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Nonword Repetition in Children and Adults: Effects on Movement Coordination

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Abstract

Hearing and repeating novel phonetic sequences, or novel nonwords, is a task that taps many levels of processing, including auditory decoding, phonological processing, working memory, speech motor planning and execution. Investigations of nonword repetition abilities have been framed within models of psycholinguistic processing, while the motor aspects, which also are critical for task performance, have been largely ignored. We focused our investigation on both the behavioral and speech motor performance characteristics of this task as performed in a learning paradigm by 9- and 10 year-old children and young adults. Behavioral (percent correct productions) and kinematic (movement duration, lip aperture variability -an index of the consistency of inter-articulator coordination on repeated trials) measures were obtained in order to investigate the short-term (Day 1, first 5 vs. next 5 trials) and longer-term (Day 1 vs. Day 2, first 5 vs. next 5 trials) changes associated with practice within and between sessions. Overall, as expected, young adults showed higher levels of behavioral accuracy and greater levels of coordinative consistency than the children. Both groups, however, showed a learning effect, such that in general, later Day 1 trials and Day 2 trials were shorter in duration and more consistent in coordination patterns than Day 1 early trials. Phonemic complexity of the nonwords had a profound effect on both the behavioral and speech motor aspects of performance. The children showed marked learning effects on all nonwords that they could produce accurately, while adults' performance improved only when challenged by the more complex nonword stimuli in the set. The findings point to a critical role for speech motor processes within models of nonword repetition and suggest that young adults, similar to children, show short- and longer-term improvements in coordinative consistency with repeated production of complex nonwords. There is also a clear developmental change in nonword production performance, such that less complex novel sequences elicit changes in speech motor performance in children, but not in adults.

The ability to hear and repeat novel phonetic sequences is crucial to word learning throughout lifetime. This seemingly simple human capacity which begins in infancy is the cornerstone of language acquisition and involves complex multistage processes (Gathercole, 2006; Gupta, 2007). Mediated initially by phonological learning, nonword repetition eventually results in lexicalization of the sounds constituting new words. A number of

models have been proposed to account for the different stages involved in the repetition of novel sequences (Gathercole, 2006; Gupta & MacWhinney, 1997; Jones, Gobet, & Pine, 2007). Such models have attributed relevant roles to different mechanisms, including phonological storage, phonological short-term memory and its interaction with longer-term memory. Among these models, the theoretical framework proposed by Gathercole (2006) has received considerable experimental attention. Gathercole's framework involves various stages, including auditory processing, phonological analysis, phonological storage and retrieval, speech motor planning and execution.

The effects of communication differences and disorders on the ability to repeat nonwords have been tested extensively (Edwards, Beckman, & Munson, 2004; Gathercole & Baddeley, 1990; Papagno & Vallar, 1995). It is now well established that poor nonword repetition performance is a behavioral marker of specific language impairment (Bishop, North, & Donland, 1996; Dollaghan & Campbell, 1998; Michas & Henry, 1994). Such findings highlight the diagnostic relevance of performance in nonword repetition to the underlying language and speech motor processes.

The results from studies of nonword repetition have been interpreted within the scope of underlying language processes (for a review, see Gathercole, 2006). Measured primarily as the percent of phonemes produced correctly, nonword repetition performance is influenced by factors that have an effect on initial phonological learning as well as later lexicalization of the learned phonological sequences. For instance, the ability to repeat nonwords has been associated with digit span in both children and adults (Baddeley & Wilson, 1993; Butterworth, Campbell, & Howard, 1986; Gathercole, Briscoe, Thorn, & Tiffany, 2008; Gupta, 2003). Nonword repetition has also been associated with vocabulary size and strength of existing long-term representations, although this effect is evident in older children and adults only in situations where lexically-supported learning, based on existing representations, is possible (e.g., Gathercole, Hitch, Service, & Martin, 1997; Gupta, 2003). For example, younger children experienced more difficulties in repeating nonwords that did not resemble words compared to word-like nonwords, and such differences diminished with age (Munson, 2001). Nonword repetition is also influenced by the frequency of phonemic sequences in a language measured as high vs. low phonotactic probability (e.g., Gathercole, Frankish, Pickering, & Peaker, 1999; Storkel, Armbruster, & Hogan, 2006; Storkel, 2001). Thus, findings from earlier studies of nonword repetition have been interpreted within the context of strength of existing phonological representations and short-term phonological storage capacity. However, another critical process underlying nonword repetition abilities involves the output implementation mediated by the speech motor system. But, the role of speech motor output processes underlying nonword repetition abilities and the changes at the motor level with the acquisition of novel phonetic strings have not been investigated extensively. It could be argued that some of the variables known to influence nonword repetition accuracy such as, nonword length, word likeness, and phonemic complexity, also operate on speech motor output processes such as speech kinematics. In fact, measures of speech kinematics would likely provide a much more sensitive index for the underlying processes mediating formulation and implementation (e.g., Smith & Goffman, 1999). In addition, evidence from speech disordered populations indicates that the contributions of speech motor processes to nonword repetition abilities are critical for a complete understanding of the necessary underlying functions. For example, poor performance in nonword repetition has been reported in individuals diagnosed with stuttering (Hakim & Ratner, 2004; Anderson, Wagovich, & Hall, 2006) and in articulation disorders (Yoss & Darley, 1974), where a primary component of the disorder involves the speech motor system. In summary, the speech motor processes mediating the implementation of nonword repetitions have received little experimental attention, and it is these production processes that are the focus of the present investigation.

The nonword repetition task engages the speech motor system and offers an opportunity to investigate the effects of successive repetition of novel material on speech movement coordination through the process of motor learning. Schmidt (1988) defined motor learning as a set of internal processes associated with practice or experience leading to relatively permanent changes in the capability for responding. It results in increasing movement accuracy and speed with increasing coordination and decreasing variability with practice. Both transient and persistent changes in the neural substrates supporting motor learning are thought to result in short and longer-term changes in movement coordination (Monfils, Platz, & Kleim, 2005). Thus, movement coordination is achieved through a neurophysiologically mediated motor learning process (Harris & Wolpert, 1998; Smith & Zelaznik, 2004). A theoretical notion that has received considerable attention in the limb motor literature is the *neuromotor noise hypothesis*. Accordingly, changes with motor learning are the consequences of reducing variability in neural command signals (Kleim et al., 2003, 2004; Newell, Liu, Mayer-kress, 2003). Both children and adults exhibit higher levels of neural noise during the acquisition of new movement sequences, which is evident as higher movement variability (Green et al., 2002; Smith & Zelaznik, 2004; Takahasi et al., 2002; Van Galen, Portier, Smitsengelsman, Schomaker, 1993; Walsh, Smith, & Weber-Fox, 2006; Yan et al., 2000). With maturation and practice, increasing neuronal synchronization results in reduced neuromotor noise levels, thereby facilitating motor coordination through the formation of optimal movement synergies. For instance, Smith and Zelaznik (2004) and Walsh and Smith (2002) demonstrated that children continue to show increasingly consistent articulatory coordination over the adolescent years, with adult levels of speech rate and speech coordination consistency being achieved only after 16 years of age.

Experimental evidence for changes in speech coordination with nonword repetition has been reported (Schultz, Stein, & Micallef, 2001; Walsh et al., 2006). These findings offer preliminary support for the role of speech motor process within the theoretical frameworks of nonword learning that have been proposed, although further experimentation is required to understand how the different task-relevant variables, such as phonemic complexity, influence speech coordination. For example, Walsh et al. (2006) investigated short-term plasticity (within a single experimental session) of the speech motor system of twenty 9- to 10-year-old children and 20 young adults in a nonword repetition task. They employed a kinematic measure of consistency of upper lip, lower lip, and jaw coordination, called the *lip aperture variability (LA VAR) index*. The aim of the study was to investigate changes in movement coordination with repeated nonword production. Participants were presented with blocks of 5 pseudo-randomized nonwords, and changes in LA VAR from the first 5 to the last 5 correctly produced trials of each nonword across the blocks were analyzed. Their findings supported within-session changes in speech coordinative patterns with nonword repetition in children.

The findings from studies investigating limb movement coordination have supported the occurrence of both short- (within session) and longer-term (between sessions) changes in coordination consistency with skill acquisition in both children and adults. Such changes, seen as reductions in movement variability and durations due to practice and other associated processes, such as sleep (e.g., Walker et al., 2002; Walker et al., 2005), are thought to reflect transient and persistent changes in cortical and subcortical motor maps (Kleim et al., 2004; McNamara et al., 2007; Monfils et al., 2005). Interestingly, the adult participants in the Walsh et al. study failed to show a learning effect on movement coordination, while the 9- to 10-year-olds showed significant reductions in lip aperture variability with increasing practice within a single session. A closer examination of the nonwords used by Walsh et al. (2006) revealed that while these may have challenged the speech motor system in children, perhaps the adults were performing at ceiling, thereby failing to show changes in movement coordination with repeated nonword production. It

remains to be seen whether adults will show a motor learning effect, similar to that seen in children, if the nonwords are sufficiently complex to challenge the mature motor and phonemic systems. Furthermore, the extent to which the short-term changes in speech movement coordination for nonword repetition observed in children within a session is preserved the following day remains to be tested.

Thus, the primary goal of this investigation was to elucidate the role of speech motor output processes within existing theoretical frameworks proposed to account for nonword repetition. More specifically, the present study was designed to extend earlier findings of changes in speech movement coordination with nonword repetition in both the developing motor systems in 9 to 10-year-olds (e.g., Walsh et al., 2006) and the mature systems in young adults. Both behavioral (percent correct productions) and kinematic (lip aperture variability, movement duration) measures were used to evaluate performance in the nonword repetition task. We hypothesized that: a) Based on the neuromotor noise hypothesis, children will exhibit higher error rates and movement variability compared to adults, and both children and adults will show higher variability in oral motor coordinative consistency on Day 1 compared to Day 2; b) Young adults will show changes in movement coordination within a session when the phonemic complexity of the nonwords is higher than those used by Walsh et al.; c) The short-term changes in accuracy and movement variability observed within a session will persist overnight. In other words, changes in speech coordinative consistency observed on Day 1 will persist in both children and adults such that, performance on the first five trials of Day 2 will approximate those of the last five trials of Day 1 while being lesser than the variability of the first five trials on Day 1; d) Finally, we hypothesized that the short- and longer-term changes associated with speech motor learning of nonwords result in progressive modification and organization of movement synergies leading to more consistent and accurate performance in both children and adults.

Methods

Participants

Nineteen children (10 males) aged 9–10 years (M age = 9.75, SD = .40), and an equal number of adults (10 males) in the age range of 18 to 25 years (M age = 22.3, SD = 2.0) participated in the study. Participants completed 2 experimental sessions over consecutive days (Day 1 and Day 2). We chose children in the 9 to 10-year age range based on past reports that children at this age show sensitivity to potential interactions between the developing speech motor and language systems, and because they are able to perform the nonword repetition task (Smith & Zelaznik, 2004; Walsh et al., 2006). All participants were native speakers of North American English. Participants were recruited based on their responses to a screening form that was used to rule out a positive history of language, hearing, and/or neurological deficits, and current usage of drugs likely to affect the outcome of the experiment (e.g., drugs for ADHD and anti-anxiety drugs). Children were screened for language deficits using the *Clinical Evaluation of Language Fundamentals test - 3* (CELF - 3; Semel, Wiig, & Secord, 1995). Normal articulatory structures and movements in both the age groups were confirmed using the *Oral Speech Mechanism Screening Evaluation-Revised* (OSMSE-R; St. Louis & Ruscello, 1987). Finally, participants passed a hearing screening test performed at .5, 1, 2, 4, and 8 KHz (20dB) in both ears.

Nonword repetition skills and short term memory skills for participants in both groups were determined using the Nonword Repetition test (Dolloghan & Campbell, 1998) and the forward and backward Digit span tests (*Weschler's Memory scale*, Weschler, 1997). The Nonword Repetition test was administered to all participants as a baseline measure of the ability to perceive and repeat nonwords. The nonwords spoken by a native English speaker were pre-recorded and presented over loudspeakers and participants were required to repeat

each nonword. The nonwords varied in length (1 – 4 syllables) and consisted of tense vowels and consonants acquired early in development while excluding the late-eight consonants and consonant clusters (Dollaghan & Campbell, 1998). Performance in this task was analyzed by the first author offline by counting the percent consonant and vowel errors for each nonword length. Children and adults performed near ceiling for the 1-, 2-, and 3-syllable nonwords. For the 4-syllable category, adults ($M = 91.6\%$, $SE = 1.4$) performed better than children ($M = 85.6\%$, $SE = 1.4$), $t = 2.85$, $p = .007$. Reliability coding was performed on participant responses by a trained research assistant and inter-judge reliability computed using Pearson product-moment correlation was .75 ($p < 0.01$). In the digit span subtests, children had an average span of 8.3 ($SD = 1.9$) and 6.2 ($SD = 3.1$) in the forward and the backward digit span subtests respectively, while the adults' scores were 11.3 ($SD = 2.1$) and 8.3 ($SD = 2.5$). While scores on these tests were not used as screening criteria for subject inclusion, the scores approached the range reported in earlier studies (e.g., Gathercole, Willis, Emslie, & Baddeley, 1994; Gupta, 2003).

Nonword Stimuli for the Kinematic Study

Four nonwords and a control word on which we did not expect motor learning to occur, the compound word, /*pate ɪ toʊ tʃ ɪ p*/, were the stimuli. The first syllable /*mæb*/ and the last phoneme /*b*/ were identical for all nonwords. This strategy was used to enable selection of consistent start and end points for oral movement data extraction on the basis of lower lip peak opening velocities during the articulatory trajectory analysis. For similar reasons, the composition of the compound word, /*pate ɪ toʊ tʃ ɪ p*/, allowed consistent demarcation of the start and end points. Of the four nonwords, two—/*mæb¹fa²ɹ²fe³ɪb³*/ (3-syllable) and /*mæb¹fe²ɹ²ta³də⁴ɪb⁴*/ (4-syllable)—used by Walsh et al. (2006), consisted of syllables containing consonants acquired by 4 years of age. To increase nonword complexity in the present experiment, two additional 4-syllable nonwords were added to this list. The third nonword, /*mæb¹sɒ²ɔ²kwi³fle⁴ɪb⁴*/ included three consonant clusters, /*sp*/ /*kw*/ /*fl*/, (with varying combinations of vowels and diphthongs) acquired between 4 and 6 years of age, and for this reason is argued to be phonemically more complex than nonwords 1 and 2. Finally, the fourth nonword, /*mæb¹skri²spl³ɔ⁴ɹ⁴strub⁴*/, included three consonant clusters, /*skr*/ /*spl*/ /*str*/, (with varying combinations of vowels and diphthongs) acquired between 7 and 11 years of age and thus is phonemically more complex than the other nonwords. We also used the Vitevich and Luce (2004) method to obtain a global measure of nonword complexity that was based on the sum of phonotactic probabilities of all biphones (all possible two-sound combinations) in each nonword. These authors proposed using the sum of biphone probabilities to find the median value for this measure from the set of potential stimuli. Items greater than the median value are operationally defined as nonwords with high phonotactic probability, and items less than the median value are defined as nonwords with low phonotactic probability. The lower the sum of biphone probability of a nonword as compared to the median, the lower is the phonotactic probability of the biphones constituting the nonword and higher the nonword complexity. The sum of biphone probabilities were .0172 for /*mæbfa ɪ fe ɪ b*/, the only 3 syllable nonword, .0335 for /*mæbfeɪtəɪdɔɪb*/, .0179 for /*mæbsɒɔkwiflɪb*/, and .0149 for /*mæbskrisplɔɹstrub*/, with a median biphone probability of .0179 for the three 4-syllable nonwords. The compound word, /*pate ɪ toʊ tʃ ɪ p*/, was included to compare novel nonword performance to that of a familiar word that is comparable in phonemic composition to the nonwords but that also has a known lexical representation. The stimuli, produced by a native female American English speaker, were recorded and digitized using PRAAT software. For all the nonwords, the primary stress was on the first syllable with a weak secondary stress on the third syllable. This particular stress pattern was chosen to be consistent with the predominant stress pattern for a majority of English words. We hypothesized that this stress pattern would reduce the number of production errors related to stress placement. The duration of each stimulus

model was: /mæbfa ɪ f e ɪ b/ – 1.41 ms, /mæb f e ɪ aɪ d əɪ b/ – 1.44 ms, /mæbspoukwɪfle ɪ b/ – 2.00 ms, /mæbskrispl əɪ strub/ – 2.35 ms, and /pateɪ t o t f ɪ p/ – .83 ms.

Apparatus

Participants were seated in front of an Optotrak 3020 camera (Northern Digital, Waterloo, Ontario), a commercial system that allows tracking of movements in 3D with an accuracy of less than 0.1mm. Eight small (7 mm) infra-red light emitting diodes (IREDs) were attached to track articulatory movements of the upper lip, lower lip, and jaw. Four of the IREDs were mounted on a set of goggles that participants wore during the experimental session. One IRED was placed in the center of the forehead. Together, these five IREDs were used to calculate the 3D head coordinate system (Smith, Johnson, McGillem, & Goffman, 2000), which allowed head movement artifact to be eliminated. To track the motion of the lips, one IRED was placed at the center of the vermilion border of the upper lip and one at the center of the vermilion border of the lower lip (this marker represents combined actions of the lower lip and jaw). The IRED motions were sampled at a rate of 250 Hz. A condenser microphone placed 8 cm away from the participant's mouth was used to record the speech signal. This acoustic signal was digitized on an A/D channel of the Optotrak system and was thus synchronized with the movement data. The acoustic signal was digitized at the rate of 16,000 Hz and low-pass filtered with a cut-off frequency of 7500 Hz.

Procedure

On Day 1, participants were instructed that they would hear novel words that do not exist in English. They were asked to listen carefully and repeat each novel word as best as they could. Following instructions, each nonword was presented via loudspeakers. Participants' productions during practice were monitored and corrected for pronunciation and stress errors by the experimenter. A majority of participants were able to repeat the nonwords with the primary stress on the first syllable. Practice was terminated when a criterion score of two correct productions was achieved for each target item. A minimum of two trials and a maximum of five trials were allowed for each participant. The data indicated that for a majority of the stimuli, participants were able to achieve a minimum of two consecutive, correct productions within five practice trials. Following the practice trials, each nonword was presented once more, and participants were required to produce them in the carrier phrase "Say _____ again". Participants then completed the experimental task, producing the target items embedded in the carrier phrase. The carrier phrase was used to control articulatory positions at the beginning and ending of the target nonwords.

The experimental session lasted approximately 60 min on Day 1 and 30 min on Day 2. Both sessions were similar except for the practice trials, which were excluded on Day 2. During each session, the nonwords were presented auditorily in 13 pseudo-randomized blocks. Each block consisted of 5 trials, with the four nonwords and 'potato chip' occurring once in random order. During the experiment, the participant was instructed to repeat the target nonword played by the experimenter in the carrier phrase. Each target stimulus was separated by a 2 sec gap. Participants' responses were recorded by the experimenter during each session to determine if the subject had produced a minimum of 10 correct trials for each stimulus, because this number of repetitions is needed for the trajectory analysis. Failure to obtain 10 correct productions within the 13 blocks resulted in the presentation of two or three additional blocks. The experiment was then terminated regardless of whether 10 correct productions had been obtained. Correct responses were defined as those trials which were free of disfluencies or articulation errors. The first and third authors ran the experiment and had clear visibility of the face and articulators of participants' at all times. Both consonant and vowel errors were considered, but online scoring was 'all or none'. Only trials agreed upon by both experimenters as correct productions were included in the offline

LA VAR analysis. Even within the correctly produced tokens, repetitions with inter-syllable pause (>3 seconds, evident as flat lines of the LA VAR trajectories) and stress errors were kept to a minimum based on instructions and correction of errors during initial practice.

Data Analysis

The acoustic and kinematic data from each session were loaded into MATLAB digital signal processing software for analysis (for details on the analysis, see Smith et al., 2000; Smith & Zelaznik, 2004). Following low pass filtering of the upper lip and lower lip displacement signals, the velocity signal was computed from the lower lip displacement using the 3-point difference method. Then, the displacement trajectories associated with correct productions of the stimuli were obtained by identifying each stimulus from the 13 – 15 blocks and segmenting the corresponding displacement files. The start and end points of the upper lip and lower lip data thus segmented were determined using the lower lip velocity signal. The start point for each segment was the point of maximum opening velocity for /m/ (in the first syllable /mæb/) and the end point was the point of maximum opening velocity of the lower lip opening gesture for /b/ (in the last syllable). For /pate noʊtʃ ɪp/, the start and end points were based on the maximum opening velocity of the lower lip for the initial and final /p/. These peak velocity regions were easily located by the experimenter, and a MATLAB algorithm selects the peak opening velocity within a user-defined window. Each data segment selected in this manner was then reassessed for fluency and accuracy of extraction by listening to the associated audio record. If there were more than 10 correct productions of a target nonword, the trajectories associated with the first 10 were used in the data analysis.

Following extraction of the upper lip and lower lip movement trajectories for each set of 10 productions of every target nonword, a multi-step analysis was performed using a custom MATLAB program. This analysis resulted in computation of the lip aperture variability index (LA VAR; Smith & Zelaznik, 2004), which is a measure of the trial-to-trial spatial and temporal variability associated with the lip aperture (LA) trajectory. First, the LA signal was obtained by a sample by sample subtraction of the lower lip displacement signal from the upper lip displacement signal was carried out to obtain the difference between the upper and lower lip IRED markers as a function of time. Second, the 10 LA trajectories for each nonword were amplitude normalized, which involved subtracting the mean and dividing by the standard deviation. Third, using interpolation, the LA trajectories were time normalized to a fixed record length of 1000 points. Fourth, standard deviation values were calculated at 50 point intervals (2% intervals in relative time) of the normalized waveform. The cumulative sum of the 50 standard deviations was computed to obtain an LA VAR value, a cumulative spatial and temporal coordinative index. A higher LA VAR index suggests a greater degree of trial to trial variability in interarticulatory coordination for nonword production, and vice versa. In addition to LA VAR, the movement duration in real time was computed as the total duration of the LA signal for each target production.

Statistical Analyses

In order to investigate any changes in movement coordination with nonword repetition in children and adults, three repeated measures ANOVAs were conducted on the behavioral (percent correct responses) and kinematic (duration, LA VAR) data. For the behavioral analysis, Age and Sex were the between-subjects factor, while Complexity (/mæbfa ɪ fe ɪb/, /mæb fe ɪta ɪdɪb/, /mæbspoʊkwɪfle ɪb/, and /mæbskɪsplɔ ɪstrub/) and Day (1 vs. 2) were the within-subjects factors. For the kinematic analysis, two separate repeated measures ANOVAs were run, one on movement duration and one on LA VAR. For these analyses, Age and Sex were the between-subjects factors while Complexity (/mæbfa ɪ fe ɪb/, /mæb fe ɪta ɪdɪb/, and /mæbspoʊkwɪfle ɪb/), Day (1 vs. 2), and Trials (first 5 vs. later 5) were the within-subjects factors. Fischer's least significant difference post hoc test was used to

identify sources of the significant main and interaction effects. For adults who produced 10 correct trials of /*mæbskrisplə ɪstrub*/, the LA VAR scores were analyzed using paired-sample t-test. The /*pate ɪoʊtʃ ɪp*/ productions were not included in the ANOVAs, rather separate statistical tests were run to ascertain group differences on kinematic data from this word. The magnitude of learning (in percent) for each nonword across both days was also estimated ([Day 1, LA VAR First 5 trials] – [Day 2, LA VAR Later 5 trials]/[Day 1, LA VAR First 5 trials]). This value reflects the increase in coordinative consistency from the earliest trials on Day 1 to the final trials on Day 2. The percent values obtained from this calculation were compared in children and adults using a repeated measures ANOVA with Age as the between-subject factor and Complexity (/ *mæbfa ɪ fe ɪb*/, / *mæb fe ɪtaɪdɔɪb*/, and / *mæbspɔkwɪfle ɪb*/) as the within-subject factor. Due to the limited number of correct productions of /*mæbskrisplə ɪstrub*/ in children, the magnitude of learning for this nonword was measured only in adults.

Kinematic Pattern Analysis

In order to test the hypothesis that speakers are making systematic adjustments in oral coordination to achieve a final pattern in the nonword repetition task, a correlation analysis (Smith et al., 1995) was performed on the time and amplitude normalized lip aperture trajectory for each subject as a function of day. An average lip aperture template was computed for trials 9 and 10, and a zero-lag cross-correlation was computed for the lip aperture trajectories of each trial (1–8) with this template (see Figure 5). The resulting correlations from the nonwords were analyzed in a repeated measures ANOVA with Age and Sex as the between-subjects factors and Complexity (/ *mæbfa ɪ fe ɪb*/, / *mæb fe ɪtaɪdɔɪb*/, and / *mæbspɔkwɪfle ɪb*/), Day, and Trial (1–8) as the within-subjects factors. Correlation data from adults for /*mæbskrisplə ɪstrub*/ were analyzed in a separate ANOVA as a majority of the children were unable to produce 10 correct repetitions of this nonword.

Results

For all statistical analysis reported below, no effects of Sex were found; therefore all results are reported collapsed across Sex.

Behavioral Data

Percent correct productions—Figure 1 shows the Mean and SE for the percent correct productions on Days 1 and 2 for children and adults. The ANOVA indicated significant main effects of Age, $F(1, 35) = 13.0, p = .001, \eta^2 = .27$, Complexity, $F(3, 111) = 31.2, p = .0001, \eta^2 = .47$, and Day, $F(1, 35) = 46.1, p = .0001, \eta^2 = .56$. A significant Complexity \times Age interaction was also obtained, $F(3, 111) = 7.1, p = .0001, \eta^2 = .16$. Differences in performance were seen between children and adults for the more complex nonwords, / *mæbspɔkwɪfle ɪb*/ and /*mæbskrisplə ɪstrub*/, with the adults, as expected, performing better at both these complexity levels as compared to the children. An effect of learning was also evident from the Complexity \times Day interaction, $F(3, 111) = 3.1, p = .03, \eta^2 = .08$. Both adults and children showed an improvement in performance on the second day, which was significant for /*mæbfaɪ fe ɪb*/, /*mæb fe ɪtaɪdɔɪb*/, and /*mæbspɔkwɪfle ɪb*/ . A trend for similar improvement on Day 2 was seen only in adults for the most complex nonword, / *mæbskrisplə ɪstrub*/.

A separate repeated measures ANOVA was performed on arcsin transformed values of the percent of correct productions in children and adults. This analysis was performed, because the range of the percentage correct responses for the four nonwords varied between 0 and 100 (Bartlett, 1947; Studebaker, 1985). The results of this analysis were similar to the ANOVA results reported above.

Kinematic Data

Duration—The overall movement duration associated with each target word was measured as the time between the initial and final lip opening movements, and indicates the speaking rate for each movement sequence. For /*pate itoʊf p*/, age had a significant effect on movement duration with children showing longer movement durations, $F(1, 32) = 15.2, p = .0001$. No other significant main or interaction effects were obtained.

In Figure 2, the duration of the nonwords is plotted for both groups across Days 1 and 2. The most difficult nonword, /*mæbskrisplə ɪstrub*/ was excluded from the ANOVA as only 2 children on Day 1 and 5 on Day 2 could produce this nonword. Age had a significant effect on movement duration, $F(1, 20) = 20.09, p = .001, \eta^2 = .49$, with adults showing shorter durations. No other main effects were obtained. A facilitatory effect of nonword repetition on movement duration was also observed in a Complexity \times Day interaction, $F(2, 46) = 3.9, p = .03, \eta^2 = .14$. Although participants showed shorter durations for all the nonwords on the second day, the post hoc test revealed this reduction to be significant only for /*mæbspɔkwɪfle ɪb*/ . The 4-way interaction of Complexity \times Day \times Trial \times Age approached significance, $F(2, 46) = 2.8, p = .07, \eta^2 = .11$. In adults, for /*mæbskrisplə ɪstrub*/ (note most children were unable to produce this nonword), paired-sample t-test revealed a reduction in movement duration with practice, that is, the production duration of the first 5 trials was significantly longer than the later 5 trials, $t(12) = 1.9, p = .03$, on Day 1. Retention of learning was observed as a reduction in movement durations of the first, $t(12) = 2.2, p = .02$, and later 5 trials on Day 2, $t(12) = 2.7, p = .009$, as compared to the first 5 trials on Day 1.

Lip aperture variability—For the compound word, /*pate itoʊf p*/, age had a significant effect on the LA VAR scores with children showing higher LA VAR scores and variable LA trajectory patterns, $F(1, 31) = 19.2, p = .0001$. No other significant main or interaction effects were obtained. Figure 3 shows sets of the amplitude- and time-normalized lip aperture trajectories and the average LA VAR scores for /*mæb fe ita ɪdɔɪb*/ on Day 1 in a 10-year-old and a young adult. The 10-year-old shows more variable lip aperture trajectory patterns for the 10 trials, which is reflected in the higher LA VAR score. In contrast, the adult speaker shows a relatively consistent inter-articulatory coordination pattern. In Figure 4, Means and SE for LA VAR scores for the four target nonwords are plotted for both days. Again, because most children could not produce the most difficult nonword, their data are not included in Figure 4. Statistical analysis (for /*mæbfə ɪ fe ɪb*/, /*mæb fe ita ɪdɔɪb*/, and /*mæbspɔkwɪfle ɪb*/) confirmed that the children showed more variability than adults in the inter-articulatory trajectory pattern associated with repeated productions of each nonword, $F(1, 20) = 20.7, p = .001, \eta^2 = .47$. An effect of Complexity indicated that participants in both age groups used more consistent inter-articulatory coordination patterns over multiple repetitions of the least complex nonword, /*mæbfə ɪ fe ɪb*/, $F(3, 60) = 12.8, p = .0001, \eta^2 = .39$. The LA VAR scores were lower on the second day in both children and adults, $F(1, 20) = 20.01, p = .0001, \eta^2 = .50$.

As illustrated in Figure 4, children and adults differed in the pattern of change in LA VAR with nonword complexity across both days. A significant Complexity \times Day \times Trial \times Age interaction, $F(2, 48) = 3.4, p = .04, \eta^2 = .12$, revealed effects of nonword repetition on movement coordination in both children and adults. Children showed a reduction in the LA VAR scores for all 3 nonwords. Adults, on the other hand, failed to show this effect for the least complex nonword, /*mæbfə ɪ fe ɪb*/ . With increasing phonemic complexity, both children and adults showed a reduction in LA VAR that was most evident between Days 1 and 2, rather than within a session, i.e., first 5 vs. later 5.

For adults who produced 10 correct trials of /*mæbskrisplɔ ɪstrub*/, the LA VAR scores were analyzed using paired-sample t-tests. A reduction in LA VAR was seen from the first 5 to the last 5 trials on Day 1, thus showing a clear effect of nonword repetition on movement coordination with practice, $t(16) = 3.05, p = .004$. Significant reductions in the LA VAR scores were also observed on the first, $t(16) = 2.6, p = .009$, and later 5 trials on Day 2, $t(16) = 4.7, p = .0001$, as compared to the first 5 trials on Day 1, thereby showing a speech motor consolidation effect. Finally, the analysis of magnitude of learning revealed that the extent of speech motor learning in children and adults was comparable for /*mæbfɑ ɪ feɪb*/, /*mæb fe ɪtɑ ɪdɔ ɪb*/, and /*mæbspɔkwɪfle ɪb*/, $F(1, 24) = 1.46, p = .23$ (see Table 1).

Kinematic Pattern Analysis

Figure 5 illustrates the zero-lag cross-correlation pattern analysis that was computed for trials 1–8 with the average template of trials 9 and 10 for one adult subject for Day 1. Correlation values were squared before entering them into the ANOVA. In Figure 6, the mean correlation (squared) values for /*mæb fe ɪtɑ ɪdɔ ɪb*/, and /*mæbspɔkwɪfle ɪb*/ are plotted for children and adults for Day 1 and Day 2. Overall, this analysis did not reveal a main effect of Age, both children and adults showed highly positive correlations. A significant main effect of Trial, $F(7, 133) = 6.3, p = .0001$, revealed that the trajectories of the later trials (6–8) correlated more highly with the final template compared to the earlier trials (1–3). An interaction effect of Complexity \times Day was also obtained, $F(2, 38) = 17.2, p = .0001$. As illustrated in Figure 6, for both /*mæb fe ɪtɑ ɪdɔ ɪb*/ and /*mæbspɔkwɪfle ɪb*/, higher correlations were observed between the individual trial lip aperture trajectories and the final template on the second day as compared to the first day. In adults, for /*mæbskrisplɔ ɪstrub*/, a significant main effect of Trial, $F(7, 77) = 2.4, p = .02$, was obtained.

Discussion

In the present study, we examined transient, short-term (within-session) and persistent, longer-term (between-sessions) changes in movement coordination with the repetition of phonemically simple and complex nonwords. Past studies of nonword repetition typically have reported the percent of phonemes produced correctly, and theories of nonword repetition based largely on such reports have attributed a role to existing phonological representations and storage capacity to performance in this task while focusing less on the speech motor output aspects (e.g., Gathercole, 2006). Furthermore, earlier studies of changes in movement coordination with nonword repetition have failed to show effects in adults, while demonstrating significant gains in oro-motor coordination consistency and movement speed within an experimental session in children (Walsh et al., 2006). Our findings demonstrate that nonword repetition involves incremental changes at both behavioral and kinematic levels of performance in both children and adults. The findings suggested that when humans learn new words, even with only five to 10 practice trials, short-term increases in movement coordination occur. Furthermore, the changes that occur within a 30-min session persist overnight to result in further consolidation of the observed changes in movement coordination. The correlation pattern analysis revealed that these changes from early to later trials were systematic in both children and adults, suggesting adjustments in the motor commands toward a more optimal coordinative strategy. The short- and longer-term changes in movement coordination associated with nonword repetition are speculated to result eventually in the acquisition of optimal movement trajectories.

Effect of Phonemic Complexity of Nonwords on Movement Coordination

Behavioral data revealed that both children and adults showed a learning effect seen as an increase in the percent of correctly produced nonwords on Day 2, although as expected, such differences were significant in adults only for the more complex nonwords. This finding

corroborates earlier reports of changes in word learning with increasing exposure to novel words using other tasks, such as, phoneme monitoring, that also facilitate phonological learning (e.g., Gaskell & Dumay, 2001; Leach & Samuel, 2007). A majority of the children were unable to achieve 10 correct productions of the most complex nonword, /*mæbskrisplɔ ɪstrub*/ on both days. Thus, behavioral performance demonstrated a clear effect of phonemic complexity on nonword production. Improvements in behavioral performance were paralleled by similar changes at the kinematic level in both the age groups. In children, speech motor coordination for all nonwords improved within a short experimental session involving approximately 10 repetitions. This finding, previously reported by Walsh et al. (2006), offers evidence for short-term changes in coordination consistency with nonword repetition in children. For the first time, we also demonstrate that if the nonwords are sufficiently challenging in phonemic complexity, young adults show reductions in movement variability with repeated nonword production similar to that seen in children.

The nonword complexity in the present study was varied based on syllable number, age of acquisition of the consonants, and the extent of left-branching length of the consonant clusters (Sevold, Dell, & Cole, 1995). Behavioral studies have demonstrated that phonemic complexity of nonwords varied based on these factors influenced speech production speed and accuracy in children as well as adults (e.g., Gathercole & Baddeley, 1990; Gathercole et al., 1997; Storkel, 2001). Kinematic studies of nonword repetition have, however, failed to demonstrate an effect of these factors on movement coordination in adults (e.g., Walsh et al., 2006). The significant Complexity \times Day \times Trial \times Age effect demonstrates that a learning effect is indeed evident in adults for multisyllabic nonwords containing consonants clusters that are acquired at a later age. For the least complex nonword, /*mæbfa ɪfe ɪb*/, behavioral performance was at ceiling and differences in movement coordination were not observed between Days 1 and 2 in adults. For the same nonword in children, movement variability was lesser for the later 5 trials on Day 1 compared to the first five trials (Fischer LSD, $p = .048$). This finding, also reported by Walsh et al. (2006), suggests the absence of an effect of nonword repetition on movement coordination in adults for relatively simple nonwords. However, with increase in phonemic complexity, for instance in /*mæb fe ɪa ɪdɔ ɪb*/, initial performance was not at ceiling and improvements in oral motor coordination consistency and reduction in lip aperture variability were observed between the first and later five trials on Day 1 (Fischer LSD, $p = .02$) and between the first five trials of Day 1 and the first (Fischer LSD, $p = .01$) and later five trials on Day 2 (Fischer LSD, $p = .01$). With further increase in phonemic complexity, that is, for /*mæbspɔkwɪfle ɪb*/, significance reduction was observed in movement variability only between the first five trials on Day 1 vs. the last five trials on Day 2 (Fischer LSD, $p = .031$). This finding suggests that adults show speech motor learning for phonemically complex nonwords for which they do not have previously established optimal coordinative synergies.

Taken together, the behavioral and kinematic data offer preliminary evidence that even within nonwords of equal length in syllables (e.g., /*mæbfe ɪaɪdɔ ɪb*/, /*mæbspɔkwɪfle ɪb*/, /*mæbskrisplɔ ɪstrub*/), changes in movement coordination with nonword repetition varies based on syllable-internal, phonemic composition. One future line of research is necessary to determine the effect of nonword complexity, indexed by frequency of phonemic transitions (i.e., phonotactic probability) within syllables, on movement coordination. Such an investigation will enable direct testing of speech production models that posit the existence of a mental syllabary to account for production differences between high and low frequency syllables in a language (e.g., Levelt, Roelofs, & Meyer, 1999). Furthermore, some of the observed behavioral and kinematic changes may also be related to improved phonological representation of the nonwords in working memory with repeated practice. While our study was not designed specifically to test the independent contributions of

cognitive and linguistic factors on movement coordination, future studies are required to isolate the effects of such variables on movement coordination.

Short and Longer-term Changes in Movement Coordination with Nonword Repetition

Effects of nonword repetition on movement coordination were observed in both children and adults on both Days 1 and 2. Overall, children exhibited longer movement durations and more variability in the lip aperture trajectories. This finding is consistent with previously reported age-related differences in speech (Green et al., 2002; Smith & Zelaznik, 2004; Walsh & Smith, 2002) and limb (Takahasi et al., 2002; Vangalen, Portier, Smitsengelsman, Schomaker, 1993; Yan et al., 2000) motor performances. We hypothesize that the higher variability in children is associated with higher levels of general neuromotor noise, which results in suboptimal movement trajectories (Harris & Wolpert, 1998). We found additional support for higher levels of general neuromotor noise in children from the Age effect for the compound word, /*pate itotʃ ip*/. In the absence of a learning effect, that is, a reduction in lip aperture variability from Day 1 to 2, higher movement variability associated with this familiar target word suggests further that the speech motor systems in children are physiologically constrained by inherently high neuromotor noise levels, even for the production of familiar syllable sequences that do not require practice. Interestingly, despite the higher variability in children, a comparable magnitude of learning was observed in both children and adults on the nonwords. This suggests that although performance efficiency is limited by neuromotor noise, children show adaptive changes with learning to the same extent as do adults - A finding that alludes to the potential role of external factors, such as, extended practice and external feedback, in facilitating learning in children (e.g., Miall & Wolpert, 1996; Newell et al., 2003). For instance, with extended practice would children show a learning effect, similar to that seen in adults, for the most complex nonword, /*mæbskrisplə ɪstrub*/?

With testing the next day, the gains in consistency and speed of production were maintained in the first five trials. In adults, improvements in oral motor coordination consistency on Day 1 were retained in the early trials on Day 2, although not for all nonwords. Such changes are thought to be the result of both practice and sleep-related consolidation effects (Walker et al., 2002; Walker et al., 2005). As noted earlier, this consolidation effect was also accompanied by an increase in the percent of correct nonwords produced on Day 2. We speculate that short and longer-term increases in coordinative consistency with nonword repetition reflect decreases in general background noise and decreased variability in the motor commands required to generate the speech movement sequences. Evidence for the latter mechanism is provided by the correlation analysis, which indicates systematic changes in movement trajectories towards an optimal coordinative pattern in both children and adults. From the limited evidence in the motor control literature, we speculate that the reduction in the variability of motor commands for the speech movement sequences would reflect reorganization of cortical microcircuitry through changes in synaptic efficiency/weights (Monfils et al., 2005; Newell et al., 2001; Takahasi et al., 2002).

Conclusions

For the first time, we demonstrate that the mature motor systems of adults show neural plasticity, similar to that seen in children, with the repetition of phonemically complex nonwords. The findings also suggest that the phonemic composition of the nonwords determines the extent of the effect of repetition on movement coordination as well as the extent of consolidation of learning thereby supporting a role for speech motor output processes within models of nonword repetition. Our study demonstrates that the short-term changes observed within a single session persist the next day. We interpret this to suggest that the changes that occurred in the short experimental session were associated with

underlying changes in the neural circuitry that control speech movements. One possibility could be that the short-term changes do not translate to persistent, stored changes in patterns, in which case, the lip aperture variability would have been identical for Days 1 and 2. Thus we can hypothesize that the short-term changes do reflect changes in synaptic densities and weights. With consolidation, our pattern correlation analysis indicated that changes in motor commands to muscles occur in a systematic way to reach an optimal coordinative pattern in both children and adults. Future lines of research are proposed to understand further the nature of speech motor learning and the changes associated with the learning of novel phonetic strings in children and adults.

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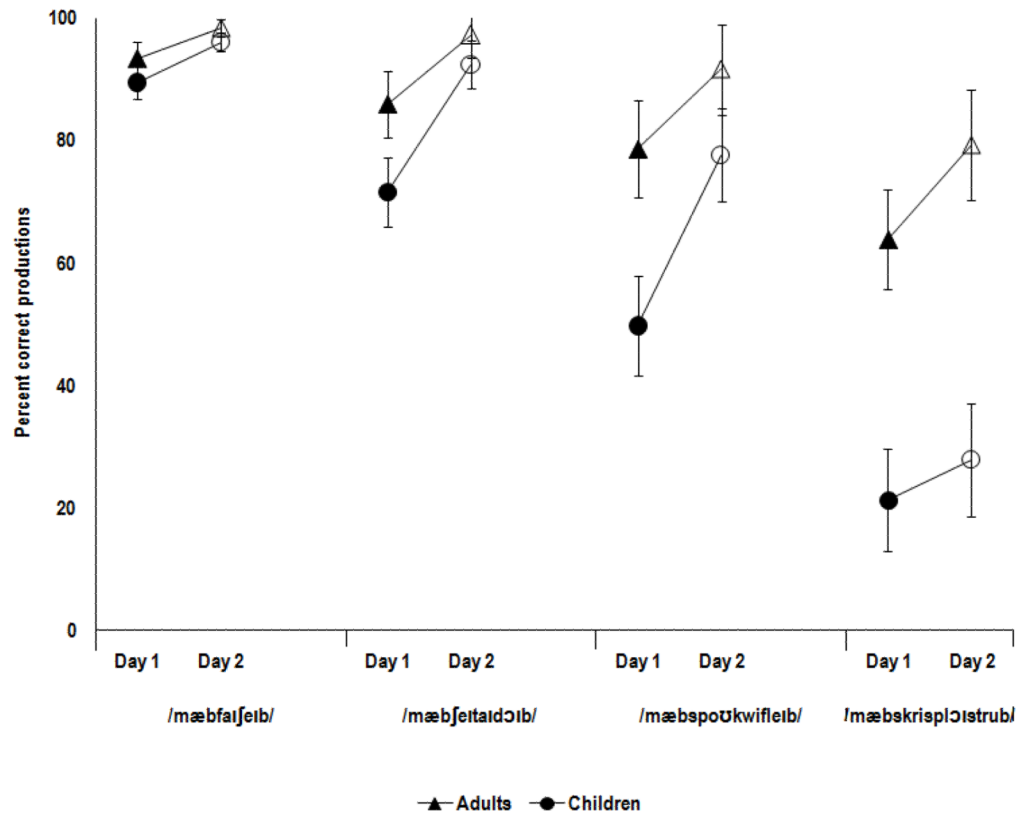


Figure 1. Mean percent correct productions and SE bars for each age group are plotted as a function of nonword and day.

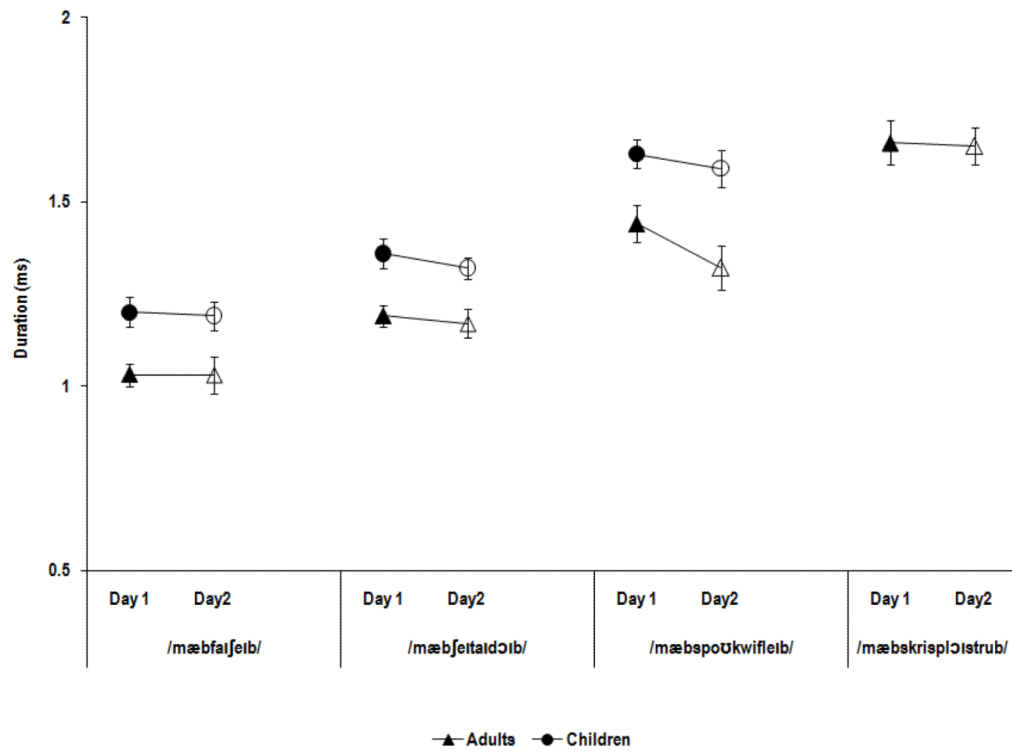


Figure 2. Mean duration and SE of target nonwords on days 1 and 2 are plotted for adults and children.

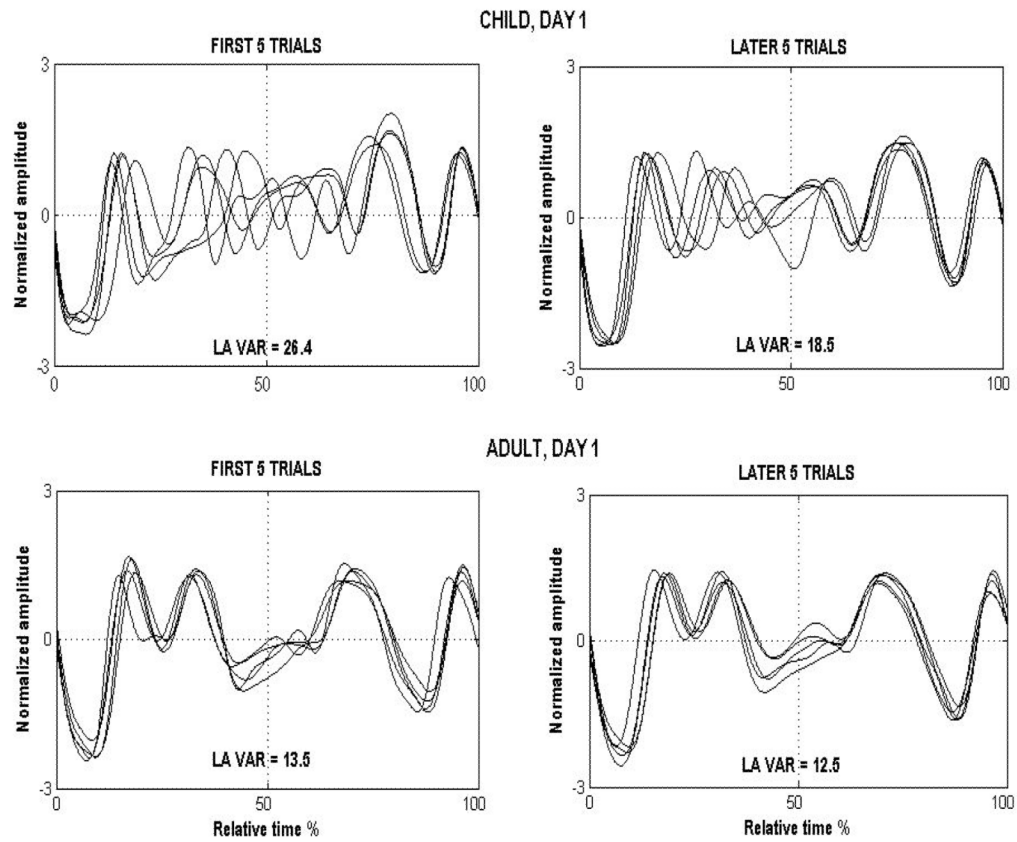


Figure 3. Comparison of data from a 10-year-old and a young adult. In the left panel, amplitude and time normalized articulatory trajectories for the first 5 trials of nonword /mæbspəʊkwɪflə ɪb/ are plotted and the trajectories for the later 5 trials are plotted in the right panel.

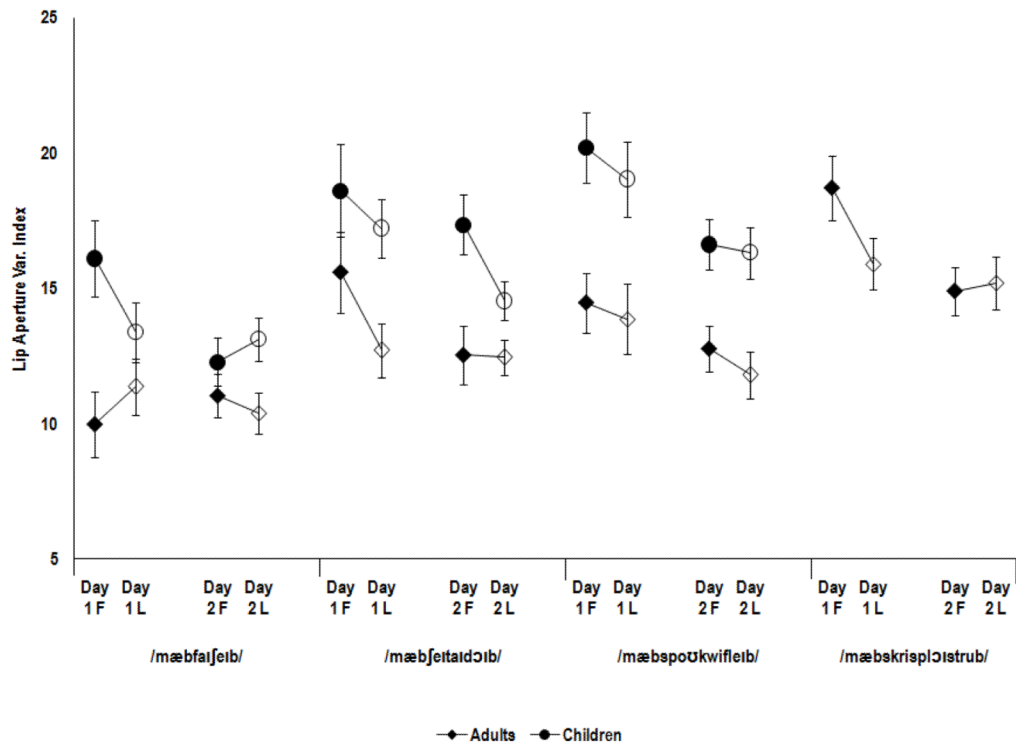


Figure 4. Mean and SE bars for lip aperture variability for the first 5 (F, filled) and later 5 (L, open) trials on Days 1 and 2 are plotted for children and adults.

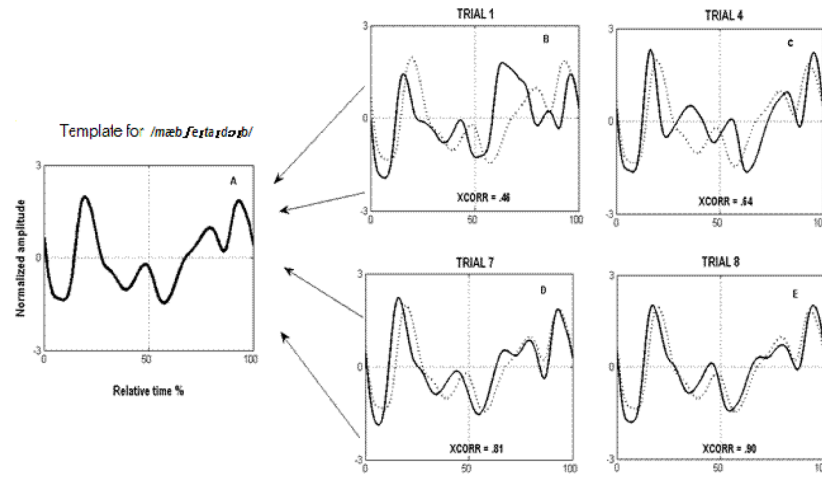


Figure 5.

An illustration of the zero-lag cross-correlation (XCORR) pattern analysis. Plot A—average template from trials 9 and 10. Plots B to E—LA trajectories for trials 1, 4, 7, and 8. The dotted lines plotted with the LA trajectories for each trial is the average template for trials 9 and 10. This subject shows a dramatic increase in the XCORR from trial 1 to 8.

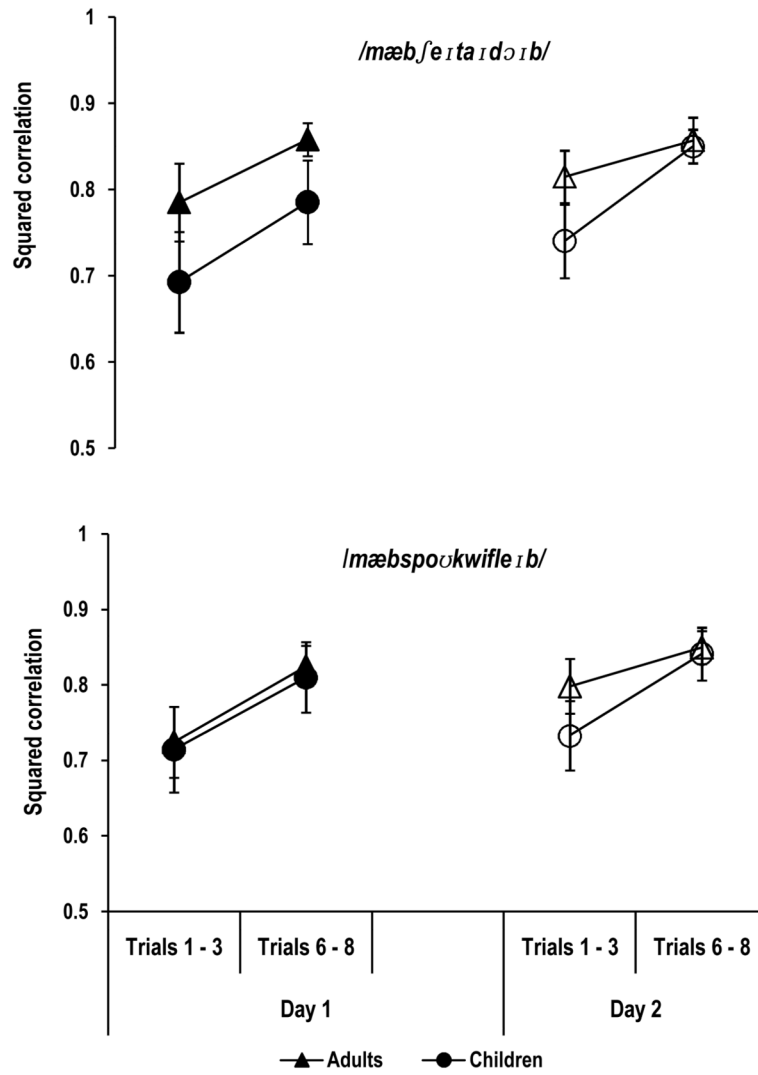


Figure 6.

Illustrated are the mean squared cross-correlation values for the early trials (1–3) and later trials (6–8) with the final template (average of trials 9 and 10) for */mæbfɛɪtɑɪdɔɪb/* and */mæbspɔkwɪflɪb/*.

Table 1

Magnitude of learning (%) in children and adults

Age Group		/mebfafj e i p/	/mce.fetaadob/	/mebspookwiftep/	/mebskrisplozstrub/
Young	M	-6.5	18.4	16.8	16.8
	SE	9.8	5.0	5.4	4.3
9 to 10- year-olds	M	4.8	15.7	15.0	
	SE	8.4	7.8	7.5	