# Articulatory Movements in Adolescents: Evidence for Protracted Development of Speech Motor Control Processes

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In order to contribute to a more comprehensive model of speech motor development, we examined the movement trajectories of the upper lip, lower lip, and jaw to determine (a) if there are changes in articulatory motor control in late adolescence; (b) if there are sex differences during this developmental period, perhaps related to differences in craniofacial growth rates; (c) if control of jaw motion is adultlike earlier than control of the upper and lower lip; and (d) if control of spatial and temporal aspects of articulatory movement co-develop in adolescence. Participants were 12-, 14-, and 16-year-olds, and young adults (mean age 21.2 years), with 15 males and 15 females per group. A measure reflecting spatiotemporal consistency in trajectory formation for repeated productions of a phrase was calculated for the upper lip, lower lip, and jaw movements. Overall trajectory variability was higher for adolescents compared to young adults. Jaw trajectories were less variable than upper lip or lower lip trajectories, but all effectors showed parallel decreases in variability as age increased, suggesting that control of jaw movement does not reach adult performance before control of the lips. Separate temporal and spatial measures revealed that adolescents had significantly longer movement durations, lower velocities, smaller displacements, and greater variability on these measures than young adults. There were no sex differences on any measure examined, suggesting that peripheral growth factors do not account for this protracted developmental time course. These results provide initial evidence of significant changes in speech motor control processes during adolescence.

**KEY WORDS: speech production, motor control, kinematics, development, adolescence**

The term “puberty” refers to the biological changes that occur during adolescence. It is characterized by dramatic cognitive development, physical growth, changes in body composition, and full maturation of the circulatory, respiratory, and reproductive subsystems (Steinberg, 1996). The present study focuses on oral motor control for speech during this late developmental period. We employ several types of analyses—one focusing on the variability of upper lip, lower lip, and jaw movement trajectories for a phrase, in addition to spatial and temporal measures of articulatory movements.

The study of the development of any motor behavior relies on measurements of invariance, stability, and homeostasis (Golani, 1981). For example, Thelen and Smith have conceptualized locomotor development as a changing ontogenetic landscape that settles into "attractors" or preferred movement trajectories as a mature pattern of locomotion emerges. Thus, the developmental trend of motor behaviors is characterized by decreasing variability in performance and the emergence of very stable attractors (Thelen & Smith, 1994). Kinematic studies of speech production generally suggest that as children get older, they become less variable with respect to the timing, velocity, amplitude, and patterning of their speech movements (Goffman & Smith, 1999; Green, Moore, Higashikawa, & Steeve, 2000; Green, Moore, & Reilly, 2002; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Smith & McLean-Muse, 1986; Watkin & Fromm, 1984). These studies focused on production in children under age 10 years and typically included small numbers of participants. It is critical from a clinical perspective to have a comprehensive model of how speech motor processes normally develop from infancy through adulthood. "When asking questions about the development of motor skills, we should be equally concerned with the cessation of change as we have been with its initiation" (Phillips & Jensen, 1987, p. 180). Thus, one goal of the present study is to compare the speech production of older children and adolescents with that of adults to learn precisely when adultlike speech motor control is achieved.

Speech production is the result of coordination and complex interactions between the respiratory, laryngeal, and articulatory subsystems, and it is hypothesized that these subsystems may influence each other's courses of development (Thelen & Smith, 1994; Thelen & Smith, 1998). As reviewed in the next paragraph, recent large-scale studies of speech acoustics and respiratory kinematics provide evidence of a protracted developmental time course, as well as sex differences. Theoretically, if the three speech subsystems co-develop, we posit that articulatory control of lip and jaw movements for speech will also have an extended developmental time course and may be different for boys and girls.

Acoustic studies of speech production during the 1970s and 1980s employed analyses of formant frequencies, voice onset time, and the duration of syllables, words, and sentences to index vocal tract maturation. Collectively, these studies established that mean values and variability of these measures were adultlike by age 11 (DiSimoni, 1974; Eguchi & Hirsh, 1969; Kent, 1976; Kent & Forner, 1980; Tingley & Allen, 1975); however, these studies did not include children over age 12 years. Recent studies provide evidence of a more protracted developmental time course, one that is affected by growth of the vocal tract (Huber, Stathopoulos, Curione, Ash, & Johnson, 1999; Lee, Potamianos, & Narayanan, 1999). In a large-scale study of children and adolescents (5–18 years) and adults, Lee et al. (1999) reported that duration variability for vowels and the fricative /s/, as well as the variability of formant frequencies, diminished with age until around 14 years, possibly paralleling vocal tract development. Huber et al. (1999) found that F1, F2, and F3 reached adultlike values in females by age 12 but were not adultlike in males until 16–18 years of age. Huber and colleagues proposed that sex-specific growth patterns of vocal tract structures were primarily responsible for these differences. In a study of laryngeal function and respiratory kinematics during a syllable production task, Stathopoulos and Sapienza (1997) reported that respiratory functioning in both boys and girls was mature by 14 years; however, laryngeal functioning was significantly affected by sex-related differences in laryngeal structure sizes.

Not only do these recent studies of speech acoustics support a protracted developmental course for the speech subsystems, but they also raise important issues regarding the effect of somatic growth on speech production. Since craniofacial and oral growth continues into mid-puberty and is markedly different in boys and girls (Farkas, 1994; Farkas, Posnick, & Hreczko, 1992), it is possible that these changes could affect how the articulators are controlled for speech production. In their review of craniofacial development, Kent and Vorperian (1995) reported that facial bones continue to grow until puberty or, in some cases, into adulthood. Accelerated growth of the tongue occurs between 11 and 14 years, and reaches maturity by about age 16 (Brulin & Talmant, 1976; Farkas, 1994; Kerr, Kelly, & Geddes, 1991). The mandible changes in size and shape between 8 and 17 years, with different growth curves occurring for males and females (Bishara, Jamison, Peterson, & DeKock, 1981; Farkas, 1994). With respect to lip length and thickness, Mamandras (1984) recorded marked growth between 12 and 14 years, although females reached adult length and width earlier than males.

In addition to coordinating the respiratory, laryngeal, and articulatory subsystems, neural subsystems must also simultaneously integrate semantic, syntactic, and phonological aspects of language during speech production. Imaging studies provide evidence that cortical development also follows an extended and variable course of development into the mid-teen years (Benes, Turtle, Khan, & Farol, 1994; Huttenlocher, 1990; Paus et al., 1999; Paus, Collins, Evans, Pike, & Zijdenbos, 2001). The development of neural pathways, including dendritic arborizations, synaptic connections, axon diameter, and myelinization, affects the speed and efficiency of transmission among the multiple, widespread brain regions essential for integrated cognitive and motor tasks such as speech production. Continued anatomical, neurological, and physiological development could influence how the articulators are controlled for speech production. Thus, we predict that speech motor control processes follow a protracted developmental time course and are influenced by sex-related differences in somatic growth.

The present experiment uses a composite measure of spatial and temporal variability computed from repeated productions of an utterance. It may be calculated for single movements or for multiple movement sequences for syllables, words, or phrases (Smith, Johnson, McGillem, & Goffman, 2000). The method involves the traditional approach in motor control of linearly time- and amplitude-normalizing movement trajectories to reveal aspects of underlying templates or patterns of movement (Bullock & Grossberg, 1988; Georgopoulos, Kalaska, & Massey, 1981). We include large numbers of participants in older age groups traditionally excluded from developmental speech research and examine the movement trajectories of three effectors critical to speech production (upper lip, lower lip, and jaw) to determine whether or not changes in articulatory control occur in adolescence, or conversely, whether by age 12 years these processes are already adultlike.

In light of evidence suggesting that control of jaw movements precedes control of other effectors such as the lips and tongue in children (e.g., Green et al., 2002; Lindblom & Sundberg, 1969; MacNeilage & Davis, 1990; MacNeilage, Davis, Kinney, & Matyear, 2000), we predict that upper lip, lower lip, and jaw may show structure-specific developmental courses as indexed by the composite measure of spatial and temporal variability for each effector. Green and colleagues (2002) hypothesized that control of lip movements emerges later to allow time for lip gestures to become fully integrated with already established jaw movement patterns.

Although a composite measure of spatial and temporal variability of articulatory movement trajectories will reveal differences among the groups' abilities to consistently reproduce articulatory patterns, we also include spatial and temporal "point" measures to determine the developmental course for these aspects of oral motor control. It has been suggested that perhaps children achieve control of temporal parameters of speech before their movement amplitudes are adultlike, perhaps because subtle changes in timing can significantly affect perception of the acoustic signal (Levelt, 1989; Walsh & Diehl, 1991). However, Smith and McLean-Muse (1986) argued the reverse, suggesting that physical growth (e.g., nervous system, orofacial structures), as well as "higher order" processes involving the formulation and planning of speech movement sequences, delays the development of adultlike duration of speech output. In order to address this issue, we measure duration, displacement, and velocity of selected components of the movement sequence to determine if these aspects of movement control follow parallel or divergent developmental courses.

In summary, the present study was designed to determine (a) if there are changes in articulatory motor control in late adolescence, (b) if there are sex differences during this developmental period perhaps related to differences in craniofacial growth rates, (c) if control of jaw motion is adultlike earlier than control of the upper and lower lip, and (d) if control of spatial and temporal aspects of articulatory movement co-develop in adolescence.

# Methods

## Participants

A total of 120 children and adults comprising four age groups (15 males and 15 females per group) participated in this experiment. The age groups were: 12-year-olds (*M* = 12;4 [years;months], *SD* = 1.53 months, range 12;0 to 12;11), 14-year-olds (*M* = 14;4, *SD* = 1.13 months, range 14;0 to 14;11), 16-year-olds (*M* = 16;7, *SD* = 3.18 months, range 16;1 to 16;11), and young adults (*M* = 21;2, *SD* = 1.67 years, range 20 to 22 years). These participants performed at age-appropriate levels on speech, receptive and expressive language, and oral-motor tests, including the Clinical Evaluation of Language Fundamentals Screening Test–Third Edition (Semel, Wiig, & Secord, 1996) and the Oral Speech Mechanism Screening Evaluation–R (St. Louis & Ruscello, 1987). All participants passed a hearing screening of pure tones administered at 20 dB at 500, 1000, 2000, 4000, and 6000 Hz. In addition, all participants or their caregivers completed a screening questionnaire to verify that American English was their first and primary language, that they had no speech, language, or learning disabilities, and that they wore no orthodonture. Participants or caregivers completed a developmental and medical case history form, and signed a consent form. Prospective participants were excluded from participation in the study if they failed any screening tests, had a positive history for medications affecting motor or cognitive performance, or had suffered a head injury.

These participants completed the protocol described below and, as part of a larger research project, completed additional tasks in a data collection protocol that included kinematic, anthropometric, EMG (7-year-olds, 12-year-olds, and young adults only), and speech acoustic recordings.[1] Participants were recruited with newspaper advertisements or by word-of-mouth and were paid for their participation.

## Data Collection/Experimental Protocol

The kinematic data recording session lasted approximately 30 minutes. Participants were comfortably seated

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[1] The data reported here for some of the present participant groups will be analyzed for separate presentation in papers planned for future submission. These papers will address issues in speech motor development and will include additional analyses of the kinematic records.

in a chair positioned 1.5 m in front of a Northern Digital OPTOTRAK 3020 three-camera system. The system recorded three-dimensional movements of small (7 mm) infrared light emitting diodes (IREDS) attached to the upper and lower lip and the jaw. Motion of each IRED was sampled at 250 Hz. The IREDS were attached to the skin surface and to a pair of modified Plexiglas sport goggles (two splints affixed to the outside edges of the glasses extended downward), with double-sided adhesive collars. The goggles were fitted snugly to the participant's head with an elastic strap. One IRED was placed on the center of the forehead at midline, two at the right and left upper corners of the goggles, and two on the goggle splints directly across from the right and left corners of the mouth. Upper lip movements were recorded with one IRED affixed at midline on the vermilion border of the participant's upper lip. An IRED placed in the center of the lower lip recorded lower lip motion. The jaw IRED was mounted to a lightweight splint attached at midline under the chin on the skin overlying the inferior aspect of the mandibular symphysis. Participants were asked to produce several strings of bilabial syllables to ensure that the upper and lower lip IREDs did not interfere with one another.

After positioning the IREDS, the experimenter explained the experimental protocol and asked the participants to sit still for a 10-second trial to complete a rigid body construction using the forehead and goggle markers. The rigid body calculation was used to eliminate artifact due to head movements recorded during the experiment. Next, two 30-second samples of conversational speech were collected. A short story was presented before the target sentence "Buy Bobby a puppy" to provide a meaningful context. The participants were instructed to listen carefully to the experimenter model the sentence and then practice producing it independently. This step ensured that each participant produced the phrase in a perceptually similar manner. The cameras were activated, and the experimenter cued the participant to say the sentence each time a small stuffed dog was raised. These methods were adopted because very young children participated in the same protocol. Approximately 2-second intervals separated each sentence repetition. Each 30-second trial typically included 6–8 repetitions of the sentence for these participants. All participants produced the sentence using habitual speech rate and intensity; the trials continued until at least 10 fluent productions were obtained. A fluent production was judged to be free from errors, disfluencies, aberrant prosody, or inappropriate pauses. Judging was done by one experimenter "online," and later during data analysis by a second experimenter. The speech acoustic signal was digitized with an A/D unit synchronized to the Optotrak system and was used to ascertain that appropriate productions had been selected for kinematic analysis. All participants were videotaped so that the experimenter could view a particular experimental session to judge accuracy or fluency if needed.

### Data Analysis

A composite measure of spatial and temporal variability, the STI (Smith et al., 2000; Smith, Goffman, Zelaznik, Ying, & McGillem, 1995), was computed separately for the upper lip, lower lip, and jaw for all 120 participants. Additional analyses of duration, displacement, and velocity were then performed on selected components of the movement sequence for the lip plus jaw signal.

### STI Computation for Upper Lip, Lower Lip, and Jaw

All kinematic analyses were completed on 10 repetitions of the target utterance "Buy Bobby a puppy" for each participant. The kinematic signals were analyzed using MATLAB (MathWorks, 2001) signal processing software. Displacements of upper lip, lower lip, and jaw in the superior-inferior dimension were digitally low-pass filtered at 10 Hz in the forward and backward directions, and velocity was computed from the filtered displacement records using the three-point difference method. For each trial, displacement and velocity records for upper lip, lower lip, and jaw were displayed on a computer monitor. Movement recorded from the lower lip IRED includes a jaw component. Thus, the jaw signal was subtracted from the lower lip signal to estimate the position of the lower lip in the frame of reference of the mandible.

To segment the displacement data for analysis, velocity signals were used to extract upper lip, lower lip, and jaw records at consistent kinematic landmarks: from the peak velocity of the first opening movement (release of the /b/ in the word "buy") to the final opening peak velocity for the utterance (release of the /p/ to /i/ in "puppy"; Smith, Goffman, et al., 1995). The segmented displacement signals were amplitude and time normalized. Amplitude normalization was accomplished by subtracting the mean of the displacement record and dividing by its standard deviation. For time normalization, a cubic spline procedure was used to interpolate each displacement record onto a constant length axis of 1,000 points (Smith et al., 2000; Smith, Goffman, et al., 1995). The STI serves as a measure of variability in movement trajectories across repeated performance of a target utterance and reflects the stability of underlying movement patterns in the absence of differences due to linear changes in duration and amplitude. A standard deviation was computed across the 10 time- and amplitude-normalized displacement waveforms for each articulator at successive points at 2% intervals in relative time. The 50 standard deviations were summed, resulting in a variability index, the STI.

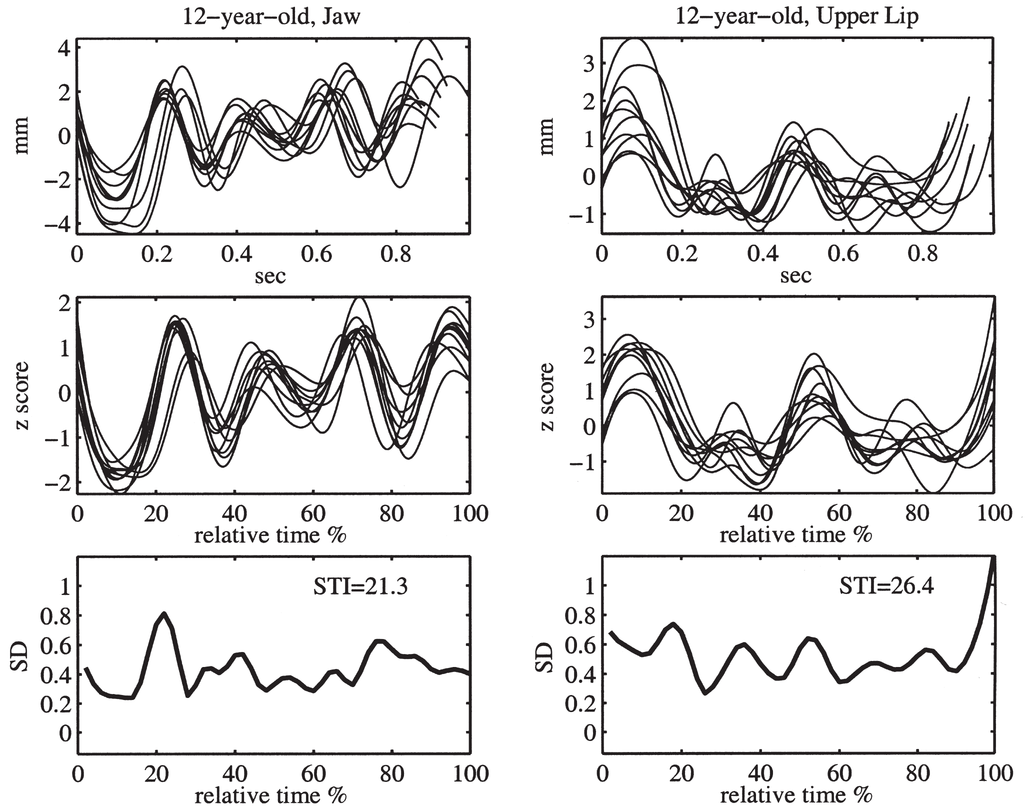
## Duration, Displacement, and Velocity Measures

To obtain a measure of the duration of the overall movement sequence for the phrase, duration of the lower lip plus jaw record was computed in real time for each target production. As stated above, this was the interval between the first and last velocity peaks (release of the /b/ in the word "buy" to the release of the /p/ to /i/ in "puppy").

Spatial and temporal measures for selected internal components of the movement sequence were then computed for the lower lip plus jaw marker signal only. This marker is functionally relevant to articulatory control because it represents the combined action of the lower lip and the jaw. This strategy was adopted because computing separate duration, displacement, and velocity measures for all three effectors would result in a large and cumbersome data set. The (nonnormalized) lower lip plus jaw signal was used to compute the following measures: mean displacement and velocity for the opening movements of "Bob" and "pup" and the mean durations of the open-close movement sequences for "Bob" and "pup" (Goffman & Smith, 1999; Smith & Goffman, 1998). These were chosen as representative spatial and temporal parameters for internal components of the movement sequence. The variability of the total movement sequence duration, open-close duration for "Bob" and "pup," and opening displacement and velocity for "Bob" and "pup" were determined by computing the mean within-subject standard deviation.

Repeated measures ANOVAs were used to assess between-groups factors, age and sex, and the within-group factors relevant for each measure. To avoid errors due to violating the assumption of sphericity, in appropriate cases the degrees of freedom were adjusted using a Greenhouse-Geisser correction. All significant Tukey HSD post hoc comparisons and Cohen effect sizes are listed in the inserts of Figures 3, 4, and 5 (Cohen, 1988). These effect sizes are calculated as coefficients of correlation, and Cohen has suggested that effect sizes in the range of $r = .1$ are "small effects," $r = .3$ are "medium effects," and $r = .5$ are "large effects."

**Figure 1.** Upper lip and jaw data set for a 12-year-old. The top panels show the 10 original displacement signals during production of "Buy Bobby a puppy," the middle panels depict the result of time and amplitude normalization, and the bottom panels show the standard deviations as a function of relative time. The STI value is shown as an insert.



# Results

## Composite Spatiotemporal Stability

An STI was calculated for the upper lip, lower lip (minus jaw), and jaw for each participant. Figures 1 and 2 illustrate the movement trajectories for upper lip and jaw for a 12-year-old and 16-year-old, respectively, whose data are representative of their age group. We show upper lip and jaw data (and omit plots of lower lip) because jaw and upper lip demonstrate the range of variability observed. The upper lip was consistently the most variable effector, whereas the jaw was the least variable. The top panels show the 10 original displacement trajectories for upper lip and jaw. The middle panels illustrate the result of time and amplitude normalization on displacements for each effector, and the bottom panels show the standard deviation plotted as a function of relative time. The speech movement trajectories of the 12-year-old do not converge on an underlying pattern or template as consistently as those of the 16-year-old, which illustrates the general finding that variability decreases with maturation even after 12 years of age.

A repeated measures ANOVA was calculated to determine the between-subject effects of both age and sex and the within-subject effect of articulator on the STI. Age had a significant effect on the STI, $F(3, 112) = 22.70$, $p < .001$. As predicted, the 12-year-olds had the highest STIs, whereas the young adults had the lowest (see Figure 3). All between-group comparisons were significantly different except the 12-year-old/14-year-old and 16-year-old/adult comparisons (Tukey, HSD, $p < .05$). Notably, the 14-year-old/young adult contrast was significant, providing initial evidence of a protracted developmental time course for articulatory control. There was no sex effect, $F(1, 112) < 1$. The overall mean STIs for all articulators combined were 19.4 ($SD = 5.1$) for female participants and 19.9 ($SD = 4.5$) for males, and no interaction of sex with age was observed $F(3, 112) = 1.46$, $p = 0.23$.

There was a significant effect of articulator on the STI, $F(2, 224) = 59.12$, $p < .0001$; however, there were no significant interactions between articulator and age, $F(6, 224) = 1.20$, $p = 0.31$, or sex, $F(2, 224) < 1$. Post hoc testing revealed that the jaw STI was significantly lower than the upper and lower lip STIs (or jaw movements were the least variable) across all ages (Figure 3). However, the upper lip and lower lip STIs did not differ (Tukey, HSD, $p < .05$).

**Figure 2.** Upper lip and jaw data set for a 16-year-old. The top panels show the 10 original displacement signals during production of "Buy Bobby a puppy," the middle panels depict the result of time and amplitude normalization, and the bottom panels show the standard deviations as a function of relative time. The STI value is shown as an insert.

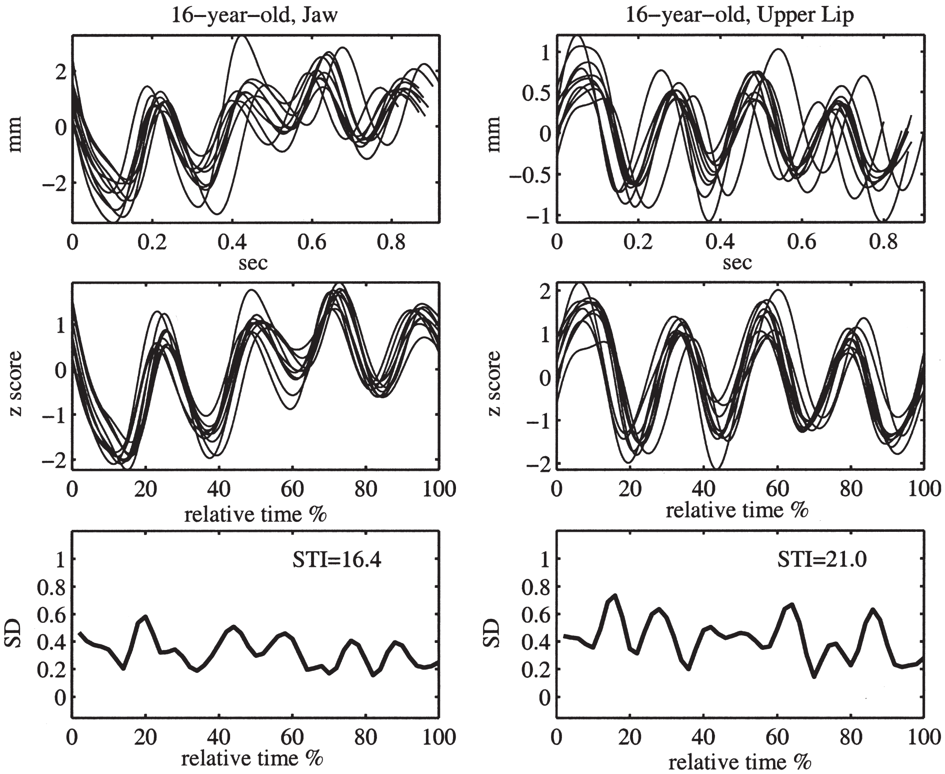
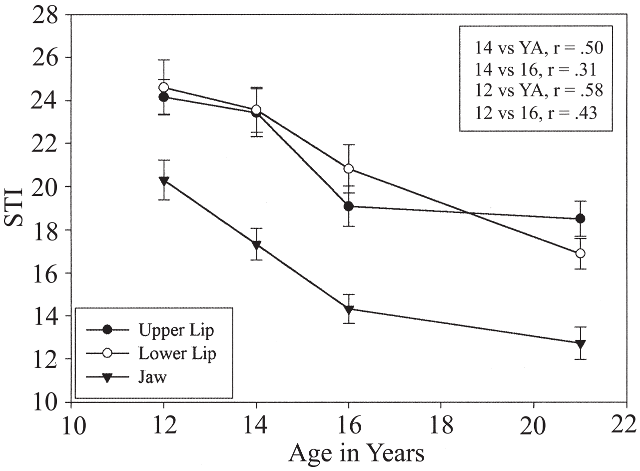


**Figure 3.** STI values for upper lip, lower lip, and jaw across the four age groups (males and females combined). Cohen's *r* effect sizes are listed beside each significant age-wise comparison in the text insert (Tukey, HSD, $p < .05$).

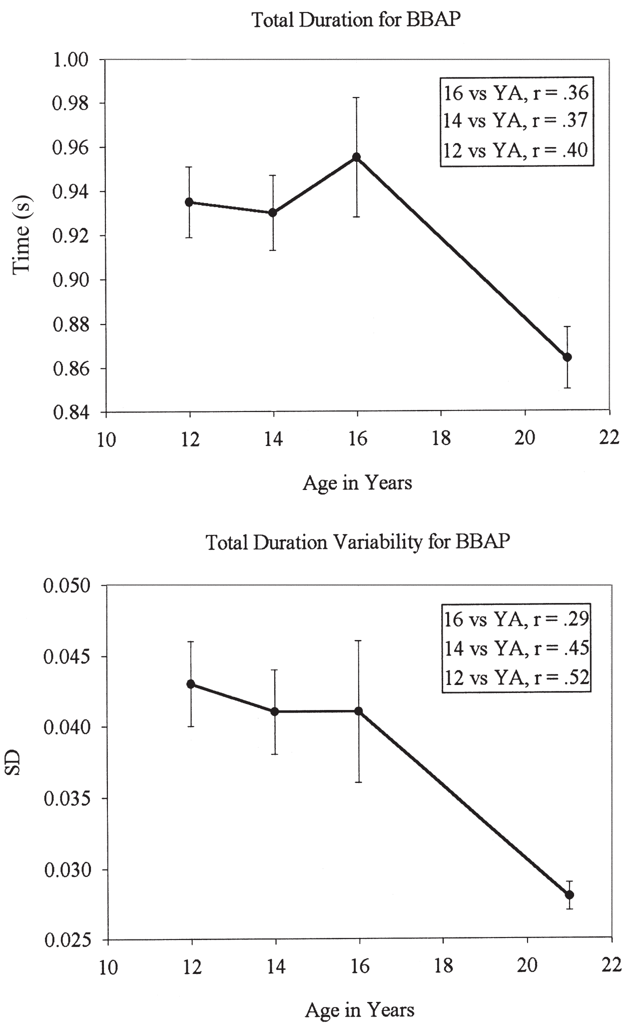


## Total Movement Sequence Duration

The total duration of the movement sequence (which reflects overall speech rate) was computed from the lower lip plus jaw marker for each participant's 10 productions of "Buy Bobby a puppy." In Figure 4, the total duration is plotted as a function of age. Total movement sequence durations are similar for 12-, 14-, and 16-year-olds; however, there is a notable drop in overall duration between 16 and 21 years. The decrease in movement sequence duration over the 12-year-old to young-adult period was approximately 70 ms, representing a 9–10% increase in speaking rate. This drop contributed to a significant age effect on overall duration, $F(3, 112) = 4.18$, $p < .008$. There were no sex differences for total sequence durations, $F(1, 112) < 1$, nor any interaction of age and sex. Tukey post hoc tests of the total duration revealed that values for 12-, 14-, and 16-year-olds were significantly different from those for young adults ($p < .05$), but the adolescent group values were not statistically different from each other.

The variability of total duration was calculated by computing the mean within-subject standard deviation. Figure 4 reveals that duration variability does not change during the 12- to 16-year period, but decreases between 16 and 21 years. A repeated measures ANOVA confirmed an age effect, $F(3, 112) = 4.18, p = .008$; however, no sex effect was found, $F(3, 112) < 1$. Tukey post hoc tests of the total duration sequence variability revealed that values for 12-, 14-, and 16-year-olds were significantly more variable than those for young adults ($p < .05$), but the adolescent group values were not statistically different from each other.

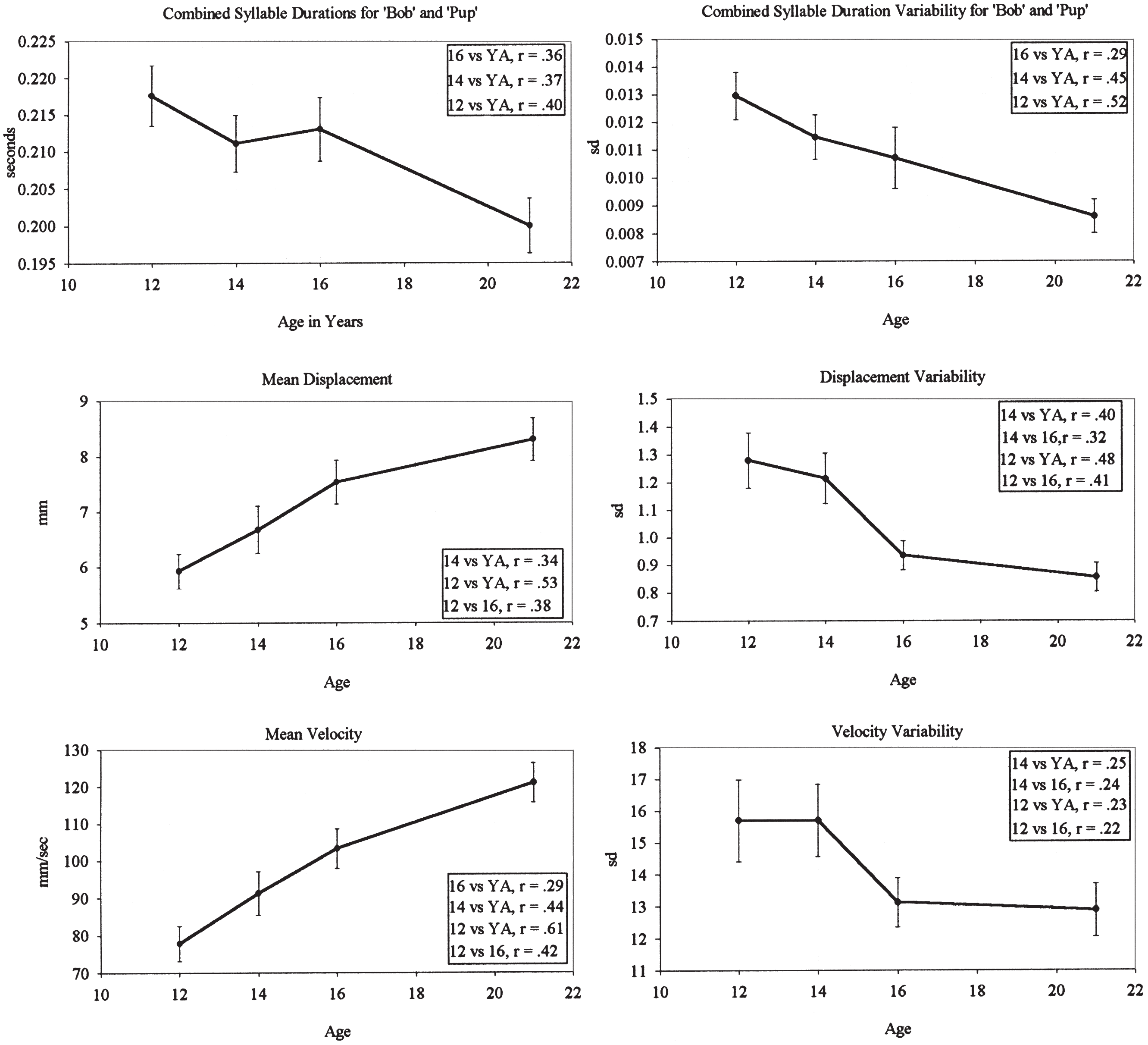
**Figure 4**. The top plot shows mean duration for the entire movement sequence for the four age groups. Bars indicate the standard error. The bottom plot shows the variability of duration as a function of age expressed as the mean standard deviation. Cohen's *r* effect sizes are listed beside each significant age-wise comparison in the text insert (Tukey, HSD, $p < .05$).



## Duration, Displacement, and Velocity Measures for Internal Movement Components

Durations were computed for the open-close movement sequences for "Bob" and "pup" from the lower lip plus jaw signal. Durations of the two-movement sequences for "Bob" and "pup" reflect the trend seen for total duration; the durations of these subcomponents are relatively steady during the 12- to 16-year period, then decrease to adult values after age 16. As expected, the duration of "Bob" was consistently longer than that of "pup" across all groups. The durations for both syllables combined are plotted in Figure 5. As this figure

**Figure 5.** The left-hand side of the figure shows the mean values for opening-closing durations and opening displacement and velocities for the four age groups. Bars indicate standard error. The variability of these measures, or the average group standard deviations, are shown by the three plots on the right-hand side of the graph. Cohen's *r* effect sizes are listed beside each significant age-wise comparison in the text inserts (Tukey, HSD, $p < .05$).



illustrates, there was an effect of age, $F(3, 112) = 4.27, p < .007$; the 12-, 14-, and 16-year-olds had longer syllable durations than the young adults but did not differ from each other (Tukey, HSD, $p < .05$).

For velocity and displacement measures, the lower lip plus jaw opening gesture for "Bob" and "pup" were analyzed. Figure 5 shows the combined opening displacement and velocity values for "Bob" and "pup." To aid interpretation, opening velocities are plotted as positive. These data clearly reveal a trend of increasing movement amplitudes and velocities as a function of age. From age 12 through young adulthood, opening movement amplitude increased by 2.4 mm, whereas velocity increased by approximately 43 mm/s. Separate repeated measures ANOVAs confirmed an age effect for opening displacement, $F(3, 112) = 7.8, p < .0001$, and velocity, $F(3, 112) = 10.20, p < .001$, but no sex effects for either measure $F(3, 112) < 1$. The insert in Figure 5 lists significant post hoc group comparisons for movement amplitude and velocity using Tukey HSD post hoc measures ($p < .05$), as well as Cohen's *r* effect sizes for these comparisons.

## Variability of Internal Measures

The right-hand side of Figure 5 shows mean within-subject standard deviations for syllable duration and opening displacement and velocity as a function of age. There was an age effect for duration variability, $F(3, 112) = 6.27$, $p < .0006$. The 12-, 14-, and 16-year-olds were significantly more variable in duration of the open-close sequences for "Bob" and "pup" than young adults (Tukey, HSD, $p < .05$). There was also an age effect for displacement variability, $F(3, 112) = 5.52$, $p < .0001$, and velocity variability, $F(3, 112) = 2.84$, $p = .041$; however, there was no sex effect, $F(3, 112) < 1$, for either measure.

## Comparative Growth Curves

The results of the analyses collectively show that, compared to adolescents, young adults are consistently faster, have the larger movement amplitudes, and are less variable speakers. Because the spatial and temporal measures are expressed in different units (e.g., mm, sd, s, mm/s), it is difficult to compare growth curves across these disparate measures. Therefore, we chose to express each group's mean as a relative percent of the adult value, which serves as a reference or 100%. This technique allows us to make direct comparisons of the growth curves for different aspects of speech motor control and to analyze the rate of convergence onto adultlike values.

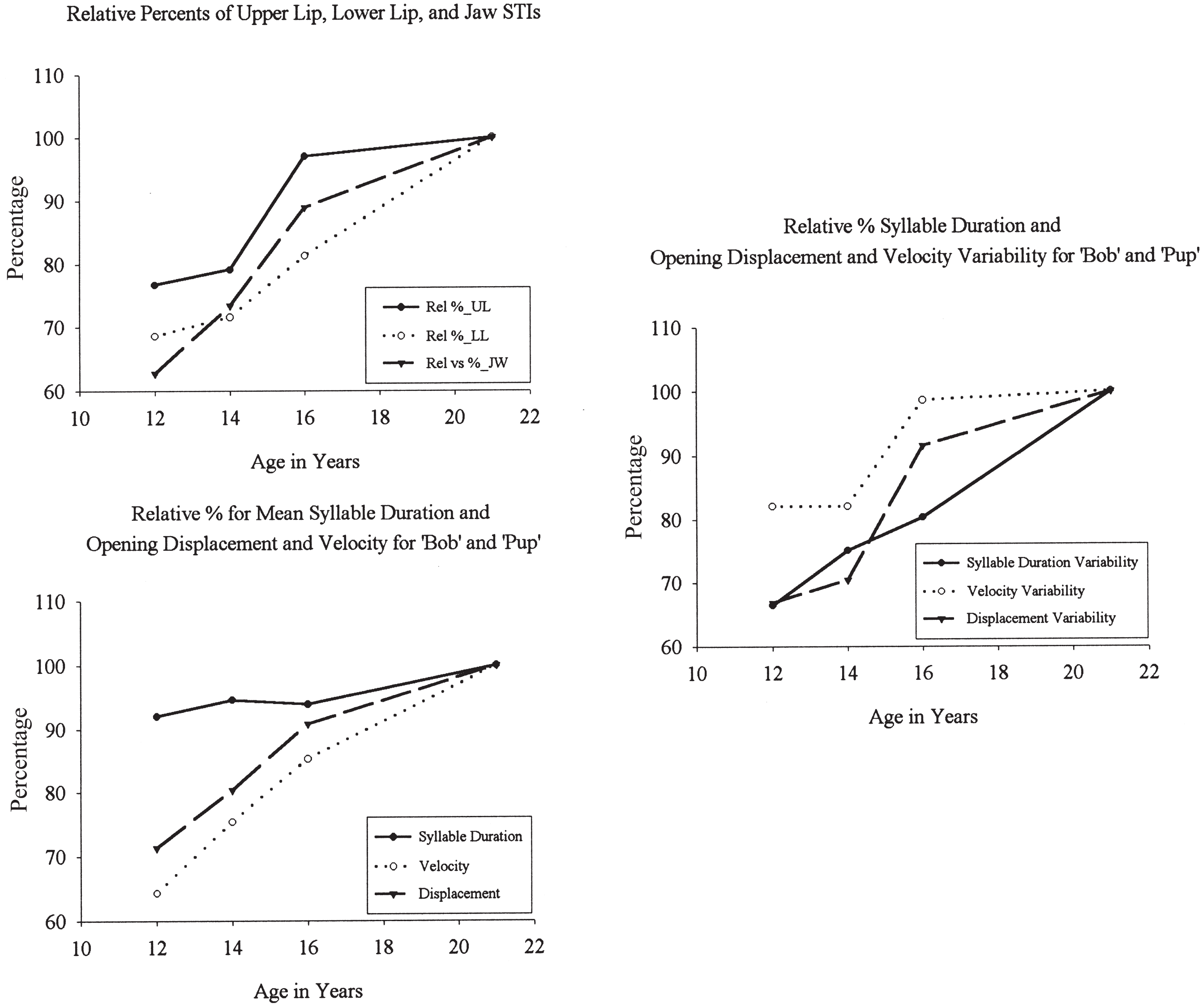
Figure 6 shows the relative percentages plotted for the various measures included in this study. Although jaw trajectories were consistently the least variable, the top plot of Figure 6 reveals that control of the three articulators develops in parallel, or that one articulator does not reach the adultlike level of variability before another. The middle plot of Figure 6 shows that by age 12 years, speakers have already reached 90% of the adult value for syllable duration, although the 12-, 14-, and 16-year-olds had significantly longer total movement and open-close movement durations than the young adults. Overall movement duration showed the same growth trajectory to adult values, so it was not plotted. In contrast, the 12-year-olds' movement amplitudes and velocities are only 60–70% of the adult values. The right plot of Figure 6 shows the variability of these measures also plotted in relative percentage of the young adult standard deviations. At age 16 years, temporal variability lags displacement and velocity variability; thus, mean duration and duration variability follow distinct developmental courses.

# Discussion

At present, there is not a widely accepted, comprehensive model for the acquisition of speech motor processes. Such a model would specify the factors contributing to speech motor development as the child matures and the time course of acquisition of various components of speech motor performance. Most experimental and theoretical attention has focused on babbling and the transition to speech production in infants and young children (e.g., MacNeilage & Davis, 1990). Although this period of acquisition and development of speech production is fundamentally important, a comprehensive account should include the entire developmental process until adultlike articulatory control and coordination for speech is achieved. By studying specific ontogenetic trends from infancy through adolescence, the properties of the speech subsystems and their potential interactions will be better understood. To our knowledge, there have been no studies of articulatory kinematics in children older than 12 years. Therefore, it is not known how marked cognitive and physical changes after age 12 affect speech production during adolescence, or when the developmental process is essentially complete. The results of the present study provide initial evidence supporting a protracted developmental time course for speech motor processes, one that extends past age 16 years.

Although each participant produced the phrase in an error-free and perceptually consistent manner, analyses of upper lip, lower lip, and jaw movements showed that speakers as old as 14 years had more variable articulatory trajectories compared to young adults. How should this finding be interpreted? Investigators also report increased variability in the speech production of disordered populations such as with those who stutter or have apraxia (e.g., Boutsen, Brutten, & Watts, 2000; Smith & Kleinow, 2000; Strand & McNeil, 1996). Increased kinematic variability in disordered speech production is attributed to a deficiency in the underlying motor control mechanisms. Clearly we do not suggest that adolescents have similar motor control deficits. Any measure of variability must be interpreted relative to the appropriate control populations, and typically developing adolescents are more variable in their speech motor behaviors than normal adults. Within classic developmental models, we conceptualize that the protracted time course and variability of speech motor behaviors is adaptive and appropriate for a system that is co-developing with other systems that are still undergoing maturation. In other words, adolescents are using more variable movement strategies to achieve perceptual goals. Thelen and Smith (1994, 1998) proposed that variability plays a constructive developmental function by imparting a greater degree of flexibility, thus allowing the speech motor system flexibility to compensate for ongoing changes in peripheral biomechanics and in central networks mediating speech production. This does not imply that adult speakers lack flexibility in the sense that they cannot compensate for brief perturbations during speech. Although we found evidence suggesting that adults have less variable articulatory trajectories, they are able to adapt to online perturbations such as a mechanical

**Figure 6.** These plots show each adolescent group's mean values expressed as a percent of the adult means. Thus the adult values for each dependent variable were set as 100%. The top left plot shows upper lip, lower lip, and jaw STIs. The lower left plot is open-close duration for "Bob" and "pup" and opening velocity and displacement for these syllables. The right plot shows the variability of these measures.



Relative Percents of Upper Lip, Lower Lip, and Jaw STIs

Relative % for Mean Syllable Duration and Opening Displacement and Velocity for 'Bob' and 'Pup'

Relative % Syllable Duration and Opening Displacement and Velocity Variability for 'Bob' and 'Pup'

stimulus applied to the lip during a speaking task (e.g., Abbs, Gracco, & Cole, 1984; Munhall, Lofqvist, & Kelso, 1994). Rather, our argument is that flexibility allows children and adolescents to use different strategies to achieve the same perceptual target. Because the speech motor system is undergoing continued development during adolescence, movement solutions need to adapt to these changes.

When interpreting the significance of increased movement trajectory variability, another important question to consider is how higher movement variability affects acoustic output. On the one hand, we can hypothesize that formant analyses would also be more variable in adolescence arising from greater instability of the articulatory movements that configure the vocal tract. On the other hand, it is possible that control over the individual effectors is coordinated, such that the dynamics of higher-level goals, such as lip aperture, are less variable than the trajectories of the individual effectors. Higher order targets presumably would have more significant effects on the acoustic output. Future studies of the dynamic coordination of articulatory structures will be necessary to address this question. In the acoustic domain, we know of no studies of dynamic formant tracking in adolescence, but analyses of formant steady states indicate that variability of formant frequencies is not mature until after 14 years (Lee et al., 1999). Essentially, however, the trajectory variability measures provide a window onto the dynamics of speech motor processes and reveal that adolescents' speech motor systems are not yet mature.

Our results do not support the idea that protracted variability in articulatory control in teenage speakers is the consequence of ongoing orofacial growth. If peripheral growth were the primary factor affecting the maturational course of oromotor control for speech, we would expect to see sex differences. Despite significant sex differences in structure sizes and developmental growth curves (e.g., females enter puberty before males, males have a late growth spurt, and adult males have larger vocal tract structures than adult females), there were no significant sex effects, or interactions of sex and trajectory variability values. Rather, our results suggest that changes in articulatory dynamics are not sex-specific and that full maturation is not predicted by the cessation of peripheral growth.

We hypothesized that the development of articulatory control would be distinctive for the lips and jaw, specifically that the consistency of jaw control (as measured by the STI) would be adultlike before control of the lips. Indeed, jaw trajectories at the phrase level showed the least variability across all age levels. We hypothesize that this is related to the fact that there are fewer degrees of freedom for jaw motion due to inherent biomechanical differences. The jaw comprises muscles that insert onto a bony framework, and the jaw-closing muscles are densely supplied with spindles (Smith, 1992). The lips have interdigitating muscle fibers that lack spindles and attach to soft tissues by small fascicles, allowing freedom of movement in all directions (Blair, 1986). Although jaw movements were the least variable, we found that the consistency of trajectory formation for the lips and jaw follow a parallel developmental time course during adolescence (Figure 3). Our original proposal that control of jaw trajectories would mature before the lips was derived from evidence suggesting that control of jaw movement develops earliest in young children (Green et al., 2000; Green et al., 2002; Lindblom & Sundberg, 1969; MacNeilage et al., 2000; MacNeilage & Davis, 1990). The general hypothesis is that the jaw open-close cycle provides a foundation on which lip and tongue motions for speech are added and elaborated.

Green et al. (2002) observed that 6-year-old children's jaw amplitude modulation patterns for /baba/ are more adultlike than their upper and lower lip patterns and that spatial and temporal coupling of the articulators continues to increase between age 6 years and adulthood. The present study addresses the variability of articulatory trajectories over repeated productions of a linguistically more complex phrase (compared to /baba/) in adolescents. The parallel development of articulatory control for lips and jaw in late development could be explained in part by overlapping cortical representations (Huang, Hiraba, Murray, & Sessle, 1988; McGuinness, Siversten, & Allman, 1980) and the requirement for parallel, interactive control of these structures during speech (Abbs, Gracco, & Cole, 1984; Munhall, Lofqvist, & Kelso, 1994). The parallel, protracted development of control of the articulators may reflect the maturation of these integrative neural systems. Finally, a caveat is necessary to close this discussion of trajectory variability. We studied only one sentence and were not able to record tongue motion. It is critical to determine whether our findings will be replicated in other speech samples and articulators.

## Overall Duration

We computed the average total movement sequence duration for each group to compare the overall speaking rate in teenagers and adults. A number of studies have established that as children get older, their speech segments decrease in duration (e.g., DiSimoni, 1974; Eguchi & Hirsh, 1969; Kent & Forner, 1980; Tingley & Allen, 1975). Surprisingly, we find that 16-year-olds are also speaking at significantly slower rates than young adults but that there was no significant increase in rate in the 12- to 16-year period. Plotting this data in relative percentages (Figure 6) revealed that by age 12 years, children are speaking at 90% of adult rate. Thus, at 12 years, children are almost achieving adultlike movement sequence durations, but then they reach a developmental plateau. Smith, Kenney, and Hussain (1995) also found that although children had longer 1–2 syllable durations than adults, the younger children in the group did not necessarily have longer durations than older children. The final 10% rate increase occurs late in development during the 16- to 21-year period. Logically, there is no biomechanical factor that would prevent 16-year-olds from speaking at adult rates. Like the composite trajectory variability data discussed above, the speaking rate growth curves again point to more central factors, perhaps related to speed of cognitive and language processes. In future studies it would be important to explore individual difference analyses to determine if, for example, precocious language development is associated with earlier maturation of speech motor processes.

Another important conclusion can be drawn from the analysis of overall duration of the movement sequence for the phrase: group differences in trajectory variability are not simply a reflection of differences in speech rate. The STI measure for each articulator significantly decreases between age 12 and age 16 years (Figure 3), although duration shows a plateau during this same period. Another dissociation between speaking rate and STI values occurs in the 16- to 21-year period.

## Temporal and Spatial Measures for Selected Movement Components

The STI computed on movement trajectories for the entire phrase and overall duration analyses revealed that adolescents have more variable articulatory trajectories and longer durations at the phrase level than do young adults. We also wished to determine whether control in the temporal and spatial domains follows similar time courses. The present data suggest that the answer to this question is "no." Both internal timing measures and overall durations were approximately 90% of adult values by 12 years, leveled off, then dropped to adult levels between 16 and 21 years. The developmental profiles for opening velocities and displacements for "Bob" and "pup" paralleled one another but were distinct from the duration measures. Mean displacement and velocity values reached 60–70% of adult values at age 12 years, and then showed steady increases between 12 and 21 years, with no plateaus (see Figure 6). Thus, from ages 12 to 16 years, teenagers on average are developing higher velocities and larger displacements, with no net change in movement time. On the basis of average group data, we are unable to speculate about individual movement strategies; however, future studies could address the hypothesis that the early acquisition of adultlike speech rate is accomplished by using a reduced movement amplitude and speed relative to the capabilities of the system. These results suggest that in terms of the mean target value, children reach temporal goals before spatial goals. Although 12-year-olds have reached 90% of the adult target rate, speakers as old as 16 years are still 20% more variable in timing than the adults. It appears that the adolescent speakers are sacrificing timing consistency in order to reach a faster/adultlike rate. The "speed-accuracy trade-off" is commonly reported for limb movements as well as higher-level tasks such as speech production (Dell, 1985; Mackay, 1971).

The analyses of variability, duration, velocity, and displacement collectively reveal that teenagers have smaller displacements, longer durations, lower velocities, and are more variable than young adult speakers. By age 16 years, orofacial growth has neared completion; thus, we hypothesize that experience combined with continued development of the neural processes mediating language processing and speech production could be responsible for these quantitative differences between adolescents and adults. As children get older, they also become more practiced speakers. Schmidt (1991) defined motor learning as "a set of processes associated with practice or experience leading to relatively permanent changes in the capability for skilled performance" (p. 153). Analogous to speech, handwriting is the result of integrated cognitive, motor, and biophysical processes (for review, see Van Galen, 1993). Developmental studies of handwriting show that the velocity of handwriting increases, whereas the amplitude and variability of movement trajectories decrease with subsequent age and practice (Hamstra-Bletz & Blote, 1990; Van Galen, 1993). Applied to speech production, increasing proficiency may also be quantified by decreases in spatiotemporal variability of trial-to-trial productions coupled with increased velocity (MacKay, 1981; MacKay, 1982; Smith et al., 2000; Smith & Goffman, 1998; Smith, Goffman, et al., 1995). However, speakers ultimately reach a plateau or a preferred or habitual speaking pattern, and subsequent increases in speed and/or decreases in variance are restricted by the biomechanics of the system (MacKay, 1981; MacKay, 1982).

We know that neurophysiological maturation of the brain (e.g., myelinization, neuronal density, and dendritic and synaptic growth) continues into mid-adolescence (Benes et al., 1994; Huttenlocher, 1990; Paus et al., 1999, 2001) and that the areas involved in language functions also follow a protracted developmental time course. Event-related potentials (ERPs) to aurally and visually presented linguistic stimuli provide evidence that neural systems governing language functions are still undergoing significant development until 15–16 years (Grossi, Coch, Coffey-Corina, Holcomb, & Neville, 2001; Holcomb, Coffey, & Neville, 1992; Neville, 1995). It is plausible that the lower velocity/longer duration strategy adopted by adolescents allows additional time for language processing as well as for organizing and issuing motor commands (Bullock & Grossberg, 1988; Smith & Gartenberg, 1984).

# Conclusion

In order to understand disorders affecting speech production, it is imperative to specify the time course for typical speech motor development. This is the first study to report speech motor development into late adolescence, as participants as old as 16 years had more variable articulatory trajectories, longer segment durations, smaller displacements, and lower velocities than young adults.

Perhaps it is not surprising that speech motor processes follow a much longer developmental course than we previously suspected. In fact, our findings mirror the overall biological development during this period; early and middle adolescence are marked by rapid physical growth and maturation, whereas late adolescence marks a period of refinement toward maturity (Steinberg, 1996). This study contributes to a more comprehensive model of speech development by demonstrating that peripheral growth factors are not the major determinant of the time course of late adolescent maturation, because girls do not reach adultlike performance before boys on any of the measures that we considered. This is in contrast to acoustic studies of speech production in which growth factors, particularly at the laryngeal level, play an important role in determining the age of adultlike performance. We hypothesize that central factors, for example cognitive and language processes, may play a significant role in prolonging the development of the speech motor processes studied.

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# Articulatory Movements in Adolescents: Evidence for Protracted Development of Speech Motor Control Processes

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