stuttering (P)
CWS-3	M	61	132	6	93	121	48	9.73	None
CWS-4	M	77	118	6	99	92	54	6.81	None
CWS-5	M	50	107	5	87	92	42	4.33	Language (P)
CWS-6	M	49	112	6	92	107	37	7.11	Stuttering (C)
CWS-7	M	58	112	6	89	99	24	6.76	None
CWS-8	M	71	98	5	93	98	42	2.60	Language (P)
CWS-9	M	68	118	7	94	110	30	3.19	None
CWS-10	M	56	100	7	107	102	24	10.74	None
CWS-11	F	60	112	6	99	107	36	1.86	None
CWS-12	M	79	116	4	98	119	52	12.37	Stuttering (C)
CWS-13	F	58	114	7	102	110	46	1.95	None
CWS-14	F	58	105	4	115	122	48	4.41	None
CWS-15	M	55	90	6	100	111	22	2.47	Stuttering (C)
CWS-16	M	68	109	5	90	114	36	12.73	Stuttering (C)

* Note: Both the type of therapy (i.e., treatment of stuttering or language skills) and the status of therapy (P = previously received treatment, C = currently receiving treatment at the time of participation in this study) are indicated.

Sentence stimuli

Table 3

Sentence Length	Syntactic Complexity	Sentence	No. of Words, Syllabus	Relative Clause
Short	Simple	<i>The birds and the butterflies played.</i>	6, 8	–
Long	Simple	<i>The birds and the butterflies played by the pond.</i>	9, 11	–
Short	Complex	<i>The birds that saw butterflies played.</i>	6, 8	+
Long	Complex	<i>The birds that saw butterflies played by the pond.</i>	9, 11	+