ABSTRACT: Speech production is a highly skilled behavior that requires rapid and coordinated movements of the orofacial articulators. Previous studies of speech development have shown that children have more variable articulatory movements compared to adults, and cross-sectional studies have revealed that a gradual transition to more stable movement patterns occurs with age. The focus of the present investigation is on the potential role of short-term changes in speech motor performance related to practice. Thus we developed a paradigm to examine the influences of phonological complexity and practice on children (9 and 10-year-olds) and adults' production of novel nonwords. Using two indices that reflect the degree of trial-to-trial consistency of articulatory movements, we analyzed the first and last five productions of the novel nonwords. Both children and adults accurately produced the novel nonwords; however, children showed a practice effect; their last five trials were more consistently produced than their first five trials. Adults did not show this practice effect. This study provides new evidence that children show short-term changes in their speech coordinative patterns with practice. In addition, the present findings support the contribution of neuromotor noise or background, inherent variability to speech motor development.

INTRODUCTION

Speaking is a highly skilled motor behavior resulting from coordinative control of the respiratory, laryngeal, and orofacial systems. At the same time, cognitive and language networks are actively formulating the ideas that we wish to convey, while the semantic, syntactic, and phonological aspects of our messages are encoded. Studies of the development of motor control for speech production demonstrate that children tend to have slower speech rates and more variable amplitude, velocity, timing, and patterning of their articulatory movements (i.e., upper lip, lower lip, and jaw) compared to adults (Goffman & Smith, 1999; Green, Moore, Higashikawa, & Steeve, 2000; Green, Moore, & Reilly, 2002; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Smith & McLean-Muse, 1986; Smith & Zelaznik, 2004; Walsh & Smith, 2002). A transition to more stable movement patterns and faster speech rate occurs very gradually with age, and adult performance is not reached until 14–16 years (Smith & Zelaznik, 2004; Walsh & Smith, 2002). These cross-sectional studies generally attribute this improvement in speech motor skills to long-term motor learning, generally related to developmental stage.

Earlier studies of speech motor development from our laboratory and others focused on the separate movement trajectories of the upper lip, lower lip, and jaw, but we know from studies of natural (e.g., Gracco & Lofqvist, 1994; Nitttrouer, Munhall, Kelso, Tuller, & Harris, 1989; Tuller & Kelso, 1984) and perturbed speech (e.g., Kelso &
Tuller, 1983; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984; Munhall, Lovqvist, & Kelso, 1994) that articulatory movements must be dynamically coordinated to produce speech.

Bernstein (1967) defined the development of motor coordination as “the process of mastering redundant degrees of freedom of the moving organ, in other words its conversion to a controllable system” (Bernstein, 1967, p. 127). The degrees of freedom for movement are reduced through the soft assembly of muscle synergies, which are hypothesized to be the fundamental units of motor control. Muscle synergies consist of collectives of motor neurons that control assemblies of muscles to achieve movement goals (Bernstein, 1967; Gelfand, Gurfinkel, Tsetlin, & Shik, 1971).

In order to study the development of oral motor coordination for speech, Smith and Zelaznik (2004) examined the maturation of functional muscle synergies. They examined a higher-order synergy, which involved the coupling of three effectors, the upper lip, lower lip, and jaw to control oral opening and closing (i.e., lip aperture), and a lower-order synergy, the coupling of the lower lip and jaw. In this large, cross-sectional study of 240 children aged 4 through 14 years and young adults, they found that, on average, children had higher variability of articulatory coupling, while adults relied on extremely stable movement synergies. Both synergies became less variable with age; however, for all age groups the lower-order synergy was more variable. Smith and Zelaznik (2004) hypothesized that there are hierarchical levels of motor control for speech production, and the lower lip/jaw synergy is subordinate to the higher order goal of control of oral opening. This is logical, because in terms of the acoustic output for speech, the distance between the lips is a highly relevant parameter (Stevens & House, 1955); however, the relative positions of the lower lip and jaw are not.

Less refined timing, greater variability, and decreased accuracy of limb motor behaviors, including simultaneous clapping and stepping (Getchall & Whitall, 2003), goal-directed reaching (Konczak, Jansen-Osmann, & Kalveram, 2003; Takahashi, Nemet, Rose-Gottron, Larson, & Cooper, 2003; Yan, Thomas, Stelmach, & Thomas, 2000), bimanual circle-drawing tasks (Robertson, 2001), repetitive finger tapping (Greene & Williams, 1993; Inui & Katsura, 2002), and pointing (Bourgeois & Hay, 2003). In the developmental limb motor control literature, investigators have proposed that different sources contribute to the variability in children’s performance. One source of variability has been hypothesized to be a global factor, neuromotor noise. It is postulated that motor commands are issued against a background of noise arising from a combination of sources (Crossman & Szafran, 1956; Fitts, 1954; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Welford, 1956). For example, the motor neuron pools controlling muscle activation have many sources of inputs, which in the developing system could generate higher levels of “noise” or motor neuron activity unrelated to the movement goal. Inherent noise constrains movement proficiency and inevitably affects children’s motor performance. Gradually the noise decreases over the course of development, resulting in adultlike motor performance (Smits-Engelsman & Van Galen, 1997; Yan et al., 2000). Noise could also be the result of variable motor neuron recruitment mechanisms for achieving the movement goal (Jones, Hamilton, & Wolpert, 2002), or ongoing developmental changes within an organism (Manoel & Connolly, 1995); for example, skeletal and craniofacial growth continues well into puberty (see Kent & Vorperian, 1995; Steinberg, 2004 for reviews).

Neurological development also follows a protracted developmental time course. The maturation of neural pathways, dendritic arborizations, synaptic connections, axonal diameter, and myelination, is also not complete until later on in adolescence (Benes, Turtle, Khan, & Farol, 1994; Huttenlocher, 1990; Paus et al., 2001). Thus, noise in the neuromotor system, which arises from a variety of sources, could affect the integrity of neural transmission (Fietzek et al., 2000; Muller & Homberg, 1992), motor planning (Smith & Goffman, 1998; Harris & Wolpert, 1998), and ultimately, patterns of muscle activation (Engelhorn, 1988; Wohldr & Smith, 2002). Although the concept of neuromotor noise has not been specifically invoked in earlier studies of speech motor control and coordination, interpretation of the data are consistent with the neuromotor noise concept (Sharkey & Folkins, 1985; Smith & McLean-Muse, 1986; Smith & Zelaznik, 2004; Walsh & Smith, 2002).

Deutsch and Newell (2002, 2003, 2004) proposed another perspective on developmental motor control based upon their studies of the control of isometric grip. They argued that practice and the utilization of feedback allow children to reduce variability and adapt to task requirements. Although children may be more variable initially than adults on motor tasks, they are able to adapt their motor performance and become more accurate and faster within a short period of time (i.e., within an experimental session) on goal directed arm and hand movements (Engelhorn, 1988; Manoel & Connolly, 1995; Thomas, Yan, & Stelmach, 2000), on an isometric force tracking task (Lazarus, Whitall, & Franks, 1995), when required to adapt to an externally applied limb perturbation (Konczak et al., 2003; Takahashi et al., 2003), and to visual perturbation during a drawing task (Ferrel-Chapus, Hay, Olivier, Bard, & Fleury, 2002). These changes in movement proficiency that occur in the short-term cannot be accounted for by decrements in system noise due to
physiological constraints, as these would be expected to change gradually over the course of development (Takahashi et al., 2003). In their review article, Newell, Liu, and Meyer-Kress (2001) proposed that there are different time scales operating in motor development, such that some changes operate over long periods and have persistent effects, while other changes occur over a short period, such that changes may be observed in a single experimental session. No earlier studies of speech motor control have examined the potential occurrence of such short-term changes in performance in children or adults after practice.

To summarize, Smith and Zelaznik (2004) found that adults have highly stable movement synergies for speech. Adults are highly practiced speakers and have low inherent noise variability. Children, on the other hand, are in the process of acquiring functional synergies for speech; they are less practiced and have higher inherent noise variability. Short-term changes in movement proficiency may offer important, albeit overlooked, clues into the development of mature motor profiles. In this experiment we investigate overall differences in movement performance and potential, short-term changes in 9- and 10-year-old children and adults’ higher- and lower-order articulatory synergies during a nonword repetition task. We chose to have the participants produce novel nonwords to minimize familiarity effects. The task requires the participant to convert the acoustic signal into elemental linguistic units, hold the ordered strings of units in phonological memory, and then generate and issue articulatory motor commands. Thus, this task provides an ideal opportunity to observe developing and mature speech motor systems engaged in learning new words (Dollaghan & Campbell, 1998; Gathercole & Baddeley, 1989).

METHOD

Participants

Participants were 20 young adults between the ages of 18 and 31 years ($M = 23; 0$ years) and 20 children between the ages of 9 and 10 years ($M = 10; 2$ years range 9; 1–10; 11), with 10 males and 10 females in each group. We chose the 9–10 year age group because Smith and Zelaznik (2004) found that children at this age are still highly variable in their articulatory coordination. Further, at this age they could be expected to successfully perform a novel nonword repetition task with increasingly longer and complex items.

The participants performed within age-appropriate limits on a speech, language, and oral-motor screening battery [Clinical Evaluation of Language Fundamentals Screening Test-Third Edition (CELF; Semel, Wiig, & Secord, 1996) for the 9–10-year-old participants, the Text of Adolescent and Adult Language (TOAL-3; Hammill, Brown, Larsen, & Wiederholt, 1994) for the young adults, and the Oral Speech Mechanism Screening Evaluation-Revised (OSMSE-R St. Louis & Ruscello, 1987) for all participants]. Each participant passed a hearing screening with pure tones administered binaurally through headphones at 20 dB HL at 500, 1,000, 2,000, 4,000, and 6,000 Hz. Additionally, the participants or caregivers answered screening questions to verify that Standard American English was the first and primary language and that they had no known speech, language, or learning disabilities. Finally, the participants or caregivers completed a developmental and medical case history form, and signed a consent form. A prospective participant was excluded if he/she failed any portion of the screening assessments, wore orthodonture, was taking medications expected to affect motor or cognitive performance, or suffered a traumatic head injury. The Purdue University Committee on the use of Human Subjects (IRB) approved all recruitment and experimental procedures.

Apparatus

The participants were seated in front of an Optotrack 3020 three-camera system (Northern Digital). This system records articulatory movements by tracking the positions of small (7 mm) infrared emitting diodes (IREDS) that are attached to the surface of the skin with adhesive collars. 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 overlaying the inferior aspect of the mandibular symphysis. In order to eliminate head motion artifact, head motion was recorded, and a three-dimensional head coordinate system was constructed for each participant (Smith, Johnson, McGillem, & Goffman, 2000). Superior-inferior upper lip, lower lip, and jaw movements were then calculated relative to the head coordinate system. Motion of each IRED was sampled at 250 Hz.

Protocol

After positioning the IREDS, the experimenter explained the protocol, informing a participant that the task required saying several “new words.” These nonwords were adapted from those used by Dollaghan and Campbell (1998), so that they contained more labial sounds (e.g., m, p, b), which make lip and jaw movements highly constrained to reach the consonant targets. The nonwords increased in both length (from one to four syllables) and phonological complexity: /maeb/pronounced “mab” (rhymed with “lab”), /maeb? aIb/ pronounced “mab-shibe” (second syllable rhymed with “bribe”), /maebfaI? eIb/ pronounced “mabfieshabe” (second syllable rhymed with “shake”), and /maeb? eitaId?Ib/pronounced “mabshatiedoib” (the diphthong vowel in the last syllable rhymed with the diphthong in “void”). A fifth nonword, /maebtibibi/ (pronounced “matbteebeebee”), was included as a length control as it has four syllables but is not as phonologically complex. Each word began with the same syllable and ended with a /b/ in order to provide
consistent starting and ending points to segment the articulatory movement trajectories for analysis.

To ensure that participants could correctly produce the novel target words before data collection started, each participant heard a recorded model of a nonword presented via loudspeaker and then attempted to repeat it. Stress or emphasis was consistently placed on the initial syllable (mab) of each nonword model. The duration of each nonword model was as follows: 400 ms for “mab,” 900 ms for “mabshibe,” 1,100 ms for “mabhfeshabe,” 1,200 ms for “mabhshaytaidoib,” and 1,150 ms for “mabhstebeebee.” The experimenter determined whether the participant’s nonword production was perceptually accurate. If not, the model of the nonword was repeated. Each participant was required to produce each nonword correctly two consecutive times before data collection began. During data collection, the participants heard the recorded model for each nonword, then produced the nonword embedded in the carrier phrase, “Bob says ____ again” using their preferred rate and loudness. The five nonwords were randomized within a block of five productions for presentation. After each production attempt, the experimenter paused for approximately 2 s before playing the model for the next nonword within the block. The participants were given a short break (approximately 1 min) after producing six blocks (with five nonwords in each). Because the first production of each nonword was not included in the analysis, each subject produced each nonword at least 11 times. However, data collection continued until ten fluent exemplars of each nonword and carrier phrase had been obtained. A fluent production of the entire phrase was judged to be free from errors (i.e., substitutions, omissions, additions, distortions, disfluencies, aberrant prosody, or inappropriate pauses) by one experimenter “on-line” and later during data analysis by a second experimenter.

**Data Analysis**

After discarding the first trials of each nonword, kinematic analysis was completed on the first five and last five fluent productions of each nonword for each participant. The upper lip, lower lip, and jaw movements associated with fluent productions were corrected for head motion artifact and then imported into MATLAB (Mathworks, 2005) signal processing software for analysis. An interactive program that offered a simultaneous display of the superior-inferior displacement and velocity records from the lower lip for each fluent production was used to extract the embedded nonwords from the carrier phrase. The experimenter segmented each nonword by selecting consistent kinematic landmarks from the velocity records with a computer mouse. Starting points were chosen as the peak velocity of the opening movement for the /m/ in “mab,” while end points were selected as the peak lower lip opening velocity for the /b/ that ended all five nonwords (Fig. 1). The lower lip start and end points were then used to segment the data from the nonnormalized upper lip and jaw signals, and were also used to compute the duration of the total movement trajectory of each nonword. Because the speech acoustic signal was digitized at 7.5 kHz with an A/D unit synchronized to the Optotrak system, the experimenters were able to listen to each extracted interval to ensure that it was an acceptable production and that they selected the appropriate start and end points, without inadvertently cutting off the signal.

From the first five and last five displacement-time waveforms of the upper lip, lower lip, and jaw for each of the five nonwords, two difference measures were obtained according to methods described by Smith and Zelaznik (2004):

1. **Lip Aperture Synergy (Higher-order):** Lip aperture was calculated by a sample-by-sample subtraction of the lower lip displacement signal from the upper lip displacement signal. This difference signal reflects the coordination of the upper lip, lower lip, and jaw to produce the target oral opening as a function of time.

2. **Lower Lip/Jaw Synergy (Lower-order):** The lower lip/jaw synergy was calculated by a sample-by-sample subtraction of the jaw displacement signal from the lower lip displacement. This difference signal reflects the relative actions of the lower lip and jaw as a function of time.

In order to examine differences in articulatory coordination between the groups and to document potential changes in proficiency that occurred with practice, lip aperture, and lower lip/jaw variability indices were computed using the first five and last five productions of each nonword for each subject. These indices quantified the degree of combined spatial and temporal variability in the first/fifth five sets of trajectories for each nonword production. The variability indices were calculated by

![FIGURE 1 Sample raw data: These plots show original data from an adult participant during one production of the nonword “mabhshaytiedoib.” Displacement trajectories from the upper lip (UL DISP), lower lip (LL DISP), and jaw (JW DISP) are plotted. The lower lip velocity signal (LL VEL) is shown above. The lower lip velocity signal was used to segment the data for all utterances produced by each speaker. In this figure, the vertical dotted lines pass through the velocity peaks of the initial and last opening movements for the nonword. The time between the dotted lines represents the duration of the overall movement sequence for each nonword. The segments of the target nonword are shown approximately at the places where they occur along the lower lip displacement trajectory.](image-url)
time- and amplitude-normalizing the lip aperture and lower lip/jaw movement trajectories (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995; Smith et al., 2000; Smith & Zelaznik, 2004). Figure 2 illustrates this procedure for data from one 9-year-old participant producing the nonword “mabfieshabe.” The variability indices were calculated by time and amplitude-normalizing the lip aperture and lower lip minus jaw movement trajectories (Smith et al., 1995, 2000; Smith & Zelaznik, 2004). As the middle panel of Figure 2 illustrates, for time-normalization, a cubic spline procedure was used to project each displacement record onto a constant axis length of 1,000 points. Each record was amplitude normalized by subtracting the mean of the displacement signal and dividing by its standard deviation. Finally, as shown in the bottom panel of this figure, the standard deviation of the five early and five late time- and amplitude-normalized lip aperture or lower lip/jaw synergy trajectories were calculated at fixed 2% intervals in relative time. These 50 standard deviations were summed resulting in a coordinate index for the lip aperture and for the lower lip/jaw synergy. Lower values of the coordination indices reflect convergence of the difference trajectories over the five trials.

A repeated-measures ANOVA with the between-subject effect ‘group’ (adults vs. children), and within-subject effects of ‘nonword’ (5 nonwords), ‘practice’ (first five vs. last five productions), and ‘synergy’ (lip aperture vs. lower lip/jaw) was used to detect differences in speech motor consistency. We did not anticipate sex effects in these age groups, as they were only present in the Smith and Zelaznik (2004) study for 4 and 5-year-old children. The total duration of each nonword was computed from the lower lip marker.

The effect of duration was analyzed with a repeated measures ANOVA with between-subject factor of group, and within-subject factors of nonword and practice. All F-values are reported utilizing the Greenhouse-Geisser probability adjustment to account for the possibility of statistical error resulting from making multiple measurements on the same participant. Effect sizes, indexed by the partial-eta squared statistic ($\eta^2$), are reported for all significant effects.

RESULTS

Behavioral Data

Table 1 lists the means for the total number of productions and the number of errors including substitutions, omissions, additions, distortions, disfluencies, aberrant prosody, or inappropriate pauses that the children and adults made on each nonword and/or carrier phrase. The 9 and 10-year-olds produced each nonword one more time, on average, than the adults. This difference was significant, $F(1, 38) = 4.13, p = .049$. Children’s mean number of errors was slightly higher on four of the five nonwords when compared to the adults. Table 1 presents the mean number of total productions and mean number of errors with standard errors in parentheses for children and adults for each nonword.

Table 1. Mean Number of Total Productions and Mean Number of Errors with Standard Errors in Parentheses for Children and Adults for Each Nonword

<table>
<thead>
<tr>
<th>Nonword</th>
<th>Mean Total Productions (SE)</th>
<th>Mean Number of Errors (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Children</td>
<td>Adults</td>
</tr>
<tr>
<td>mab</td>
<td>14 (.1)</td>
<td>13 (.2)</td>
</tr>
<tr>
<td>mabshibe</td>
<td>15 (.3)</td>
<td>14 (.3)</td>
</tr>
<tr>
<td>mabfieshabe</td>
<td>16 (.6)</td>
<td>15 (.5)</td>
</tr>
<tr>
<td>mabshaytiedoib</td>
<td>17 (.7)</td>
<td>16 (.7)</td>
</tr>
<tr>
<td>mabtseebeebe</td>
<td>14 (.3)</td>
<td>13 (.7)</td>
</tr>
</tbody>
</table>
nonword stimuli compared to adults; however, this difference was not significant, \(F(1, 38) = 3.40, p = .07\).

### Coordination Indices

Tables 2 (lip aperture) and 3 (lower lip/jaw) present the mean (and standard error) of the coordination indices for the first and last five productions of the five nonwords by children and adults. To provide some illustrations of representative data from individual participants, we include samples of one child’s (Fig. 3) and one adult’s (Fig. 4) data. Figures 3 and 4 show sets of time- and amplitude-normalized lip aperture (top) and lower lip/jaw synergy trajectories (bottom). For both participants, the panels on the left are the first five productions, while the right panels are the last five productions of the nonword, ‘mabshaytiedoib.’ The top two panels show lip aperture trajectories, while the bottom two panels are lower lip/jaw synergy trajectories. The coordination indices for the lip aperture and lower lip/jaw synergies are shown in the panel insets. These indices reflect the degree of variability over repeated trials; therefore, a higher score signifies higher variability for speech movement patterning. As illustrated by these individual records, we see an effect of practice for the children; lip aperture variability decreases for the last five trials, but the practice effect was not seen in the adult participants. However, no trend is apparent for children or adults lower lip/jaw trajectories.

The overall ANOVA computed for both lip aperture and lower lip/jaw synergies revealed that the school-aged children were more variable than adults, \(F(1, 38) = 40.89, p < .001, e^2_p = .52\). The within-subject effect of synergy was significant, \(F(1, 38) = 62.48, p < .001, e^2_p = .62\); the lip aperture synergy was consistently less variable than the lower lip/jaw synergy. There was also a significant nonword effect, \(F(4, 152) = 21.74, G-G p < .001, e^2_p = .36\). There were higher-order interactions between synergy, nonword, and group, \(F(4, 152) = 26.39, G-G p = .045, e^2_p = .07\), synergy, practice, and group, \(F(1, 38) = 4.60, p = .039, e^2_p = .12\), and synergy, practice, nonword, and group, \(F(4, 152) = 2.842, G-G p = .035, e^2_p = .07\). Because the overall ANOVA detected these interactions, repeated measures ANOVAs were computed separately for the lip aperture and lower lip/jaw synergies to examine the effects of group, practice, and nonword on each index.

Mean and standard error bars for the lip aperture variability index for adults (circles) and 9 and 10-year-olds (triangles) are plotted for the first (filled symbols) and last (open symbols) five productions of each nonword in Figure 5. As in the overall ANOVA with both synergies included, significant effects of group, \(F(1, 38) = 29.50, p < .001, e^2_p = .44\), and nonword, \(F(4, 152) = 49.82, G-G p < .001, e^2_p = .57\), were found. Additionally, there was a significant practice by group interaction, \(F(1, 38) = 12.32, p = .001, e^2_p = .25\). Post hoc tests showed that the 9 and 10-year-olds’ first five productions were more variable (had higher lip aperture variability indices) compared to their last five trials (Fishers LSD \(p < .05\)), while the adults showed no change in the last five compared to the first five productions. Adults, unlike the 9 and 10-year-olds, did not adjust interarticulatory coupling after programming and executing the first five productions of the nonwords. Although children significantly decreased their lip aperture variability, their last five productions were still significantly higher than the adults’ last five productions (Fishers LSD < .05).

For the lower lip/jaw synergy variability index, the effects of group, \(F(1, 38) = 30.55, p < .001, e^2_p = .45\), were significant; the children were more variable on this measure compared to adults. Nonword also produced significant effects on the variability of movements of the lower lip/jaw synergy, \(F(4, 152) = 9.65, G-G p < .001, e^2_p = .20\) (e.g., variability was highest for the longest words). As the means listed in Table 3 suggest, for the lower-order synergy there was no practice effect, \(F(1, 38) = 1.83, p = .18\), or practice by group interaction, \(F(1, 38) = .29, p = .59\). Unlike the lip aperture synergy,

### Table 2. The Mean Lip Aperture Variability Index Values from Adults and Children Are Listed for the First and Last Five Productions of Each Nonword

<table>
<thead>
<tr>
<th>Nonword</th>
<th>mab</th>
<th>mabshibe</th>
<th>mabhieshabe</th>
<th>mabshaytiedoib</th>
<th>mabteebeebee</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Adult</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First five</td>
<td>6.2 (.8)</td>
<td>9.7 (.7)</td>
<td>11.2 (.9)</td>
<td>14.6 (1.1)</td>
<td>10.4 (1.1)</td>
</tr>
<tr>
<td>Last five</td>
<td>6.2 (.8)</td>
<td>10.0 (.8)</td>
<td>11.2 (.9)</td>
<td>14.6 (1.1)</td>
<td>11.0 (.8)</td>
</tr>
<tr>
<td><strong>Children</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First five</td>
<td>8.6 (1.0)</td>
<td>15.2 (1.8)</td>
<td>18.1 (1.0)</td>
<td>21.1 (1.5)</td>
<td>17.6 (1.7)</td>
</tr>
<tr>
<td>Last five</td>
<td>8.1 (.8)</td>
<td>14.3 (1.0)</td>
<td>14.6 (.9)</td>
<td>16.1 (.9)</td>
<td>14.6 (1.0)</td>
</tr>
</tbody>
</table>

Standard errors are shown in parentheses.
school-aged children did not change lower lip/jaw coordination with practice.

Duration
The time between peak velocity of the initial and final opening movements was used to measure the overall duration of each nonword. Figure 6 is a plot of the adults’ (circles) and 9 and 10-year-olds’ (triangles) mean durations in seconds with standard error bars for the first five (closed symbols) and last five (open symbols) trials for each nonword. Overall, children’s nonword productions were longer than adults’, \( F(1, 38) = 17.20, p < .001, \pi^2 = .31 \), there was a significant effect of nonword, \( F(4, 152) = 991.605, G-G p < .001, \pi^2 = .96 \), and nonword by group interaction, \( F(4, 152) = 8.053, G-G p < .001, \pi^2 = .18 \). As expected, the production of longer and more complex nonwords required more time for both groups, however as illustrated in Figure 6, it is apparent that the children needed significantly more time to produce these stimuli compared to adults.

The practice by group interaction was significant, \( F(1, 38) = 15.29, p < .001, \pi^2 = .29 \). Post hoc tests revealed that the 9 and 10-year-olds’ first five productions were significantly longer than their last five productions, while adults’ durations did not change (Fisher’s LSD, \( p < .05 \)). A nonword by practice by group interaction suggested that the decrement in children’s durations with practice varied

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### Table 3. The Mean Lower Lip/Jaw Variability Index Values from Adults and Children Are Listed for the First and Last Five Productions of Each Nonword

<table>
<thead>
<tr>
<th>Nonword</th>
<th>mab</th>
<th>mabshibe</th>
<th>mabshaytiedoib</th>
<th>mabteebeebee</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Adult:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First five</td>
<td>12.8 (2.4)</td>
<td>13.0 (1.2)</td>
<td>10.8 (1.1)</td>
<td>17.4 (1.3)</td>
</tr>
<tr>
<td>Last five</td>
<td>10.3 (1.3)</td>
<td>13.3 (1.1)</td>
<td>12.4 (1.5)</td>
<td>16.3 (1.2)</td>
</tr>
<tr>
<td><strong>Children:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First five</td>
<td>19.6 (2.3)</td>
<td>20.5 (1.1)</td>
<td>19.4 (1.0)</td>
<td>23.4 (1.7)</td>
</tr>
<tr>
<td>Last five</td>
<td>22.2 (2.8)</td>
<td>18.5 (1.4)</td>
<td>17.3 (1.2)</td>
<td>21.9 (1.6)</td>
</tr>
</tbody>
</table>

Standard errors are shown in parentheses.
FIGURE 4  The top two plots are the first five (left) and last five (right) normalized lip aperture trajectories for the nonword “mabshaytiedoib” from one adult participant. In this figure the bottom two panels are the first five (left) and last five (right) normalized productions from the lower lip/jaw synergy from the same participant. The variability indexes are reported in each panel.

FIGURE 5  Mean and standard error bars for the lip aperture variability index are plotted for the adults (circles) and 9 and 10 years old (triangles) as a function of the nonword stimuli. Closed circles/triangles represent the mean value for the first five trials, while open symbols represent the mean value for the last five trials for each nonword.
as a function of the nonword they were producing, $F(4, 152) = 2.93$, $G-G p = .031$, $e^2 = .07$. Post hoc analysis confirmed that the children had longer durations for the first five productions for all of the nonwords (Fishers, LSD, $p < .05$) except for the one-syllable “mab.” However, the adults’ durations for the first and last five productions did not change significantly for any of the nonwords.

**Individual Data and Overlap Between Groups**

To characterize individual differences and overlap between the children’s and adults’ performance, Figures 7 and 8 include plots of the lip aperture variability indices and word durations for the two nonwords that demonstrated the most robust practice effects in the children, “mabfieshabe” and “mabshaytiedoib.” Each point in the plots represents data from a single participant. From the top plots, which are the means from the first five trials, it is clear that the children’s and adults’ data are generally distinctive, with little overlap. In the bottom graphs, showing the last five trials, for both the variability measure (Fig. 7) and duration (Fig. 8), it is apparent that the children have become less variable and faster, such that their data points (triangles) significantly overlap those of the adults (circles).

**DISCUSSION**

This experiment provides the first evidence for short-term practice effects in speech motor coordination in school-aged children. In addition, the present results confirm earlier reports of age-related differences between school aged children’s and adults’ speech motor performance (Goffman & Smith, 1999; Green et al., 2000, 2002; Sharkey & Folkins, 1985; Smith & Goffman, 1998; Smith & McLean-Muse, 1986; Smith & Zelaznik, 2004; Walsh & Smith, 2002). We can view these results within the context of the two hypothetical sources of variability in children’s motor performance from the limb motor control literature, neuromotor noise (Fitts, 1954; Schmidt et al., 1979; Smits-Engelsman & Van Galen, 1997; Yan et al., 2000) and short-term changes related to practice (Deutsch & Newell, 2002, 2003, 2004; Engelhorn, 1988; Ferrel-Chapus et al., 2002; Konczak et al., 2003; Lazarus et al., 1995; Manoel & Connolly, 1995; Takahashi et al., 2003; Thomas et al., 2000).

Before discussing the contributions of short-term and longer-term sources of variability, it is important to note that our results reinforce the concept of hierarchical organization of functional synergies for speech motor control (Bernstein, 1967; Smith & Zelaznik, 2004). Unlike the lip aperture synergy, the lower-order synergy,
FIGURE 7 Individual subject data are plotted for all 40 participants; filled circles are adults, while open triangles are children’s data. The top plot shows the mean lip aperture variability index for each subject for the first five trials of the two most difficult nonwords. So, for example, each subject’s mean lip aperture variability score on “mabfieshabe” is plotted against his/her mean for “mabshaytiedoib.” The bottom plot is the analogous data for the last five trials. The lower left quadrant of the graph would contain data from the most consistent performers, while the upper right quadrant would represent the most variable performers. Clearly, the distribution of the adults’ scores changes little across the first and last five trials, while the children’s data shifts toward the lower left quadrant, indicating an increase in consistency.
Individual subject data are plotted for all 40 participants; filled circles are adults, while open triangles are children’s data. The top plot shows the mean duration for each subject for the first five trials of the two most difficult nonwords. So, for example, each subject’s mean duration on “mabfleshabe” is plotted against his/her mean for “mabshaytiedoib.” The bottom plot is the analogous data for the last five trials. The lower left quadrant of the graph would contain data from most rapid speakers, while the upper right quadrant would represent the slowest speakers. Clearly, the distribution of the adults’ scores changes little across the first and last five trials, while the children’s data shifts toward the lower left quadrant, indicating an increase in speaking rate.
composed of just the lip and jaw, was consistently more variable than the lip aperture synergy in both participant groups and showed no systematic changes in coordination over the ten productions. This suggests that for both groups, the changes in upper lip, lower lip, and jaw interactions to produce the sequence of bilabial closure and opening movements were adjusted, so that the consistency of lip aperture dynamics was maintained. Thus, these results provide additional evidence that lip aperture is a higher-order collective control variable, as postulated by early vocal tract models suggesting that the distance between the upper and lower lips is critical for speech acoustic output (e.g., Stevens & House, 1955). This is a significant point, because in the sections below, we suggest that the pattern of change in the higher-order synergy, lip aperture, reflects the operation of short-term, systematic changes in the children’s nervous system to achieve speech acoustic goals. In contrast, the lower lip/jaw synergy shows higher variability and does not significantly change with practice. Therefore, by examining the two synergies in the same experiment, we were able to disambiguate short-term practice effects from overall levels of inherent neuromotor noise.

**Short-Term Changes in Coordination and Duration**

Although children’s speech coordinative patterns show overall greater variability, we wished to determine if there were short-term changes in articulatory coordination occurring within the experimental session. This hypothesis was motivated by earlier work in limb motor control showing short-term changes in children’s movement proficiency with practice (Deutsch & Newell, 2002, 2003, 2004; Engelhorn, 1988; Ferrel-Chapuz et al., 2002; Konczak et al., 2003; Lazarus et al., 1995; Manoel & Connolly, 1995; Takahashi et al., 2003; Thomas et al., 2000). In the current study, the coordinative patterns for nonword production changed over the course of 10 trials for the 9 and 10-year-old participants, suggesting that the children’s motor control processes were adaptively changing to improve performance. As shown by the higher order lip aperture index of coordinative variability, the coupling of the upper lip, lower lip, and jaw movements became significantly less variable in the later productions of the nonwords. Interestingly, the 9 and 10-year-olds also had significantly shorter durations for the last five trials. Deutsch and Newell (2002, 2003, 2004) have proposed that children are capable of making very rapid, short-term changes in motor control processes, and that these changes are dependent on practice and the adaptive use of feedback; in their case, visual feedback. In terms of speech production, one computational model (Guenther, 1995; Guenther, Hampson, & Johnson, 1998) suggests that children would develop an auditory target for the novel nonword, and they would use somatosensory and auditory feedback to adjust motor commands to a greater extent than adults, so that the acoustic product of the movement is a better fit to the auditory target. It is attractive to speculate that children relied on feedback to develop a target for each nonword, which resulted in more variability and longer durations on the first five trials. Experiments in which auditory or somatosensory feedback is manipulated would be the necessary to test this hypothesis.

A critical question is whether children would reach adult levels of performance on the lip aperture coordination index with more practice. For example, Konczak et al. (2003) found that when damping forces were applied during reaching movements, children required more practice trials than adults to adapt to the perturbation. We postulate that the answer to this question would be no, children would not reach adult levels of speech coordination even with more repetitions, due to the persistent influences of background, neuromotor noise. In Walsh and Smith (2002) we found that, even for the production of simple phrases (such as buy “Bobby a puppy” or “Mommy bakes pot pies”), adolescents (14 and 16-year-olds) were significantly more variable than adults in their orofacial speech movement patterns. On the other hand, we note that children’s greatest decrease in coordinative variability occurred on the most difficult nonword (mabshaytiedoib), and that it approached adult values. In fact, as illustrated by the individual subject data in Figure 7, some children’s coordination indices on the two most difficult nonwords fell within the adults’ range.

Another important issue to be considered is the time frame over which children might retain the short-term changes in movement proficiency that we observed. For example, if the 9 and 10-year-olds returned to the laboratory 2 days later and produced the same set of nonwords, would their coordinative variability be lower compared to the first five repetitions of the initial session? In other words, we assume that short-term changes in speech neural networks are responsible for the increased consistency noted in the last five trials, but are changes in these putative synaptic connections or weights retained such that later performance would reflect the earlier practice? This is another question for further research.

In this experiment we chose to examine adults’ and 9 and 10-year-olds’ productions of novel nonwords. Having observed the children’s short-term improvement in consistency in the novel nonword production task, we wondered whether this phenomenon was simply a ubiquitous developmental characteristic, one that would be observed in all speech production tasks, and as such, is not uniquely associated with novel stimuli. To address this question, we reanalyzed data from an earlier experiment...
in which children produced the phrase, “Buy Bobby a puppy.” In this case the children were cued to repeat the phrase 10 times in sequence; the stimuli were not randomized as they were in the present experiment. We reasoned that if short-term changes in speech motor control occurred for a simple familiar phrase, then sequential production, compared to the randomized paradigm used in this study, would provide the optimal condition to observe practice effects. We analyzed the first five and last five lip aperture trajectories for “Buy Bobby a puppy” from 32 9 and 10-year-olds who participated in an earlier experiment. A one-sample *t*-test comparing the first and last five productions indicated that there was no practice effect for these productions, \( t = .09, df = 31, p = .93 \). However, the average value of children’s lip aperture variability index \( (M = 16.43) \) was significantly higher than that of the 30 young adults \( (M = 12.44) \) from the Smith and Zelaznik (2004) study, \( F(1, 60) = 35.20; p < .0001 \). This finding again supports the general neuromotor noise hypothesis that children are more variable even on well-practiced, familiar syllable sequences. It also confirms that the practice effect observed in the 9 and 10-year-olds is associated with learning novel nonwords and is not simply a characteristic of repeating any type of verbal material, whether familiar or not.

We considered the possibility that adult speakers would also show short-term changes in their coordinative patterns. For example, Abrams and Pratt (1993) and Novak, Miller, and Houk (2000) reported a reduction in the variability of adults’ limb movements as a function of practice. On the other hand, our earlier work showed a high degree of consistency in adults’ articulatory movements during sentence production (Maner, Smith, & Grayson, 2000; Smith & Goffman, 1998; Smith & Zelaznik, 2004; Walsh & Smith, 2002). Adults did not change their coordinative patterns after the initial five productions of each nonword. Thus, it is likely that adults possess well-established coordinative synergies to control lip aperture, perhaps organized around syllables (Levelt & Wheeldon, 1994). The syllables that comprised the nonwords in the present study were permissible phonetic sequences in English, and it appears that the adults relied on established articulatory synergies to produce these novel words. This of course is speculative, and we plan future work to examine children and adults’ productions of more difficult novel words.

In presenting the results of this investigation, we have generally relied on reports of means for children versus adults. Clearly, there was individual variation in performance, and we have illustrated the fact that the degree of overlap among the children’s and adults’ data increased from the first to the last five trials (see Figs. 7 and 8). Even in the first five trials, however, some children show lip aperture variability and duration values that are within the adult performance range. These individual differences in children’s performance would certainly be of interest for future work. For example, are the 9 and 10-year-olds who are performing at adult levels more proficient in language abilities, in general motor abilities, or a combination of the two? Munson, Edwards, and Beckman (2005) reported that better performance on a nonword repetition task in 40 pre-school children was significantly correlated with vocabulary size, but not to behavioral measures of articulatory or perceptual abilities.

**CONCLUSION**

Although the 9 and 10-year-olds and adults produced nonwords that were perceptually accurate, their speech motor performance differed. Adults appear to be operating in a smaller or preferred region of their movement space (Sporns & Edelman, 1993). They executed reliable control over their articulators and did not change their coordinative patterns after the initial planning and execution of the novel nonword. The 9 and 10-year-olds’ speech movements when producing the nonwords were, on average, more variable and significantly longer than adults. However, they evidenced more consistent articulatory coordinative patterns to control lip aperture on the last five trials. Practice also allowed the children to increase their rate on the later trials. We hypothesize that these changes reflect a system operating with a high degree of flexibility. One example of how this flexibility may be advantageous in the developing system is for second language learning (L2). There is a strong relationship between age of acquisition and perceived foreign accent, such that the earlier the age of L2 acquisition, the greater the capacity to acquire a native accent (Flege, Munro, & MacKay, 1995; Flege, Yeni-Komshian, & Liu, 1999; Moyer, 1999; Oyama, 1976; Thompson, 1991). Future studies could examine this issue by examining the kinematics as well as the prosodic contours and phonetic categories associated with the learning and production of novel words.

**NOTES**

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**REFERENCES**


