Speech movements do not scale by orofacial structure size

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Riely, Rachel R., and Anne Smith. Speech movements do not scale by orofacial structure size. J Appl Physiol 94: 2119–2126, 2003. First published February 7, 2003; 10.1152/japplphysiol.00502.2002.—The potential role of a size-scaling principle in orofacial movements for speech was examined by using between-group (adults vs. 5-yr-old children) as well as within-group correlational analyses. Movements of the lower lip and jaw were recorded during speech production, and anthropometric measures of orofacial structures were made. Adult women produced speech movements of equal amplitude and velocity to those of adult men. The children produced speech movement amplitudes equal to those of adults, but they had significantly lower peak velocities of orofacial movement. Thus we found no evidence supporting a size-scaling principle for orofacial speech movements. Young children have a relatively large-amplitude, low-velocity movement strategy for speech production compared with young adults. This strategy may reflect the need for more time to plan speech movement sequences and an increased reliance on sensory feedback as young children develop speech motor control processes.

speech motor development; speech motor control; size scaling principle; anthropometry; orofacial

Speech production is a complex motor activity that involves the coordination of the respiratory, laryngeal, and articulatory subsystems (4). The respiratory system provides the aerodynamic “power supply” for speech, driving the vibration of the vocal folds in the larynx, the voice source for speech production. The focus of the present investigation is the articulatory subsystem (the supralaryngeal airway), which acts as a dynamic acoustic filter on the energy supplied by the respiratory and laryngeal subsystems. Articulation refers to movement of the orofacial structures, such as the lips, tongue, and jaw (the articulators). Movements of the articulators dynamically alter the spatial configuration of the vocal tract. These dynamic changes in the configuration of the vocal tract cause changes in its acoustic resonant properties, and these modifications in vocal tract resonant properties result in the production of the various speech sounds of a language. In addition to its role as an acoustic filter, the articulatory subsystem also serves as a sound source for speech sounds that involve constrictions of the upper airway, for example, the friction noise in the “sh” segment or the burst that occurs when the lips are released to produce a labial consonant such as “p.” Thus the goal of articulation in speech production is to reach varying vocal tract shapes to achieve specific speech sound goals.

In the speech production process, therefore, precise spatial and temporal control of articulator motion is necessary. The fine, rapid movements of the articulators are accomplished by the contraction of many orofacial muscles. How these fine movements are controlled and coordinated to produce the rapidly changing vocal tract configurations needed for speech production is not well understood. Furthermore, the changes in motor control processes that occur with development have not been explored in detail. Researchers studying the principles of speech movement control have considered a number of hypotheses derived from the general motor control literature, including central control of movement patterns and interarticulator coordination, as well as the role of sensory feedback (22).

One putative, simple principle of speech movement control has received very little attention: the principle of movement scaling according to the general size of the orofacial structures. The operation of such a principle might be particularly relevant in explaining changes in speech motor control that occur over childhood and adolescence. It is reasonable to assume, for example, that children move their articulators smaller distances than adults because of their smaller orofacial structure sizes. However, it is common practice in speech motor development research to report measurements of speech kinematic data, such as displacement and velocity, without taking the participant’s orofacial structure size into consideration (16, 20, 27, 32). Direct kinematic investigations examining speech motor development generally have involved very few subjects. In addition, various articulators have been studied by using a variety of speech samples. As might be expected, the results of these studies are mixed. Therefore, no clear conclusion may be drawn concerning the question of whether speakers with smaller orofacial structures, e.g., young children and women, produce smaller speech movements (6, 16, 20, 23, 27, 32).

Studies of the control of motor behaviors such as locomotion, handwriting, and speech often reveal developmental trends of decreasing variability in both temporal and spatial parameters of movement and increasing velocity of movement with maturation (6, 8,
The development of locomotion is also characterized by a physical scaling principle evidenced by a linear increase in step length as limb length increases (2, 18, 29, 30, 33). This scaling principle indicates that biomechanical factors, such as structure size, directly influence kinematic parameters in locomotion. Conversely, handwriting does not show a size-scaling principle in development. In fact, an investigation examining the development of the control of handwriting in a large number of children revealed that movement amplitude decreased with maturation (8). These results indicate that maturation of underlying neural processes may have a greater effect on kinematic parameters of handwriting and other fine motor behaviors (19) than biomechanical factors.

As noted above, earlier studies of speech kinematic parameters and their potential relationship to orofacial structure size provide conflicting results. For example, Kuehn and Moll (15) reported a positive relationship between orofacial structure size, displacement, and velocity in adults, such that individuals with larger oral structure sizes exhibited greater displacements and velocities than individuals with smaller structures. In contrast, Smith and McLean-Muse (28) reported that young children and adults had similar peak velocities and articulatory displacement. The goal of the present study is to determine in a larger sample of participants whether speech movement amplitude and velocity are scaled to orofacial structure size. Thus we compare young children with adults, and, within an age group, we assess whether the larger individuals of the group make larger oral movements for speech.

METHODS

Subjects. Thirty 5-yr-old children and thirty adults between the ages of 20 and 22 yr (mean age = 21 yr) participated in this study. In both age groups, 15 of the participants were male and 15 were female. All participants spoke English as their first and primary language. All participants had no history of speech, language, or hearing disorders or neurological problems as determined by parent or self report. These subjects participated in data collection for multiple experimental protocols, as part of a larger project, that were not analyzed in the present investigation. Data from the present subjects are included in other papers that will be submitted in parallel with the present report.1

We selected the 5-yr-old group for the present study because younger children should clearly have smaller craniofacial structures than adults. Craniofacial growth is protracted and not complete until adolescence, but children’s facial structures are relatively large. For example, the 5-yr-old subjects that we studied had orofacial anthropometric measures that were on average already 83% of the adult size (see RESULTS). In contrast, their height is only 67% of the adult value. Also, earlier studies have reported mixed results for young children, with some studies showing equal amplitudes of movement in young children and adults, whereas other studies have indicated that young children move smaller distances (6, 23, 27, 28).

Screening and speech protocol. Each participant passed age-appropriate speech/language screening tests. All participants passed a pure tone hearing screening at 20 dB hearing level at 500, 1,000, 2,000, 4,000, and 6,000 Hz for each ear. All participants scored within normal range on the Oral Speech Mechanism Screening Examination-Revised, which was administered to assess the integrity of the anatomical structures and physiological functioning of the oral mechanism.

Participants produced two sentences: “Buy Bobby a puppy” (BBAP) and “Mommy bakes pot pies” (MBPP). These sentences were chosen for several reasons. They can be produced by young children, and they constrain superior-inferior lip and jaw movements, which provides a controlled, targeted movement trajectory for analysis purposes (25). The sentences predominantly contained consonants that require targeted movements of the lips and mandible, because we are limited to tracking the movement of these structures with our optical movement transduction system. The sentences were constructed to contain a variety of vowels, the primary determinant of the extent of lower lip/jaw opening. For example, “buy” and “bakes” contain diphthongs, which require relatively large, long duration opening movements, and the vowels in “pup” and “mommy” involve relatively smaller oral openings. The two sentences analyzed for this experiment were part of a set of five sentences produced by the participants as part of the larger project.

Kinematic data collection. The Optotrak 3020 motion measurement system was used to obtain the kinematic data. The Optotrak system tracks the three-dimensional movement of plastic markers containing infrared-emitting diodes with a spatial resolution of 0.1 mm. The session was audio taped with a digital audio tape recorder. The session was also videotaped.

Each participant sat in a chair positioned 1.5 m from the Optotrak camera system. The protocol was explained to each of the participants, and consent forms were signed before positioning of the Optotrak markers. As illustrated in Fig. 1, modified plastic sports goggles were placed on the partici-

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1 The speech kinematic data from the subjects in the present paper form part of a separate paper (31). This paper employs different analyses of the movement data collected from these and additional subject groups.
pant, and eight markers were attached to the skin surface as well as to the goggles with double-sided adhesive collars. The goggles were modified by adding two Plexiglas vertical rods to each side. One marker was placed in the center of the forehead, and four markers were positioned on the goggles. These five markers were used to calculate the head coordinate system. The goggles were used (rather than simply placing the reference markers on the forehead and cheeks, for example) because of the possibility of relative motion of the reference markers. If the subject raises his or her eyebrows, the forehead marker could move relative to other facial reference markers. Thus the modified sports goggles allowed us to have reference markers that will not move relative to one another, and the forehead marker ensured that the goggles were not moving relative to the subject’s head during data collection. If the reference markers move relative to each other, the head coordinate system cannot be accurately calculated.

For oral-movement tracking, one marker was attached to the upper lip at midline, one was attached to the lower lip at midline, and the jaw marker was attached to a splint at the midline under the mental symphysis of the mandible. The motion of each marker was sampled at 250 samples/s. Only the motion of the marker on the lower lip (which reflects the combined actions of the lower lip and jaw) was analyzed in this experiment. We chose to examine only the lower lip marker because this is the best indicator of oral-opening displacements. In adults, upper lip motion in speech is typically very small (1–5 mm) compared with the range of lower lip plus jaw motion (1–20 mm). Thus we reasoned that if a size-scaling principle were to be operating, it would be more likely observed in the movements of the lower lip/jaw complex, which has a larger operating range.

The participants were instructed to listen carefully and to repeat the sentences spoken by the experimenter. Each target sentence followed a sentence that provided an appropriate context for the stimulus. For example, the context sentence, “Bobby wants a puppy for his birthday,” was read by the experimenter. The experimenter then modeled the target sentence, BBAP, and asked the participant to repeat the sentence. No instructions were given concerning speaking rate or loudness; participants spoke at their preferred, habitual rate and intensity. The room in which the kinematic data were collected was not sound proofed, and the noise of the data collection process did not allow us to perform acoustic analyses of the audio signal. A small stuffed dog (or a pie plate for MBPP) was held up as a cue for the participants to repeat the target sentence. Ten accurate and fluent productions of each sentence were obtained for analysis. The number of sentence repetitions ranged from 10 to 15, and these were typically recorded in two 30-s trials, depending on each participant’s accuracy and fluency.

**Anthropometric measurements.** Anthropometric measures of the orofacial structures were made according to the procedures described by Farkas (5), and participants’ heights and weights were recorded. A spreading caliper was used for measurements projecting linear distances between landmarks on different planes. A sliding caliper was used for measurements of linear projective distances between landmarks on the same plane. A soft measuring tape was used for measurements of tangential linear distances taken along the skin surface.

During the anthropometric measurements, each participant sat on a stool and was instructed to look straight ahead. The experimenter marked the following landmarks with eyeliner pencil: the tragion (the notch on the upper margin of the tragus in the ear), the gnathion (the lowest medial point on the lower border of the mandible under the chin), and the subnasale (the midpoint angle underneath the nose where the nasal septum and upper lip meet). An additional reference point that was used but not marked with pencil was the gonion (the most lateral point on the mandibular angle at the edge of the lower jaw). These landmarks were used as reference points for the anthropometric measurements.

After locating the landmarks, four anthropometric measures were taken. A soft tape measure was used to obtain mandibular arc (measured between tragions following a curved line across the chin). The sliding caliper was used to measure the lower facial height (distance between the subnasale to the gnathion). The spreading caliper was used to obtain the lower face depth (from the tragion to the gnathion) and mandibular width (distance between gonions). Each measure was recorded twice. If the first two measurements were within 0.2 mm of each other, the first of the two measures was used in the analysis. If the two measurements differed by >0.2 mm, a third measurement was taken. In this case, the value closest to the third measure was used in the analysis (32).

**Data analysis.** To remove head-motion artifacts, movements of the lower lip marker were referenced to the head coordinate system for each participant by using software provided with the Optotrak system. The lower lip superior/inferior displacement signals were then imported into Matlab software (Mathworks) and analyzed with a custom program. A Butterworth filter was used to digitally low-pass filter the signals in both forward and backward directions at 10 Hz. Velocity of the lower lip motion was computed from the filtered displacement records by using a three-point difference technique.

Measures of displacement and velocity were used to characterize the participants’ articulatory movements during the production of the two sentences, BBAP and MBPP. Two types of measures were made: 1) displacement and velocity dynamic range computed across the entire lower lip multimovement sequence for the utterance and 2) measures of amplitude and peak velocity for selected single movements within each utterance. The displacement and velocity dynamic ranges were determined as the range that contained 80% of the points in the displacement or velocity trajectory for the entire utterance. Thus the upper and lower 10% of the points were excluded (see Discussion for the rationale of this analysis). The ranges obtained were averaged for the 10 repetitions of each sentence for each participant. Also, the mean duration of the movement sequence for the entire utterance was computed for each participant.

Movement amplitude and peak velocity were also measured for specific oral movements. Movement amplitude was measured for two lower lip opening movements per sentence (4 total). The selected movements for BBAP were the opening movement for “Bob” and the opening movement for “pup.” The movements measured for MBPP were the opening movements for “bakes” and “pot.” These opening movements were selected because they provide a range of oral opening targets for vowels, from relatively small (for “pup”) to large (“pot”) openings. To locate these single movements within the trajectory for the entire utterance, a computer program selected specified maxima and minima associated with each targeted opening movement. For example, for the opening movement for “Bob,” the program selected the second maximum and the second minimum points in the displacement record. The difference between these was calculated as movement amplitude. The corresponding opening peak velocity was automatically selected from the associated velocity record. If the program could not find the appropriate points, for example...
because there was more than the expected number of maxima or minima, the experimenter selected the points by eye. In the case of any questions about the accuracy of selecting the target movements, the audio signal associated with the selected movement could be played back. In ~7% of the cases for the 5-yr-old subjects and in <1% of the cases for the adults, movements were selected by the experimenter. Means of displacement and velocity were calculated for the 10 movements in the 10 repetitions per subject.

**RESULTS**

Reliability of measurements. For the 60 participants, there was a total of 660 anthropometric measurements. Of these 660 measurements, 18% were measured a third time.

A split-half reliability check was performed on the kinematic measurements by using an odd-even split. The data from the 10 trials of each target sentence for all subjects were divided into two groups of 5 trials with the odd trials in one group and the even trials in another. Correlations between the odd and the even means were computed across subjects for the subjects’ kinematic measurements by using an odd-even split. The mean of displacement and velocity were calculated for the 10 movements in the 10 repetitions per subject.

**Anthropometric measurements.** Table 1 includes the means and standard deviations of five anthropometric measurements for both groups. It is apparent that children’s orofacial structures and heights are significantly smaller than the adults’. Within the adult group, men are larger than women, but the 5-yr-old boys and girls have approximately equal values. On average, the four orofacial measurements in children were 83% of the adult measurements, in contrast to height, which was 67% of the adult value. A repeated-measures ANOVA was computed to determine effects of age and sex on the anthropometric measures. There was a significant effect of age [F(1,56) = 382.6, P < 0.0001], a significant effect of sex [F(1,56) = 26.71, P < 0.0001], and an interaction of age × sex [F(1,56) = 7.63, P = 0.008].

Whole utterance measurements: duration, amplitude, and velocity. Presented in Table 2 are the means and standard deviations of the overall durations for the entire lower lip movement sequence for BBAP and MBPP. Children’s total movement times were ~130% of the adult values. A repeated-measures ANOVA on total movement sequence duration indicated a highly significant effect of age [F(1,56) = 63.91, P < 0.0001], but no effect of sex [F(1,56) = 1.94, P = 0.17], and no interaction of age × sex [F(1,56) = 1.56, P = 0.22].

Figures 2 and 3 display typical displacement and velocity trajectories for a young adult and a 5-yr-old child. It is apparent that the trajectories have the same number of major movement components across the two participants. The means and standard deviations for displacement dynamic range are presented in Table 2. There was no reliable effect on movement amplitude of age [F(1,56) = 1.41, P = 0.24] or sex [F(1,56) < 1], and no interaction of age × sex [F(1,56) < 1]. Therefore, children have displacement dynamic ranges equivalent to those of adults. A significant effect of utterance was noted [F(1,56) = 7.16, P = 0.01], indicating a consistently larger displacement range for MBPP for both groups. The interaction of utterance × age narrowly failed to reach significance [F(1,56) = 3.78, P = 0.06]. The means and standard deviations for the velocity dynamic range are also presented in Table 2. It is apparent that the adults move considerably faster than the children. These group differences in velocity were significant [F(1,56) = 37.9, P < 0.0001], but there was no effect of sex [F(1,56) < 1] and no interaction of age × sex [F(1,56) < 1]. Effect of utterance was not significant [F(1,56) = 1.45, P = 0.23]; however, there was an interaction of utterance × age [F(1,56) = 10.49, P = 0.002]. This interaction indicates that scaling of veloc-

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<th>Table 1. Mean anthropometric measurements and percentages</th>
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<td>Male child/adult%</td>
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Values are means ± SD.

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<th>Table 2. Mean duration, displacement dynamic range, and velocity dynamic range for BBAP and MBPP</th>
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<td>5-yr-old subjects</td>
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<td>Young adult</td>
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Values are means ± SD. BBAP, subjects said, “Buy Bobby a puppy”; MBPP, subjects said, “Mommy bakes pot pies.”

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ity for the two sentences was not consistent between groups. Children had a larger velocity dynamic range for MBPP, whereas adults had a larger velocity dynamic range for BBAP.

Single movement measurements: amplitude and velocity. Plotted in Fig. 4 are the mean displacements of each of the four opening movements for the adults and 5-year-old subjects. Clearly, there is a trend for smaller displacement for the 5-year-old subjects in all four opening movements. However, this trend was not significant \( F(1,56) = 3.05, P = 0.09 \). There was no effect of sex \( F(1,56) < 1 \) and no interaction of age \( \times \) sex \( F(1,56) < 1 \). A significant effect of syllable was noted \( F(3,168) = 94.9, P < 0.0001 \), as well as an interaction of syllable \( \times \) age \( F(3,168) = 2.83, P = 0.04 \), indicating that the modulation of amplitude across the four opening movements was different between age groups.

In Fig. 5, the average peak velocities of each of the four opening movements are plotted for the adults and 5-year-old subjects. The adult peak velocity is clearly higher than the peak velocity of the children for these opening movements, and this difference was significant \( F(1,56) = 30.3, P < 0.0001 \). There was no effect of sex \( F(1,56) < 1 \) and no interaction of age \( \times \) sex \( F(1,56) < 1 \). There was an effect of syllable \( F(3,168) = 38.5, P < 0.0001 \) and an interaction of

Fig. 2. Displacement (top) and velocity (bottom) trajectories for a typical adult speaker for the two sentences. The words are lined up approximately with the lower lip/jaw movements that would occur during their production. For both sentences, the first and last opening movements are truncated (e.g., the left plot starts with the first opening movement for “Buy” in mid-movement) because the peak velocities of the first and last movement for the sentences were used to segment the data for analysis.

Fig. 3. Displacement (top) and velocity (bottom) trajectories for a typical 5-year-old subject for the two sentences. The words are lined up approximately with the lower lip/jaw movements that would occur during their production. For both sentences, the first and last opening movements are truncated (e.g., the left plot starts with the first opening movement for “Buy” in mid-movement) because the peak velocities of the first and last movement for the sentences were used to segment the data for analysis.
speech production, adults would move these larger structures significantly farther than children would. However, there was no evidence to support a size-scaling principle of these kinematic parameters according to the size of the effectors. Statistically, the children moved their articulators the same distances as adults. However, the 5-yr-old subjects made these movements at significantly lower velocities than adults. Thus, on the basis of between-group statistics, the children appear to have a large-amplitude, low-velocity speech movement strategy compared with young adults.

The between-group analyses also revealed a significant age × sex interaction for the anthropometric measures. The orofacial structures of adult women are on average smaller than those of adult men, whereas 5-yr-old boys and girls are equal in orofacial structure size. There were, however, no significant age × sex interactions in any of the kinematic measures. This was true for both the whole utterance measures (duration, displacement dynamic range, velocity dynamic range) and the single-movement measures. These results demonstrate that, although young adult women have smaller orofacial structures, they produce speech movements of equal amplitude and velocity to those of men. The results of the within-group correlations between the anthropometric measures and the kinematic measures are consistent with the findings of the between-group analyses. Almost all of the correlations failed to reach significance, which consequently provided no support for a size-scaling principle for displacement or velocity. Thus, in contrast to Kuehn and Moll (15), who examined a very small subject pool (n = 5 adults), we do not find evidence for a sex-related size-scaling principle for speech movements.

Our subject pools were relatively large for a speech kinematic study, but were the participants represen-

**DISCUSSION**

The results of this experiment clearly suggest that speech movement amplitude does not follow a size-scaling principle and that speech motor control is, therefore, more similar to handwriting than to locomotion (2, 8, 18). We examined this issue by using both between-group and within-group analyses. As expected, the between-group analyses indicate that young children's orofacial structures were smaller than the adult structures. If a scaling principle is applied to
tative of the general population? Farkas (5) compiled normative anthropometric data on the head and face, height, and weight of 2,326 Caucasian North Americans ranging in age from newborn to young adult. The differences between the present measurements (mandibular arc, lower facial height, lower face depth, mandibular width, and stature) and Farkas’ norms were no greater than 4%. Thus we assume that our samples of children and adults are representative of the general Caucasian North American population.

Another methodological issue concerns the rationale for our selection of the measures of displacement and velocity, particularly our use of 80% of the movement trajectory to determine dynamic ranges. In our initial approach, the whole utterance measures of displacement and velocity dynamic range were determined as the maximum minus the minimum point within the displacement and velocity trajectories for BBAP and MRPP. It became apparent that the location of the points selected with this method differed between adults and children and that the children displayed more variability in the location in the movement sequence at which maximum and minimum points were chosen. In other words, the specific movement components contributing to this dynamic range differed in children and adults, and within the child group were more variable between subjects. Therefore, comparisons of the two groups on this measure might be misleading. The dynamic range analysis was then modified to exclude the upper and lower 10% of points within a single trajectory, so that the measures would be comparable across the two subject groups. The single-movement measurements were chosen to complement the dynamic range analysis by providing movement amplitude and peak velocity information about specific movements that were the same for both age groups.

The results of the dynamic range and the single movement measurements provide a consistent picture across both utterances of a relatively large-amplitude, low-velocity strategy of speech production for children compared with young adults. Previous direct kinematic studies provided limited support for the idea that children use a low-velocity, large-amplitude movement strategy of speech production (23, 27). The data from the present study indicate that, although young children move their articulators comparable distances to adults during speech production, they make these movements at a significantly slower speed. An increase in movement amplitude coupled with a decrease in velocity results in a slower rate of speech. In fact, our measures of overall movement trajectory duration (mean durations for the 2 sentences were 1.24 and 1.38 s for the 5-yr-old subjects, and 0.87 and 0.96 s for the adults; Table 2) suggest that the children’s rates must increase by 30% to reach the adult value. A recent paper from our laboratory (31) demonstrates that this slower speech rate persists into adolescence. With more time to produce speech, one possibility is that children are allowed additional time to organize and perform the cognitive and linguistic aspects of speech production that may be more automatic for adults. Also, the premotor planning processes might be slower in children.

Another possible benefit of an increased duration in speech production resulting from a low-velocity strategy is that children take advantage of the increased amount of time to use position-sensitive feedback during speech production. Adams et al. (1) examined the effect of speaking rate on the velocity profile of the lower lip and tongue tip movement in five adults. They found that a slow speaking rate resulted in less symmetrical, multipeaked velocity profiles, whereas faster speaking rates resulted in symmetrical, single peaked profiles. Using Bullock and Grossberg’s (3) model of motor control, Adams et al. suggested that, as the speed of movement decreases, the potential contribution of information provided by feedback increases. In terms of the classic speed-accuracy trade off (34), this finding is consistent with a movement control strategy in young children in which accuracy is weighted more heavily than speed. Earlier studies have clearly established that, compared with adults, children are less consistent from trial to trial in generating speech movement trajectories (6, 23, 31). If the motor system of the young child is inherently less consistent, he/she may use a slower movement speed to preserve accuracy. To our knowledge, studies of changes in speech motor control in children as a function of changing speech rate have not been done. Children may use a low-velocity, closed-loop strategy for speech production to make use of feedback on the position of their articulators and to decrease the probability of errors, whereas adults use a more rapid, open-loop strategy. That is, speech movements may be more automatic for adults, because the nature in which target positions are achieved has been well established by years of practice.

The goal of speaking is to produce an acoustic signal that can be interpreted by a listener. As in handwriting (8), the size of the effectors does not seem to have a significant effect on the amplitude of oral movement for speech. It could be speculated that there is an acoustic advantage for a relatively large oral opening for young children. This larger oral opening would contribute to increased intensity of the speech acoustic output. Increased overall intensity of the speech signal could be advantageous in offsetting the higher fundamental frequency and formant frequencies produced by young children with small vocal folds and relatively short vocal tracts. The same speculation could be made for adult females. Although we did not measure the intensity of the speech produced by our participants, studies of the acoustic properties of speech produced by adults and young children have shown that young children produce speech of equal loudness compared with adult subjects in a laboratory testing environment (11).

In conclusion, the maturation of the neural systems underlying language processing and the production of speech follow a protracted time course of cortical, dendritic, and synaptic development (10, 12, 17) continuing into the mid-teen years. This pattern of neural
development suggests that adult-like motor control over fine movements may not be possible for young children, and a recent study (31) suggests that some aspects of oral motor control for speech are not mature even at an age of 16 yr. Therefore, children learning to produce speech and to write are less able to precisely control their motor output. This lack of precise control of movement coordination may explain why relatively large hand movements are seen in children learning to write (8) and relatively large movements of the orofacial structures are observed in children during speech production. The nonfluent writing strategy of young children is also partly attributed to a closed-loop strategy, such that sensory feedback (i.e., visual guidance) is needed to produce and correct the movements (8). Young children developing speech motor control processes may rely more on sensory feedback to control orofacial movements and may need more time for language formulation and planning; thus they adopt a slow, large movement strategy in speech production.

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REFERENCES