Developmental Changes in the Effects of Utterance Length and Complexity on Speech Movement Variability

Purpose: The authors examined the effects of utterance length and linguistic complexity on speech movement consistency for 210 participants between the ages of 5 and 22 years. Variability and durational analyses were conducted to (a) determine a more complete picture of the developmental course of earlier observations of the effects of linguistic constructs on speech motor variability and (b) describe trends for duration of the same sequence of words in different sentential contexts across development.

Method: Lower-lip movement was recorded during the production of “buy Bobby a puppy” spoken in isolation as well as embedded as a phrase in 2 longer, more complex sentences.

Results: Compared with young adults, children demonstrated higher variability in producing repeated movement sequences for the target word sequence across all conditions. Also, for all age groups except young adults, increased processing demands resulted in significantly increased movement trajectory variability. Duration analyses suggest that around age 9 years, children begin to use adult-like pre-speech processes to plan the timing of sentence internal phrases, and maturation of these planning processes continues through late adolescence.

Conclusion: These results provide further evidence for language–motor interactions and for a protracted course of speech motor development that continues well into adolescence.

KEY WORDS: speech motor control, development, variability, speech kinematics

One major theoretical issue of interest in both developing and adult systems is the relationship between speech production and language processes at many different levels, including higher levels of language processing and lower levels of speech implementation. A. Smith and Goffman (2004) discuss, in an extensive review, evidence for both “top-down” influences of linguistic goals on observable physiological measures and “bottom- up” influences of motor system constraints on language processing. This attempt to bridge the gap between language processing and speech motor processes is an important one and is the focus of the present study.

Various experimental approaches have been used to address potential language–speech motor interactions. In earlier work, transcription analysis and perceptual evaluations were used in order to relate speech production errors and/or disfluencies to the complexity and length of utterances (Haynes & Hood, 1978; Kamhi, Catts, & Davis, 1984; Pearl & Bernthal, 1980; Scollon, 1976). More recently, work from our group as well as from others (Kleinow & Smith, 2000; Maner, Smith, & Grayson, 2000;
van Lieshout, Starkweather, Hulstijn, & Peters, 1995) has examined language and speech motor interactions by assessing direct measures of motor performance, including kinematic and electromyographic data, in response to manipulations of utterance length and complexity. Maner et al. (2000) examined the influences of length and syntactic complexity on the variability of speech movements in 8 typically developing 5-year-old children and young adults. Linguistic complexity can be defined in many different ways. In the Maner et al. (2000) article, the authors used Brown’s Linguistic Stages (Brown, 1973) to quantify the complexity of the five sentences used as stimuli. They compared the consistency of oral movements for a word sequence (“buy Bobby a puppy”) spoken in isolation as a short sentence with the consistency for the same word sequence embedded as a phrase in four longer and more complex sentences. They used a measure of lip movement variability calculated across the entire sentence (the spatiotemporal index [STI] introduced by A. Smith, Goffman, Zelaznik, Ying, and McGillem, 1995) to quantify the variability of lip movement across 10 repetitions of the target sentence. Maner and colleagues (2000) found that 5-year-old children showed remarkable increases in oral movement variability when “buy Bobby a puppy” was embedded in the four longer and more complex sentences, compared with the variability when it was spoken as a short sentence in isolation. The findings of Maner et al. provided novel evidence that features of oral movement output were influenced by the linguistic context in which the word sequence was produced. They argued that their results supported the existence of much closer interactions between levels of language processing and the formulation and execution of motor commands than earlier theoretical accounts suggested (e.g., Levelt, Roelofs, & Meyer, 1999). In addition, Maner et al. (2000) reported that the adults shortened the target word sequence when it was embedded in the longer, more complex sentences, but 5-year-olds did not. We hypothesize that such contextual effects on speech motor variability and rate could have implications for the units of speech production planning in children compared with adults. Furthermore, if these results are replicated and their emergence over development is documented, fundamental information will be available to help build more complete models of speech motor development and language–motor interactions in children and adults. In addition, there is a remarkable paucity of information about development of speech motor processes over the school-age years and into adolescence. Our earlier work on these age groups (A. Smith & Zelaznik, 2004; Walsh & Smith, 2002) demonstrated that the older, generally accepted notion that speech processes are basically adultlike by age 10–12 years (e.g., Kent, 1976; Kent & Forner, 1980) is incorrect. Similarly, for some measures of respiratory and laryngeal function and acoustic measures, a protracted developmental course to adultlike performance has been reported (Huber, Statathopoulos, Curione, Ash, & Johnson, 1999; Statathopoulos & Sapienza, 1997). Therefore, for the benefit of models of normal speech motor development and for developing better treatment strategies for school-age children with developmental speech disorders, an understanding of the unfolding maturity of the speech motor system in these age groups is critical.

As part of the present investigation, we also propose to replicate and extend earlier reports concerning the effects of utterance length and complexity on duration across development. In these previous studies, measures of speaking rate were used to draw inferences about the planning and production processes for speech. Abbeduto (1985) found that normally fluent adults and children repeated sentences with more complex syntactic and semantic structures more slowly than simpler sentences. On the basis of durational measures of speech acoustic data, Abbeduto (1987) also concluded that it was not until 8 years that children started to use the syntax of an utterance, rather than rhythmic structure alone, to program units for speech production. Whiteside (1999) found that 6-year-old children demonstrated a greater number of and longer interword pauses than 8-year-old and 10-year-old children during a picture-naming task. He suggested that this finding was possible evidence for word-by-word speech planning by 6-year-old children. Therefore, in addition to charting the changes in duration of production across development, we also explore, in the present study, the idea that the duration of word sequences is a potential clue to the use of sentence internal structures in speech planning and production.

The purposes of the present study were twofold:

**Purpose 1:** To use kinematic methods to determine developmental trends in the effects of increased language processing on speech movement output. In the present study, we used the Maner et al. (2000) experimental protocol in a large cross-sectional follow-up investigation. Based on earlier findings, we hypothesized that the variability of speech movement sequences decreases with age until adultlike patterns are achieved. Walsh and Smith (2002) reported that in the production of a simple sentence spoken in isolation (“buy Bobby a puppy”), speech motor performance was not adultlike until after 14 years. We wished to determine if the increased variability of speech movements observed when the word sequence was produced as part of longer sentences (“the embedding effect”) observed by Maner et al. (2000) continues to occur throughout the school-age years and adolescence or whether it is only characteristic of very young children.

**Purpose 2:** To map the changes in speech rate across development. On the basis of earlier findings (e.g.,
Abbeduto, 1985, 1987; Walsh & Smith, 2002; Whiteside, 1999), we expected that, overall, children will demonstrate longer durations for all utterances compared with adults. We also wanted to explore the emergence of the shortening of the embedded word sequence across the age groups, as this may provide insights on speech planning processes during development.

**Method**

**Participants**

There were 210 participants, 30 (15 male, 15 female) in each of the 7 included age groups (5, 7, 9, 12, 14, and 16 years, and young adults). Table 1 provides details about the participants in the present study. The youngest participants were 5 years old because 4-year-olds cannot produce the longer, more complex sentences included in this experiment. Also, because we wanted to further investigate the widely accepted notion that mature speech motor control is attained around 10–12 years of age, we included children and adolescents at 2-year age intervals up to young adults. This enabled us to more completely and extensively study language–motor interactions from childhood through adolescence to adulthood. Different data sets collected from some of the same participants have been reported in earlier cross-sectional studies from our laboratory (A. Smith & Zelaznik, 2004; Walsh & Smith, 2002).

All participants had normal developmental histories with no speech, language, hearing, or neurological impairments according to parent report (for children) and self-report (for adults). Participants’ oral motor and receptive/expressive language skills were determined to be within normal limits using the Oral Speech Mechanism Screening Examination–Revised (OSMSE-R; St. Louis & Ruscello, 1987) and the Clinical Evaluation of Language Fundamentals–Preschool (CELF-P; Semel, Wiig, & Secord, 1992) for 5-year-old children and the Clinical Evaluation of Language Fundamentals–Third Edition (CELF-3; Semel, Wiig, & Secord, 1995) for the 7-, 9-, 12-, 14-, and 16-year-olds as well as young adults. In addition, the Bankson–Bernthal Test of Phonology (BBTOP; Bankson & Bernthal, 1990) was administered to verify that 5- and 7-year-old children demonstrated age-appropriate articulation and phonology. All of these tests were administered by student speech-language clinicians. In addition, the spontaneous speech of all other age groups was subjectively assessed to rule out the presence of any obvious articulation and phonology problems. All participants also passed an audiological screening to a 20-dB HL pure tone presented at 500, 1000, 2000, and 4000 Hz in each ear.

**Experimental Task**

The stimuli used in the present experiment were a subset of those used by Maner et al. (2000). In the original experiment by Maner et al., participants produced five sentences at three complexity levels based on Brown’s Linguistic Stages (Brown, 1973). However, no differences were found between the second (“low”) and third (“high”) levels of sentence complexity used in the Maner et al. (2000) study. Hence, only the simplest and most complex sentences from the original study were included in the present study. Participants produced the word sequence “buy Bobby a puppy” in isolation and embedded in two longer and more complex sentences “they asked us to buy Bobby a puppy this week” and “you buy Bobby a puppy now if he wants one.” The two longer, more complex sentences were matched for length; contained the same number of words, syllables, and morphemes; and were both at Brown’s Stage Late V. Note that in the current study, it is not possible to separate the effects of length of the stimuli from their complexity. Hence, effects on speech motor output are discussed as being due to both increased length and complexity (hereafter referred to as length/complexity) of the stimuli.

**Procedure**

Kinematic data were recorded using a Northern Digital Optotrak camera system with small infrared light emitting diode (IRED) markers. Participants wore a pair of plexiglass goggles with an elastic strap. From both sides of the goggles, a splint attached to the outer edge of the goggles extended downward. The IRED markers were then attached to the participant’s skin and goggles using two-sided adhesive tape: One IRED was placed at midline in the center of the forehead, two at the upper right and left corner of the goggles and two at the bottom of the right and left splints, directly across from the right and left corners of the mouth. The IREDS on the goggles and the forehead were tracked in order to record head

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**Table 1. Details of participants included in the present study.**

<table>
<thead>
<tr>
<th>Age group</th>
<th>Mean age (years;months)</th>
<th>SD (in months)</th>
<th>Age range (years;months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-year-olds</td>
<td>5;6</td>
<td>2</td>
<td>5;1–5;11</td>
</tr>
<tr>
<td>7-year-olds</td>
<td>7;6</td>
<td>4</td>
<td>7;0–7;11</td>
</tr>
<tr>
<td>9-year-olds</td>
<td>9;5</td>
<td>4</td>
<td>9;0–9;11</td>
</tr>
<tr>
<td>12-year-olds</td>
<td>12;6</td>
<td>4</td>
<td>12;0–12;11</td>
</tr>
<tr>
<td>14-year-olds</td>
<td>14;5</td>
<td>4</td>
<td>14;0–14;11</td>
</tr>
<tr>
<td>16-year-olds</td>
<td>16;7</td>
<td>4</td>
<td>16;1–16;11</td>
</tr>
<tr>
<td>Young adults</td>
<td>21;5</td>
<td>8</td>
<td>20;1–22;11</td>
</tr>
</tbody>
</table>
motion, which was later used to correct the lower lip marker for head motion artifact. IREDs were placed at midline on the vermilion border of the participants’ upper and lower lips. In addition, an IRED was attached at midline under the chin to record jaw motion. For this experiment, only the motion of the lower lip marker (which reflects the combined actions of the jaw and lower lip) in the superior–inferior dimension was analyzed.

During kinematic data collection, the displacement of the IREDs was tracked and recorded by the Optotrak camera system, with each IRED marker position sampled at 250 samples/s. An audio signal was digitized by the Optotrak Data Acquisition Unit (ODAU) at 8,000 samples/s. The audio signal enabled experimenters to make perceptual judgments of utterances during kinematic data analysis. Video recordings of the sessions were also made and were used only when information was required to supplement kinematic and audio signals.

Following the positioning of the IREDs, the experimental protocol was explained to the participants. A sentence imitation task was selected for this experiment in order to obtain multiple repetitions of the same utterances from all participants. This is required for the computation of the STI. The target sentence was initially presented a single time by the experimenter, and children and adults were instructed to repeat the sentence every time the experimenter held up a stuffed toy puppy. The production protocol started with the sentence “buy Bobby a puppy” and was followed by production of the two longer, more complex sentences in a fixed order. Each new target sentence was introduced with a brief story to give it a meaningful context. Participants produced repetitions of each sentence, pausing for 2–3 s between each repetition. Repetitions were obtained in two 30-s recording trials to obtain a total of 10–15 productions of each sentence over the two recordings. On several occasions, especially with younger age groups, extra 30-s recording trials were required in order to obtain at least 10 fluent and error-free repetitions of each of the three sentences.

**Computation of the Trajectory Stability Index and Data Analysis**

Participants’ utterances were judged by the first author for accuracy and fluency by replaying digitized audio signals using a MATLAB (The MathWorks, 2001) program. Video recordings were used as additional sources for making perceptual judgments if necessary. Utterances were independently judged by two listeners—both graduate students in speech-language pathology—for misarticulations, disfluencies, incorrect words or word order, and atypical rate or prosody. One judgment was made “online” during the recording session to guide the number of recording trials that would be needed. This judgment was later confirmed by a second graduate student (the lead author), whose judgment prevailed in the case of any discrepancy. Productions that contained one or more of the above were excluded, and only those utterances that were judged to contain no errors or other abnormal characteristics were chosen for further analysis.

Following correction for head motion artifact within the Optotrak software environment, the kinematic signal for the lower lip (plus jaw) was imported to the MATLAB signal processing program for data analysis. The lower lip displacement was digitally low-pass filtered (10 Hz) in the forward and backward directions. Only data from the lower lip IRED marker, which represents the combined motion of the lower lip and jaw, was chosen for analysis in this experiment because it is well established that the variability of motion of lip/jaw trajectory is affected by the length and complexity of utterances (Kleinow & Smith, 2000; Maner et al., 2000). The velocity was then computed from the filtered displacement data using a three-point difference method. The velocity signal was used to segment the displacement data for subsequent analysis. The continuous displacement and the corresponding lower lip velocity signals were displayed on the computer monitor using an interactive program. From each displacement file, the lower lip movement trajectory for the target word sequence “buy Bobby a puppy” was extracted using the methods described by Maner et al. (2000)—that is, by marking the first (opening for “buy”) and last (opening for “py” in puppy) lower lip opening velocity peaks.

When more than 10 productions were judged as error free, to avoid bias in selecting the tokens, a rule for token selection was adopted. If all repetitions in the first 30-s recording trial were free of errors, the first production was skipped, and then the five succeeding repetitions were selected. The experimenter then repeated this process with the second 30-s recording trial, and if necessary, the next recording trial, until a total of 10 productions was segmented for analysis for each participant in each length/complexity condition.

An STI was computed to measure the variability of repeated sequences of articulatory movements for the target word sequence “buy Bobby a puppy,” produced in isolation as well as embedded in the two longer and more complex sentences. To compute the index, the 10 displacement waveforms (from each condition) were time and amplitude normalized to reveal the underlying movement pattern in the absence of differences due to changes in overall duration and amplitude (A. Smith et al., 1995). Standard deviations were computed at 2% intervals in normalized time, and the STI is the sum of these 50 standard deviations. The STI, then, is a
composite index of the temporal and spatial dispersion of the 10 normalized trajectories for each participant and condition.

**Statistical Analyses**

Repeated measures analyses of variance (ANOVAs) were used to detect any significant influences of age, sex (between subjects), and length/complexity (within subject) on the STI values. Sex was included as a between-subjects factor because in an earlier investigation (A. Smith & Zelaznik, 2004), speech motor coordination of 4- and 5-year-old boys was found to be more variable compared with girls of the same age. Because one of the main questions of this experiment was to determine the age at which the effects of length and complexity on speech movement variability of children’s speech output begin to show evidence for transition to adultlike speech motor performance, we planned a priori to perform separate repeated measures analyses for each age group to determine if the condition effects were present at each age.

Total movement duration for each extracted displacement waveform for the word sequence “buy Bobby a puppy” was calculated, and within-subject mean durations were computed for the 10 waveforms in each complexity condition. This duration measure represents the duration of the entire movement sequence for “buy Bobby a puppy,” spoken in isolation and embedded in the two longer, more complex sentences. Thus, it is comparable to measures of sentence durations traditionally obtained from acoustic signals of speech and can be expressed as speech rate in syllables/s through simple computation. In a similar procedure described above for the variability measures, a repeated measures ANOVA was used to detect any significant influences of age (between subjects), sex, and length/complexity (within subject) on sentence duration values. Once again, ANOVAs were performed for individual age groups to examine in greater detail the developmental trends in the influence of condition on duration.

**Post Hoc Acoustic Measures**

Total sentence durations for all 3 sentences (the same 10 tokens used in the kinematic analysis) were obtained from the acoustic waveforms for 5-year-old children and young adults in each condition. This post hoc analysis was done in order to compute speech rate (syllables/s) for “buy Bobby a puppy” spoken in isolation compared to speech rate for the entire production of the two longer, more complex sentences. These two groups were selected because they represent the ends of the speech rate continuum. Based on the rate measures from the kinematic data (see Figures 1 and 2), we assumed that all other age groups’ means would fall between these extremes. Repeated measures ANOVAs were then performed on the speech rate data from these post hoc measures to determine if condition produced a significant effect on total sentence duration.

**Results**

Five 5-year-old children and one 9-year-old child did not produce sufficient repetitions of one of the longer sentences, and therefore the respective age groups’ mean values were substituted for the missing STI and duration values for these six cases, prior to statistical analyses. This strategy was adopted so that we did not have to throw out the data for the sentences that these six individuals did produce. This also helped retain equal group numbers for the statistical analyses.

**Kinematic Analysis: Trajectory Variability**

The STI was used to measure the variability of speech movements obtained from multiple repetitions of the word sequence “buy Bobby a puppy.” The index was measured for the movement trajectories in the baseline (words spoken as a sentence in isolation) as well as in the two embedded conditions across all age groups. Figures 3–5
show examples of time- and amplitude-normalized waveforms for “buy Bobby a puppy” in the baseline condition as well as in “you buy Bobby a puppy now if he wants one” (Embed 1) and “they asked us to buy Bobby a puppy this week” (Embed 2).

The overall ANOVA computed for all 210 participants revealed an age effect on the variability of repeated speech movement trajectories, $F(6, 196) = 51.16, p < .0001$. As indicated in Figure 6, younger children have higher STIs (are much more variable) than older children. Young adults were most consistent in producing the lower lip movement sequence for “buy Bobby a puppy.” There was no effect of sex on trajectory stability, $F(1, 196) = 1.75, p = .19$, and no significant Age × Sex interaction, $F(6, 196) < 1$. A significant overall condition (length/complexity) effect was found for the STI, $F(2, 392) = 35.95, p < .0001$. There were no significant interactions of Condition with any other factor.

**Temporal Measures**

The mean durations of “buy Bobby a puppy” were obtained for the baseline and two length/complexity conditions by measuring the total duration of the target movement sequence in all three conditions. Figure 1 depicts the mean durations of the target word sequence for each condition across all of the age groups. From this figure, it is evident that adults shorten “buy Bobby a puppy” when it is embedded in longer, more complex sentences compared with its production in isolation. Conversely, it is apparent that younger children have much higher variability (5-year-olds and 7-year-olds) and do not show significant durational differences between the baseline and embedded conditions. The effect of age on duration was robust, $F(6, 196) = 35.94, p < .0001$. Sex did not produce any significant effect on the sentence duration, $F(1, 196) = 1.48, p = .22$, and the Age × Sex interaction did not prove to be significant, $F(6, 196) = 1.99, p = .07$. A significant overall length/complexity effect on duration, $F(2, 392) = 9.40, p = .0001$, and a significant Age × Condition interaction, $F(12, 392) = 2.85, p < .01$, was obtained. The Condition × Sex interaction, $F(2, 392) = 1.63, p = .20$, and Condition × Age × Sex interactions, $F(12, 392) < 1$, were not significant.

Significant condition effects on duration for the utterance “buy Bobby a puppy” were noted for 9-year-olds, $F(2, 56) = 34.16, p < .0001$; and young adults, $F(2, 56) = 7.52, p < .001$.
Post Hoc Acoustic Measures

One explanation for the finding that adults and older children shorten “buy Bobby a puppy” when it is embedded in longer, more complex sentences is that adults and older children simply speak more rapidly when producing longer sentences. Although this would not be predicted based on earlier results (e.g., Abbeduto, 1985, who reported that both children and adults reduce speech rate during more complex productions), we wanted to rule out this possible explanation for the duration effects. Thus, a post hoc analysis of whole sentence durations was completed from the acoustic signal for only adults and 5-year-olds. The mean durations of the entire sentence production for the three sentences and corresponding rates of speech (in syllables/s) are shown in Table 2. Significant differences were found between the rate of speech of 5-year-old children and young adults, $F(1, 58) = 80.37, p < .0001$. The effect of condition on rate of speech was significant, $F(2, 116) = 242.97, p < .0001$, and a significant Condition × Age interaction, $F(2, 116) = 99.71, p < .0001$, was present. Both young adults and 5-year-olds slow their speech rates when producing the longer, more complex sentences. However, 5-year-olds reduce their rates by a greater percentage. Whereas adults slow their rate of speech from 5.95 syllables/s to 5.5 syllables/s (an 8% change), children slow their speech rate from 4.3 syllables/s to 3.6 syllables/s (a 16% reduction).

Comparative Growth Curves

We have reported measures of oral movement trajectory variability and duration (or speech rates), and it is clear that there are significant and protracted changes in these variables as children mature to young adulthood. In order to compare the relative changes in these two distinct kinds of variables, which are measured in
different units, we plot (in Figure 2) the relative growth curves for each variable as a percentage of the young adult mean values. The adult mean is arbitrarily set as 100%, and the mean values of each younger group are plotted as a percentage of the adults’ mean. In the top panel are plotted the relative growth curves for the STI as a function of age for “buy Bobby a puppy” spoken in isolation and embedded as a phrase in the two longer, more complex sentences. It is clear from this plot that movement variability, as a percentage of the adults’ values, for younger speakers is affected by the context in which the word sequence is produced. In the bottom panel, where the relative growth curves for speech rate are plotted (note that the kinematic duration data for the target production “buy Bobby a puppy” were used for this plot), it is clear that a similar effect is present, with younger children producing the embedded sentences at even slower rates than in the isolated production. Finally, it is also evident that the trajectory variability index and the duration or speech rate maturational curves are nonparallel, suggesting distinctive maturational profiles for these two variables. Especially dramatic are the differences the slope in the 5- to 7-year period, when speech rate increases from about 45% to 75% of the adult value, whereas the STI shows very little change toward adult values (no change in the baseline condition, and only about 10% change in the other conditions).

**Discussion**

The production of any speech output is the result of many complex neural processes, including language formulation, motor programming, and execution of the motor commands by the speech systems. Earlier studies that have examined variability, patterning, and timing of speech movements from a developmental perspective document that children are more variable than adults and that speech stability increases with age and the maturation of the speech mechanisms (Sharkey & Folkins, 1985; A. Smith & Goffman, 1998; B. L. Smith & McLean-Muse, 1986). However, these studies typically only included participants up to the age of 10 years. More recent studies (Huber et al., 1999; A. Smith & Zelaznik, 2000; Sadagopan & Smith, 2010) have shown that variability and stability continue to change in later childhood.
2004; Stathopoulos & Sapienza, 1997; Walsh & Smith, 2002) discuss a course of development of speech sub-systems and processes that is more protracted. Considering that speech production is a highly skilled, overlearned task, several researchers (Maner, Smith, & Grayson; 2000; A. Smith & Goffman, 1998; Walsh & Smith, 2002) have hypothesized that repeated productions of movement sequences for any target utterance would demonstrate little variability from one trial to another for adults, who have highly practiced, stable coordinative processes for speech. The present results confirm this prediction and also demonstrate, as predicted, that children, who are still on the path to developing mature speech motor control, show greater variability for speech sequences compared with adults. Our large-scale cross-sectional study is a novel effort in charting the trends in speech movement variability and duration across development, in varying length/complexity contexts. The results from the present study contribute further evidence for the protracted development of maturity in language–motor interaction patterns. Further, the results point toward a developmental trajectory for duration and speech rates that is distinctive from the developmental trajectory for speech movement variability.

Utterance Length/Complexity and STI

The present results confirm earlier findings by Maner et al. (2000) that for children, increased processing demands cause an increase in speech movement variability for repeated productions. Although Maner et al. studied these effects only for 5-year-old children and young adults, a similar effect is noted from the current results for all other groups of children and teenagers (7-year-olds, 9-year-olds, 12-year-olds, 14-year-olds, and 16-year-olds). The young adults did not show a significant overall influence of length/complexity on speech movement variability. Hence, even at 16 years, adolescents show increased variability of speech movements when processing demands are increased. It is important to restate here that the two embedded conditions were controlled for length and were at the same developmental level: Brown’s Stage Late V, typically acquired by 43–46 months of age. However, the baseline condition differed from the
two embedded conditions in sentence length as well as complexity, and hence the results are discussed with respect to the influence of both length and complexity on movement stability. Regardless of the confounding effects of length and complexity, the present results are novel and striking in many respects. We, and presumably most readers, would not have predicted the robust effects of length and complexity on speech movement variability as late as 14 and 16 years of age. This is especially remarkable because these sentences are of relatively low complexity when one considers the fact that these sentences are typically acquired by about 4 years of age.

**Length Versus Complexity**

Earlier studies suggest that increased length of utterances produces increased demands in speech motor processing. Sternberg, Monsell, Knoll, and Wright (1978) found that when word lists were made longer, adults required more time to plan the utterance (measured by increased reaction time). Maner et al. (2000) used two sentences of lower complexity (Brown’s Stage Early IV) in addition to the two higher complexity sentences used in this experiment. All four complex sentences were controlled for length. Maner et al. did not find any significant differences between the STIs in the two complexity conditions and therefore discussed that perhaps it was the length of the utterances that largely affected variability, although complexity could not be completely ruled out.

As far as the present results for young adults are concerned, although the current findings do not show that increased length and complexity are accompanied by increased movement variability, such potential effects should not be ruled out. As noted previously, the sentences that were longer and more complex belonged to Brown’s Stage Late V, corresponding to linguistic development between 43 and 46 months of age. Thus, it seems reasonable to suggest that relatively low demands were placed on the well-developed adult processing system. More recently, Kleinow and Smith (2006) manipulated internal clause structure to control length and complexity in a set of short and long sentences. They demonstrated that both length and syntactic complexity affected the variability of speech production in 9- and 10-year-olds and young adults. Their design also differed from ours in that they analyzed the entire movement sequence for the sentence rather than a subset target word sequence. On the basis of these results, then, we would argue that the participants aged 5 through 16 years in the present study were most likely showing increased variability in their speech movement trajectories in the embedded conditions due to effects of both length and syntactic complexity.

**Speech Rates and Sentence Durations**

Seeking potential clues to programming and production units (Abbeduto, 1985, 1987), we examined the effect of producing the same sequence of words as a sentence versus as a phrase in longer, more complex sentences on mean utterance duration. Five- and 7-year-old
children do not show any influence of context on the duration of the target word sequence. For these two age groups, the length of “buy Bobby a puppy” was the same across all three conditions. Adults and older children, on the other hand, show a significant effect of context on the duration of the target word sequence “buy Bobby a puppy.” Their durations are significantly shorter when the sequence is spoken as part of a longer, more complex sentence compared with when the same word sequence is produced as a short sentence in isolation.

One explanation might be that when adults produce longer sentences, they increase the overall rate of speech production, thereby shortening the length of the entire production. This would then result in shorter durations of productions extracted from the longer, more complex utterances. The results from the post hoc analyses show that this is, in fact, not the case. Rather, the longer sentences were spoken with a slightly slower overall rate (see Table 2). Our results are consistent with earlier findings that even for adults, increased processing demands resulted in longer syllable durations (Abbeduto, 1985) and longer reaction times (Stenberg et al., 1978). When the data are plotted as a percentage of adult values, as in Figure 2, a remarkable age-related change in the overall duration of “buy Bobby a puppy” occurs from early childhood to the school-age years and adolescence. As in earlier reports (A. Smith & Zelaznik, 2004; Walsh & Smith, 2002), we find that 14- and 16-year-old adolescents speak, on average, more slowly than 20- to 22-year-olds. Looking at the overall speaking rate from measures of the two longer sentences (see Table 2) and the comparative growth curves in Figure 2, we see that over the period from 5 years of age to young adulthood, speech rate changes from about 3.6 syllables/s (5-year-olds) to about 5.5 syllables/s (young adults), or a 52.7% increase. We recognize that it has long been documented that pre-school-age and young school-age children speak more slowly than adults (Kent & Forner, 1980; B. L. Smith, 1978; Tingley & Allen, 1975). However, it has often been assumed that after 9–10 years of age, speech rate is at adult levels, and children older than 9–10 years typically have not been studied. Our large cross-sectional studies are the first, to our knowledge, to document how the increase to adult speech rates emerges over the course of development into the teen-age years.

Returning to the issue of the embedding effects, although our results demonstrate that adults as well as 5-year-olds slow their overall rate of speech when producing longer, more complex sentences, we also show that young adults shorten the target word sequence “buy Bobby a puppy” in the two longer/more complex sentences, whereas 5- and 7-year-olds do not. Thus, some manipulation of the internal structure of productions takes place in adults but not in young children. We speculate that perhaps children and adults use different motor planning strategies (Whiteside, 1999), and the durational difference observed in this study reflects these planning differences. One possibility is that older children and adults use internal sentential structure to “chunk” or group units for production such that planning subunits are called into play when longer, complex sentences are produced. This idea is related to earlier interactive models of language formulation, which suggest that two primary processes are involved in language production: (a) the creation of a skeleton or outline of an intended production and (b) a “fleshing out” process that involves the specifics of the utterance, such as prosodic contour and phonological encoding (Bock & Levelt, 1994). Perhaps younger children use a fleshing out process that operates over smaller subunits (word- or syllable-level) and, therefore, evidence no shortening of the word sequence when it is embedded. It is important to note here that we did not include measurements such as interword pause durations that would aid in determining exact phrase boundaries. Future studies that attempt to answer questions about planning units in children and adults may include analyses that would help in determining precise phrase boundaries for longer productions. It is likely that several sentential factors (e.g., syntactic structure, intent of the utterance, and prosodic factors) play a role in the determination of the speech planning units and subunits of any given utterance.

Another finding of this study is that at 9 years of age, children begin to show an influence of embedding on the duration of internal components of the sentence, suggesting that it is around this age that the transition to adultlike speech motor planning strategies begins. That this is a “critical age” for the beginning of the maturation of timing control has been suggested by several other researchers. Our results are supported by several earlier findings (Abbeduto, 1987; Whiteside, 1999). In a study by Katz, Beach, Jenouri, and Verma (1996), children (aged 5 and 7 years) and adults described different groupings of pink, green, and white blocks based on whether blocks were together or apart (e.g., Response – “pink green… ___ and white,” when the pink and green blocks were together and when the white block was apart). Katz et al. found that 5- and 7-year-old children, unlike adults, do not use prosodic cues (word and pause durations or fundamental frequency contours) to signal phrase boundaries in their speech.

In summary, it is evident that starting around 9 years of age, children demonstrate specific changes in temporal aspects of speech output for longer/complex utterances, suggesting a shift to the use of more mature, adultlike speech motor planning strategies. However, at this age, movement variability indices are still high for the repeated movement trajectories of sentences that are longer and more complex. This indicates that although some adultlike trends are beginning to emerge,
the stability of these movements and production speed continue to develop even up to 16 years.

**Factors Affecting Protracted Developmental Course for Different Speech Subsystems**

The present results demonstrate a protracted developmental course to adultlike performance in the articulatory system engaged in the production of sentences. Similarly, large-scale cross-sectional studies of respiratory, laryngeal, and acoustic measures in children aged 4 years through adolescence and into young adulthood have revealed that performance on many of these measures is not adultlike until the teenage years. It is important to note, however, the very different sets of underlying factors hypothesized to drive the protracted developmental courses. For acoustic, laryngeal, and respiratory measures, Statopoulos, Huber, and colleagues (Huber et al., 1999; Statopoulos and Sapienza, 1997) report dramatic sex differences such that females achieve adult levels of performance around 12 years of age, whereas males show adult values later at around 16–18 years of age. Thus, they attribute changes in their measures to changes in anatomical factors during adolescence, especially to the well-known later growth spurt for males.

In the present report and in our earlier studies (A. Smith & Zelaznik, 2004; Walsh & Smith, 2002), we have observed no sex differences in consistency of articulatory processes during the teenage years. Teenage boys and girls show identical growth curves both for trajectory variability and speaking rate. We have argued, therefore, that the delayed development of articulatory motor processes is driven by the fact that the cortical circuits involved in language and other cognitive functions continue to develop into late adolescence (see review by Blakemore & Choudhury, 2006). Perhaps, then, there are at least two basic factors driving the late development of speech production. The first is related to anatomical growth factors, which will affect output measures such as fundamental and formant frequencies and respiratory volume and flow. A second factor is the protracted maturation of cortical networks that delay the adolescent from producing adultlike coordinative patterns and speech rates until approximately 18 years. As a final note on this topic, we would suggest it is not the output measure that completely determines the primary factor driving the growth curve but, rather, whether the measure is tied predominantly to biomechanical factors (e.g., fundamental frequency) or to the linguistic goals of the speaker.

**Methodological Issues/Caveats**

**Task constraints.** Although the use of an imitation task is not comparable to natural speech, it was necessary to obtain the required number of repeated productions for the computation of the STI. Future studies of language-motor interactions could perhaps use priming tasks to generate data that are more naturally planned and produced.

**Error exclusion.** The fact that utterances selected for analysis and computation of the STI were error free may seem counterintuitive to some readers. Much work on children’s speech and language productions has been devoted to error assessment, and we understand that this has been a rich source of information. But here, we ask a different question. All of the data analyzed in the present study fit the perceptual/behavioral category of “correct.” The important point, therefore, is the focus here on the qualitatively and quantitatively distinctive speech motor processes that underlie this perceptually and behaviorally equal set of productions over a long period of maturation.

**Trajectory variability: An epiphenomenon of rate?** This issue is repeatedly raised in the speech production literature, especially with regard to immature and disordered speakers, who tend to be slower speakers. There have been many demonstrations in earlier studies of dissociations between speaking rate and the variability index that we use, the STI. For example, in the first study in which the STI was used, adult speakers produced a sentence at different rates. The STIs for the fast and habitual rate conditions were not different, but clearly the fast rate duration was lower than the duration of the habitual rate condition. A. Smith and Zelaznik (2004) reported that during the period from 7 to 12 years, interarticulator coordination variability remained relatively constant, whereas speech rate increased significantly during this developmental period. In the present investigation, we also see a clear dissociation between speaking rate in the STI measure. As we noted in relation to Figure 2, the growth curves for the variability index and speaking rate are remarkably distinctive. Therefore, variability is not simply an epiphenomenon of overall speaking rate.

**Conclusion**

In designing this experiment, we proposed to investigate the influences of length and syntactic complexity on the stability and mean durations of speech movements across repeated trials of a target word sequence “buy Bobby a puppy.” The results of this study, as hypothesized, replicate and extend the findings by Maner et al. (2000) and Kleinow and Smith (2000). Further, we show evidence for protracted development of speech motor control into late adolescence. Speech rates, as a percentage of adult values, reach more mature values earlier than movement variability measures. Our findings
confirm the existence of an intricate relationship between higher level cognitive processes and speech motor output. In addition, it is evident from the results of the present study that overall utterance duration (speech rate) changes follow a different developmental trajectory than variability of speech movements.

References


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Contact author: Neeraja Sadagopan, Department of Speech, Language, and Hearing Sciences, Purdue University, 1353 Heavilon Hall, 500 Oval Drive, West Lafayette, IN 47907-2038. E-mail: sadagopn@purdue.edu.
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Neeraja Sadagopan, and Anne Smith

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