Articulator Movement Associated With the Development of Prosodic Control in Children

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This study explored the relationship between articulator movement and prosody in children at different developmental ages. Jaw, lower lip, and upper lip kinematics were examined in 4-, 7-, and 11-year-old children as they produced the declarative and interrogative forms of utterances "Show Bob a bot" and "Show Pop a pot." Articulator movement differences were found between declaratives and interrogatives during the production of vowel and consonant targets. The 7- and 11-year-olds differentiated the duration and displacement of their articulator movements to distinguish between declaratives and interrogatives. Several age-related differences in movement duration between the 4-year-olds and the older participants were associated with the production of these targets. Productions of declaratives and interrogatives were not associated with any significant differences in articulator movement variability, although variability did decrease significantly with maturation. The results suggest that children modify their articulator movements to meet the prosodic and linguistic demands of the task. While 4-year-olds appear to be able to modify lip and jaw movement to mark the declarative–interrogative contrast, refinement of these movements continues throughout childhood.

KEY WORDS: articulator movement, development, interrogative, declarative

Prosodic information can have grammatical, semantic, emotional, social, and psychological roles in English (Crystal, 1982). Prosody is defined by changes in suprasegmental features of speech that can be observed across syllables, words, phrases, and conversation. These suprasegmental patterns convey meaning but can also serve as a structure on which segmental units are overlaid. In fact, there is evidence to suggest that children master suprasegmental aspects of speech before segmental features (Bloom, 1973; Crystal, 1979; MacNeilage & Davis, 1993; Menyuk & Berholtz, 1969; Snow, 1994). This not only supports the contention that prosodic control emerges concurrently with language development but also illustrates that prosodic control has an important influence on the production of early infant vocalizations and words (Gerken, 1991; Gerken & McIntosh, 1993; Klein, 1981; Schwartz & Goffman, 1995). There are many open questions, however, regarding the role of prosody in children's productions of complex linguistic forms, such as declaratives and interrogatives, particularly in relation to the motor control required for these speech tasks. The present study examined whether articulator movements accompany the prosodic modifications required to signal the declarative–interrogative contrast in children at different developmental ages.

The importance of prosodic control for conveying linguistic meaning is evident in the distinction between contrastive utterances. For instance, falling and rising intonation contours can distinguish declaratives from interrogatives. Adults signal declaratives with falling intonation and interrogatives with rising phrase-final intonation (Cruttenden, 1981; Hirst & Di Cristo, 1998; Lieberman, 1967). Early in development, infants also appear to be able to modify acoustic parameters of frequency, intensity, and duration. Falling frequency contours are produced during infant cry as early as 3 months of age (Kent & Bauer, 1985; Kent & Murray, 1982) and mastered by 4 years of age during the spontaneous productions of one- and two-syllable words (Snow, 1998). Even in imitation tasks, children do not seem to be able to produce a distinction between declarative, interrogative, and monotone intonation contours until 5 years of age (Loeb & Allen, 1993). With respect to duration, final syllable lengthening has been reported in the babbles of 8-month-olds (Robb & Saxman, 1990) and in the early words of 16–25-month-old children (Snow, 1994). This finding is not as robust, however, in older children producing more complex linguistic forms (Snow, 1994). These studies provide evidence that the acoustic realization of prosodic contrasts changes over development. It has been suggested that these age-related changes may reflect differences in the motor complexity associated with the task (Loeb & Allen, 1993). As children produce prosodic contrasts, do acoustic changes in fundamental frequency, intensity, and duration also manifest as changes in articulator movement?

Adults have been reported to produce greater lip and jaw movement displacement and velocity during speech tasks that involve increasing fundamental frequency, intensity, and duration (Dromey & Ramig, 1998; McClean & Tasko, 2002, 2004; Schulman, 1989). As speakers differentiate between rising and falling intonation associated with interrogatives and declaratives, we may then expect to see related lip and jaw movement changes. Thus, anticipated increases in acoustic duration and fundamental frequency for interrogatives may also be accompanied by concurrent increases in articulator movement duration, velocity, and displacement.

There is some evidence to suggest that the production of prosodic contrasts involves changes in movement kinematics during development. Goffman and Malin (1999) examined lower lip movement in 4- and 5-year-old children and adults during the production of trochaic (strong–weak) and iambic (weak–strong) metrical forms. Adults modulated trochaic and iambic forms. In contrast, the children produced trochees with unmodulated, equal amplitude movement sequences (strong–strong) yet the iambs were amplitude modulated. The authors interpreted these results to support the notion that trochees are well established, requiring less distinctiveness, but that increased movement specificity may be required for the production of iambic forms in order to achieve the perceptual goal. Goffman (1999) subsequently examined the production of trochaic and iambic forms in older children (7 years of age) and children with specific language impairment (SLI). The 7-year-olds displayed an unmodulated trochaic form, similar to the 4- and 5-year-olds in their previous study, still not achieving the adult form. Children with SLI produced trochees similarly to their age-matched peers. They did not, however, modulate iambic forms to the same degree seen in the typically developing children. These findings illustrate that articulator movement differences can be seen during tasks requiring prosodic variation and that the refinement of articulatory control continues beyond the age of 7.

Articulator movement variability can also provide insight into the establishment of prosodic control. It is well documented that articulator movement is more variable in children than adults in the production of segmental units (Green, Moore, Higashikawa, & Steeve, 2000; Grigos, Saxman, & Gordon, 2005; Sharkey & Folkins, 1985; A. Smith & Goffman, 1998; B. L. Smith, 1995). Less is known, however, about the relationship between movement variability and the acquisition of prosodic forms. There is some evidence of movement stability differences associated with the production of metrical forms, with iambs being more stable than trochees (Goffman & Malin, 1999). Although this result was not anticipated, as iambic forms are thought to be acquired later than trochaic forms, it was taken to suggest that movement stability occurs as a function of the degree of articulator modulation. Overall, there is evidence that articulatory movement changes contribute to the acquisition of metrical forms. There is little known, however, about the contribution, if any, of the oral articulators to the production of other prosodic contrasts.

The present study explored the motor processes underlying the acquisition of prosodic forms to examine whether children produce kinematic distinctions as they modify prosodic control to alter the meaning of an utterance. Specifically, are the acoustic changes that are associated with rising and falling intonation (in interrogatives and declaratives) exhibited as changes in articulator movement? Examining the productions of interrogative and declarative forms in children at different developmental stages provides an opportunity to determine if there are differences in motor complexity associated with the tasks. It also provides a means to explore the relationship between motor and linguistic aspects of speech production. The information obtained can help us better understand the prosodic deficits that are characteristic of many speech and language impairments, which may then lead to improved clinical methods for use with children with prosodic impairments.

Temporal and spatial aspects of articulator movements were examined. We sought to answer the following research questions:

1. Do children modify duration, displacement, and velocity of articulator movements to mark the interrogative and declarative contrast?
2. Are there variability differences in articulator movement during the production of interrogatives and declaratives?
3. Do articulatory kinematics change across development during the production of interrogatives or declaratives?

Method

Participants

Twelve children, ages 4, 7, and 11 years, participated in the study. Four participants were included in each age group (4-year-olds: $M = 4;4$ [years;months], $SD = 3.5$ months; 7-year-olds: $M = 7;4$, $SD = 5.1$ months; 11-year-olds: $M = 11;3$, $SD = 3.3$ months). These three age groups were selected to provide an account of the kinematic differences in the production of prosody at different stages in development. Four-year-olds were chosen for the youngest group, given the cognitive–linguistic demands of the speaking task. The groups were matched for gender (2 males and 2 females per group). Participants were native speakers of American English with no reported histories of speech, language, or hearing problems and/or developmental or neurological disorders. Inclusion into the study was contingent on passing a speech and hearing screening. Speech and language skills were examined through informal play sessions and parental interviews. All children passed a pure-tone hearing screening presented bilaterally at 25 dB at 500, 1000, 2000, and 4000 Hz. Informed consent was obtained from the participants' parents.

Data Collection and Procedures

The participants were seen for one data collection session. Data were collected in a sound-treated booth with a video camera (Panasonic, Model AG-188) and a MiniDisc recorder (HHB 500 PortaDisc). The participants wore a unidirectional head-mounted cardioid dynamic microphone (Shure, SM10A) placed 1 in. from the corner of the child's mouth.

The participants were seated in a straight-backed chair. The words "Bob," "bot," "Pop," and "pot" were embedded in the phrase "Show___ a ___" to result in the target utterances, "Show Bob a bot" and "Show Pop a pot." These utterances were selected because they included the labial place of articulation in the bilabial phonemes /p/ and /b/, which allowed for visualization of lip and jaw movements. The children were introduced to a group of pictures, which included the character SpongeBob SquarePants ("Bob"), a robot ("bot"), an older male puppet ("Pop"), and a cooking pot ("pot"). Although the targets "Show Bob a bot" and "Show Pop a pot" were imperative utterances, they were produced as declaratives and interrogatives. Both forms of the utterances were elicited using contextual scenarios involving puppets of the target utterances. For example, in a scenario that involved the character SpongeBob SquarePants and a robot ("bot"), there were numerous opportunities for the child to tell the experimenter to "Show Bob a bot" (as opposed to other items) or to ask her to "Show Bob a bot?" (when he/she was unsure of whether that item should be shown to Bob). There were instances where additional verbal cues and/or models were required to elicit the question form or an appropriate stress pattern. Models were consistent across the two experimenters, with the function word "a" produced as a schwa. Only the tokens produced without direct models were analyzed. The order of phrase type (the "Bob" vs. "Pop" phrase) and sentence type (interrogative vs. declarative) was randomized across speakers. Up to 15 productions of each phrase as a declarative and as an interrogative were elicited for a maximum of 60 tokens per participant. The first 10 tokens of each phrase that were perceived by both experimenters to be accurate productions of declaratives/interrogatives and free of articulation/fluency errors were included in the analysis. Tokens that followed a direct model or had missing data points were not analyzed.

A two-dimensional passive reflective marker system was used to track articulator movement. Six reflective markers were placed midsagitally on the face using a method described by Green et al. (2000). Three of the markers were used to track lip and jaw movement: (a) one in the midline of the vermilion border of the upper lip, (b) one in the midline of the vermilion border of the lower lip, and (c) one superior to the mental protuberance of the mandible. Two reference markers were used to account for head movement, one on the nasion and another on the forehead, 2 cm above the nasion. Each marker was approximately 2 mm in diameter. Video and audio recordings were collected at each session. Video recordings were sampled at a rate of 60 Hz.

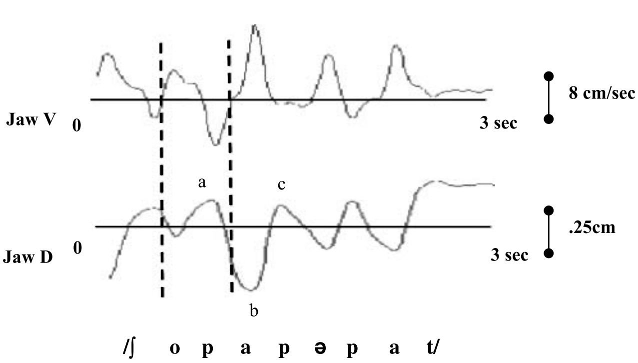
Analyses

A movement tracking system (Motus 32, Peak Performance Technologies, Englewood, CO) was used to digitize x–y coordinates from the videotape. The kinematic signals were digitally filtered using a quintic spline filter. Analysis of data was conducted using Labview Version 4.1 (National Instruments, Austin, TX). The origin was at the nasion. The nasion and forehead markers were used to determine the orientation for the vertical dimension. To account for vertical head movement, upper lip (UL) and jaw (J) movements were calculated by subtracting their y coordinates from a stationary point on the forehead (nasion; UL – nasion; J – nasion). The lower lip (LL) displacement represented the vertical lower lip movement subtracted from the jaw after jaw movement was subtracted from the nasion (LL – J). It should be noted that this jaw subtraction method does not account for rotational jaw movement, and, hence, the lower lip signal may be subject to some error as described by Westbury, Lindstrom, and McClean (2002).

Perceptual judgments. Both authors coded the target utterances as either declaratives or interrogatives from videotapes of the data collection sessions. The following percentages of tokens were eliminated from the data pool: 16% from the 4-year-old group (6% declarative/interrogative error, 5% articulation/fluency error, 5% missing data points), 9% from the 7-year-old group (4% declarative/interrogative error, 2% articulation/fluency error, 3% missing data points), and 4% from the 11-year-old group (2% declarative/interrogative error, 1% articulation/fluency error, 1% missing data points).

Kinematic analyses. Kinematic tracings of the upper lip, lower lip, and jaw were analyzed to study temporal and spatial features of lip and jaw movements. Duration, peak velocity, and displacement of upper lip, lower lip, and jaw movements were obtained for the "Bob a bot" and "Pop a pot" segment of each phrase. These measures focused on movements in the vertical dimension. All trials were examined to determine thresholds for the onsets and offsets of lip and jaw movements. Onsets and offsets of lip and jaw movements were identified separately in each articulator's velocity trace and were based on zero crossings for each trial (see Figure 1). Movement duration was

Figure 1. Kinematic traces of jaw velocity (Jaw V) and jaw displacement (Jaw D) corresponding to the utterance /**ʃo pap ə pat**/. Duration measures were based on zero crossings. For example, the duration of the close–open jaw movement in /**pa**/ (in /**pap**/) was made from the first positive point in the velocity trace after opening for /**o**/ in /**ʃo**/ to the last negative point in the velocity trace after opening for /**a**/ in /**pat**/ (marked by the dotted lines). Displacement measures were based on maximum displacement points. For example, displacement into oral opening was measured from the maximum closing movement for /p/ to the maximum opening movement for /a/ (points a to b). Displacement into oral closing was measured from the maximum displacement in the opening movement for /a/ to the maximum closing for /p/ (points b to c).



examined in three close–open sequences in each utterance: VCV1 (/o ba/ in "Sh***ow Bo***b"), VCV2 (/ab ə/ in "B***ob a***"), and VCV3 (/ə ba/ in "***a bo***t"). Changes in movement displacement were calculated as the peak-to-trough or trough-to-peak vertical displacement. For example, in jaw movement, opening displacement was calculated as the peak-to-trough displacement, and closing displacement was calculated as the trough-to-peak displacement (see Figure 1). Analyses of displacement and velocity were performed for three vowel and three consonant targets. The vowel targets were V1 (the vowel in "P***o***p"), V2 (the vowel "***a***"), and V3 (the vowel in "p***o***t"). The consonant targets included C1 (the word-initial plosive in "***P***op"), C2 (the word-final plosive in "Po***p***"), and C3 (the word-initial plosive in "***p***ot"). Similar analyses were performed for the segment "Bob a bot." These vowel and consonant targets were selected to examine the opening and closing movements associated with each syllable in the analyzed segments.

Statistical analysis. Mixed design analyses of variance (ANOVAs) were performed to examine the effects of utterance type (declarative/interrogative), age (4, 7, or 11 years), and articulator (jaw, lower lip, upper lip) on movement duration, opening displacement, closing displacement, opening peak velocity, and closing peak velocity. The unit of analysis for these analyses was the individual trial rather than the participant means. Pairwise contrasts were performed to examine differences across age and articulator for each variable. Three contrasts were performed: 4-year-olds versus 7-year-olds, 4-year-olds versus 11-year-olds, and 7-year-olds versus 11-year-olds. A Bonferroni correction factor was used that adjusted the alpha level to .017. Variability was measured using a coefficient of variation (standard deviation/mean) to remove the effect of the magnitude of the data from the description of error (Judd & McClelland, 1989). The coefficient of variation was calculated for each variable from participant means and standard deviations. Separate ANOVAs were then performed to examine the effects of utterance type, age, and articulator on duration variability, displacement variability, and peak velocity variability.

Reliability. Intrarater agreement of duration, displacement, and velocity measures was examined. Reliability measures were calculated by obtaining a second duration, displacement, and velocity measurement on 25% of the utterances from 1 randomly selected participant in each age group (4, 7, and 11 years). The correlations between the first and second measurements are reported below, with mean absolute differences and standard deviations shown in parentheses. Reliability measures for each age group were averaged across oral opening and closing gestures as well as across articulator. Reliability of duration measures was r = .981 (mean difference = .009 s, SD = .007) for the 4-year-old, r = .980 (mean difference = .009 s, SD = .007) for the 7-year-old, and r = .998 (mean difference = .002 s, SD = .004) for the 11-year-old.

Reliability of displacement measures was $r = .984$ (mean difference = .016 cm, $SD = .002$) for the 4-year-old, $r = .996$ (mean difference = .003 cm, $SD = .0003$) for the 7-year-old, and $r = .997$ (mean difference = .007 cm, $SD = .0005$) for the 11-year-old. Reliability of velocity measures was $r = .987$ (mean = .004 cm/s, $SD = .0005$) for the 4-year-old, $r = .992$ (mean difference = .002 cm/s, $SD = .0003$) for the 7-year-old, and $r = .965$ (mean difference = .002 cm/s, $SD = .0008$) for the 11-year-old.

Results

Articulator movement duration of close–open sequences, opening displacement, closing displacement, opening velocity, and closing velocity are reported. The variability of movement duration, displacement, and velocity are also described. Statistical results for main effects, interactions, and effect sizes are shown in Table 1.

Duration

The mean articulator movement duration for each age group is shown in Figure 2. The duration of close–open movement sequences differed significantly between declaratives and interrogatives. The 4-year-olds produced all three close–open sequences (VCV1, VCV2, and VCV3) of declaratives with longer duration than interrogatives. The 7- and 11-year-olds produced a similar pattern for VCV1 and VCV2; however, the duration of VCV3 was longer for interrogatives than for declaratives. Significant main effects in utterance type, $F(1, 1334) = 9.557$, $p = .002$, and age, $F(2, 1334) = 86.67$, $p < .0001$, as well as a significant Utterance Type × Age interaction, $F(2, 1334) = 4.77$, $p = .009$, were found. Overall, movement duration was longer in the 4-year-olds than in the 7- and 11-year-olds. Post hoc tests revealed the 4-year-olds to produce VCV1, VCV2, and VCV3 with significantly longer movement durations than the 7- and 11-year-olds ($p < .017$) across utterance type. Further, the 7-year-olds produced VCV2 and VCV3 with longer movement durations than the 11-year-olds. Differences in duration were observed across articulators as jaw movements were shorter than lower and upper lip movements, $F(2, 1334) = 132.49$, $p < .0001$.

Displacement

Opening displacement. Opening displacement did not significantly differ between declaratives and interrogatives. Differences in opening displacement related to age, $F(2, 1334) = 24.42$, $p < .0001$, and articulator, $F(2, 1334) = 469.73$, $p < .0001$, were observed, which appeared to have a contextual basis. The 4- and 7-year-olds produced V1 and V3 (vowels embedded in a CVC contexts "B*o*b" and "b*o*t") with greater displacements than the 11-year-olds ($p < .017$). In V2, the unstressed schwa, the 4-year-olds produced significantly greater displacements than the 7-year-olds ($p < .017$) and the 11-year-olds ($p < .017$). There were no differences for V2 between the 7- and 11-year-olds. Jaw and lower lip displacements were greatest in V1 and V3 and were significantly greater in the 4- and 7-year-olds than in the 11-year-olds ($p < .017$). These differences were supported by a significant Age × Articulator interaction, $F(4, 1334) = 30.69$, $p < .0001$ (see Figure 3).

Closing displacement. Declaratives were produced with greater closing displacements than interrogatives, $F(1, 1334) = 6.46$, $p = .011$. Across utterances, an increase in displacement was observed in C2 (word-final "b" in "Bo*b*") and in C3 ("*b*" word-initial "b" in "bot"). The 4-, 7-, and 11-year-olds all produced greater jaw displacements for declaratives than for interrogatives. The 4-year-olds also produced declaratives with greater lip displacements than interrogatives. There was a statistically significant main effect for age, $F(2, 1334) = 40.129$, $p < .0001$, although the Utterance Type × Age interaction was not significant. The 4-year-olds produced word-initial C1 and C3 with significantly greater displacements than the 7- and 11-year-olds ($p < .017$). Articulator-specific differences in displacement were observed across utterances, $F(2, 1334) = 16.21$, $p < .0001$. Jaw displacement was significantly greater than lower and upper lip displacements ($p < .017$). There was no significant difference in the Utterance Type × Articulator interaction.

Peak Velocity

Opening velocity. There were no significant differences in opening peak velocity between declaratives and interrogatives. Differences in velocity related to age, $F(2, 1334) = 4.23$, $p = .015$, and articulator, $F(2, 1334) = 604.61$, $p < .0001$, were observed. Across age and utterance, peak velocity was greater for V1 and V3 than for V2. The 4-year-olds produced V2 with greater velocity than the 7- and 11-year-olds ($p < .017$). Movement velocity did not differ between the 7- and 11-year-olds. Across ages, jaw velocity was significantly greater than lower and upper lip velocity for V1 and V3 but not for V2 ($p < .017$; see Figure 4).

Closing velocity. There were no significant differences in closing peak velocity between declaratives and interrogatives. Across utterance, age-related differences in velocity were observed, $F(2, 1334) = 20.33$, $p < .0001$. The word-final consonant C2 was produced with greater peak velocities than the word-initial C1 and C3. The 4-year-olds produced C1 and C3 with significantly greater peak velocities than the 7-year-olds ($p < .017$). Velocity differences were evident across articulator, $F(2, 1334) = 86.20$, $p < .0001$. Jaw and lower lip movement velocities in C1 and C3 significantly decreased with age ($p < .017$).

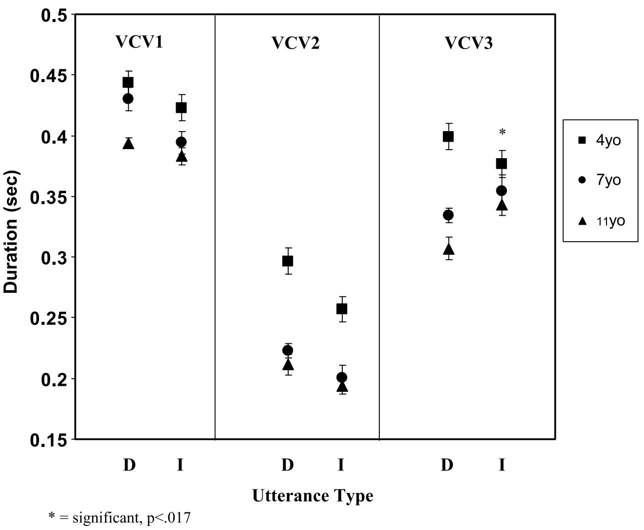
Table 1. Statistial summary for main effects (utterance type, age, and articulator), interactions, and effect sizes (ES).

		Duration			Opening displacement			Closing displacement			Opening velocity			Closing velocity		
	df	*F*	*p*	ES	*F*	*p*	ES	*F*	*p*	ES	*F*	*p*	ES	*F*	*p*	ES
Utterance	(1, 1334)	9.55	.002*	0.007	3.28	.070		6.46	.011*	0.005	3.62	.056		3.48	.062	
Age	(2, 1334)	86.67	.000*	0.115	24.42	.000*	0.035	40.12	.000*	0.057	4.23	.015*	0.01	20.33	.000*	0.03
Articulator	(2, 1334)	132.5	.000*	0.166	469.7	.000*	0.414	16.21	.000*	0.024	604.6	.000*	0.475	86.20	.000*	0.11
Utterance × Age	(2, 1334)	4.77	.009*	0.007	1.98	.139		0.66	.519		1.01	.363		0.02	.981	
Utterance × Articulator	(2, 1334)	1.31	.269		0.45	.638		2.66	.069		0.01	.993		0.69	.500	
Age × Articulator	(4, 1334)	6.89	.000*	0.020	30.69	.000*	0.084	12.91	.000*	0.037	24.85	.000*	0.069	14.91	.000*	0.04
Utterance × Age × Articulator	(4, 1334)	0.38	.820		1.42	.225		1.85	.116		1.66	.157		2.62	.033*	0.01

		Duration Variability			Opening Displacement Variability			Closing Displacement Variability			Opening Velocity Variability			Closing Velocity Variability		
	df	*F*	*p*	ES	*F*	*p*	ES	*F*	*p*	ES	*F*	*p*	ES	*F*	*p*	ES
Utterance	(1, 126)	0.017	.895		1.250	.266		0.278	.599		0.945	.333		0.165	.685	
Age	(2, 126)	9.960	.000*	0.269	8.719	.000*	0.122	6.833	.002*	0.098	10.855	.000*	0.147	14.248	.000*	0.18
Articulator	(2, 126)	0.016	.985		5.594	.005*	0.082	0.184	.832		7.055	.001*	0.101	0.189	.828	
Utterance × Age	(2, 216)	0.243	.785		0.473	.624		0.053	.949		0.144	.866		0.551	.578	
Utterance × Articulator	(2, 216)	0.070	.933		1.268	.285		2.134	.123		0.521	.595		0.721	.488	
Age × Articulator	(4, 126)	0.108	.979		0.569	.686		0.801	.526		1.003	.409		2.464	.048*	0.07
Utterance × Age × Articulator	(4, 126)	0.067	.992		0.594	.668		0.084	.987		0.655	.625		0.024	.999	

*significant difference $p < .05$.

Figure 2. The mean articulator movement duration and standard error in the close–open sequences VCV1, VCV2, and VCV3 between productions of declaratives (D) and interrogatives (I).



Variability

Across-trial variability of articulator movement duration, displacement, and velocity, as measured by the coefficient of variation, did not differ significantly between productions of declaratives and interrogatives. Age- and articulator-related differences in variability were observed across utterances (see Figure 5). As expected, the 4-year-olds produced more variable articulator movements than did the 7- and 11-year-olds.

Duration variability. The duration of close–open sequences was more variable in the 4-year-olds than in the 7- and 11-year-olds. A significant main effect for age was found, $F(2, 126) = 9.960$, $p < .0001$. Pairwise comparisons revealed the variability in duration to be significant in VCV2 between the 4- and 7-year-olds ($p < .017$) and the 4- and 11-year-olds ($p < .017$).

Displacement variability. Variability differed across age for opening, $F(2, 126) = 8.719$, $p < .0001$, and closing displacements, $F(2, 126) = 6.833$, $p = .002$. The 4-year-olds produced more variable articulator movement displacements than the 7- and 11-year-olds. Most notably, productions of V1 and V3, vowels embedded in a CVC structure, were significantly more variable for the 4-year-olds ($p < .017$). Displacement was also more variable for C2 and C3 for the 4-year-olds compared to the 7- and 11-year-olds ($p < .017$). The variability of displacement did not differ significantly between the 7- and 11-year-olds. Articulator-specific patterns in variability were observed, $F(2, 126) = 5.594$, $p = .005$, as opening displacement was characterized by greater jaw variability than lower and upper variability ($p < .017$).

Velocity variability. Articulator movement velocities were more variable in the younger children. There were significant main effects in age for opening, $F(2, 126) = 10.85$, $p < .0001$, and closing velocities, $F(2, 126) = 14.248$, $p < .0001$. Pairwise comparisons revealed opening and closing velocities to be significantly more variable in the 4-year-olds than in the 7- and 11-year-olds ($p < .017$). Specifically, differences were observed in the productions of V1 and V3 as well as C2 and C3. Variability differences in movement velocity were also observed across articulator, $F(2, 126) = 7.055$, $p < .0001$, which were characterized by greater jaw than lip variability ($p < .017$).

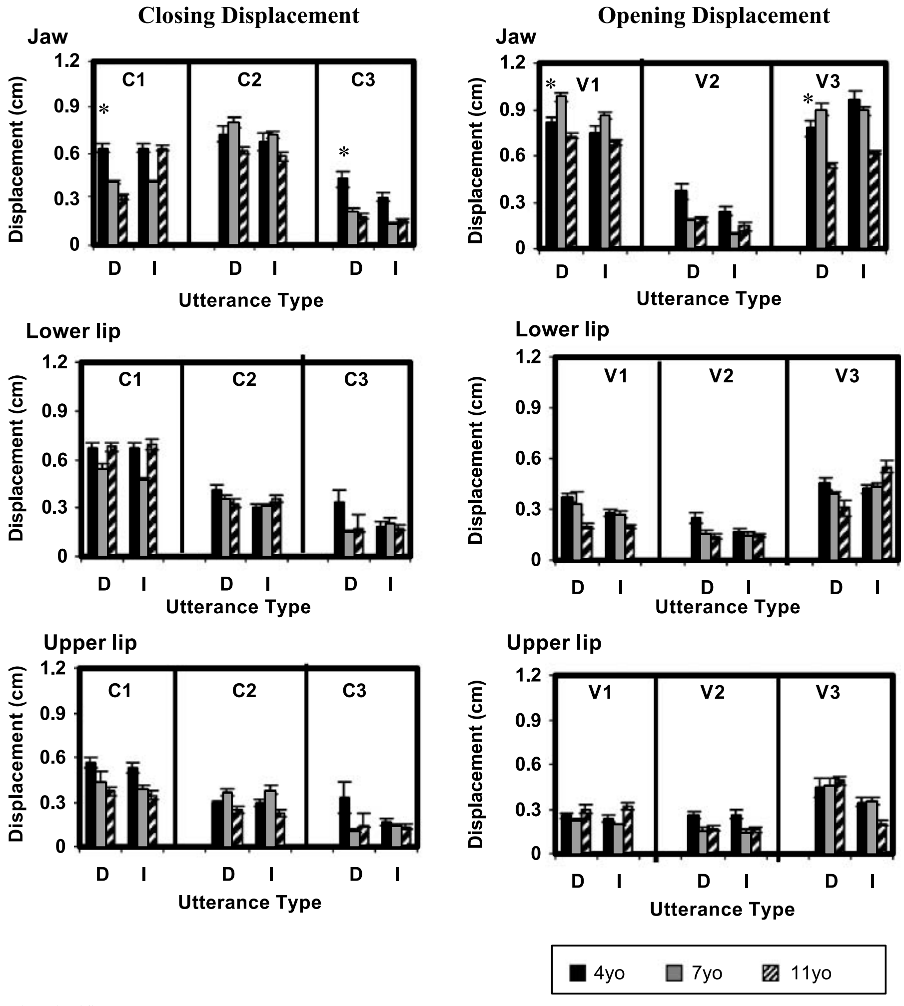
Discussion

Articulator kinematics were examined in 4-, 7-, and 11-year-old children as they produced declarative and interrogative utterances. By 4 years of age, children modified movement displacements to distinguish between declaratives and interrogatives. Differences in duration, however, were only observed in the 7- and 11-year-olds. Productions of declaratives and interrogatives were not associated with any significant differences in articulator movement variability, although age-related changes in variability were observed as the 4-year-olds produced more variable movements than the 7- and 11-year-olds. Taken together, our findings suggest that there are differences in the motor control associated with the production of the declarative–interrogative contrast, as young children differentiate their articulator movements at the prosodic level. Thus, articulator movement changes may contribute to a speaker's ability to convey rising and falling intonation.

Temporal and Spatial Changes Associated With Prosodic Contrasts

Children produced kinematic distinctions as they modified prosodic cues to alter the meaning of an utterance. The production of interrogatives and declaratives was marked by differences in the duration of close–open sequences. The 4-year-olds produced each close–open sequence in declaratives with longer movement durations than in interrogatives. In contrast, the 7- and 11-year-olds lengthened the final close–open sequence, "bo" in "*bo*t," in interrogatives but not in declaratives. This pattern is consistent with final lengthening, which has also been associated with the acoustics of interrogatives in children (Nathani, Oller, & Cobo-Lewis, 2003; Robb & Saxman, 1990; Snow, 1994). Interestingly, this timing distinction was not seen in the 4-year-olds, suggesting that young children may rely less on duration cues to mark kinematic distinctions between utterances. Thus, final lengthening, a pattern that is thought to distinguish interrogatives from declaratives, appeared to be related

Figure 3. The mean jaw, lower lip, and upper lip closing and opening displacements and standard errors between the consonant (C1, C2, C3) and vowel (V1, V2, V3) targets in the productions of declaratives (D) and interrogatives (I).



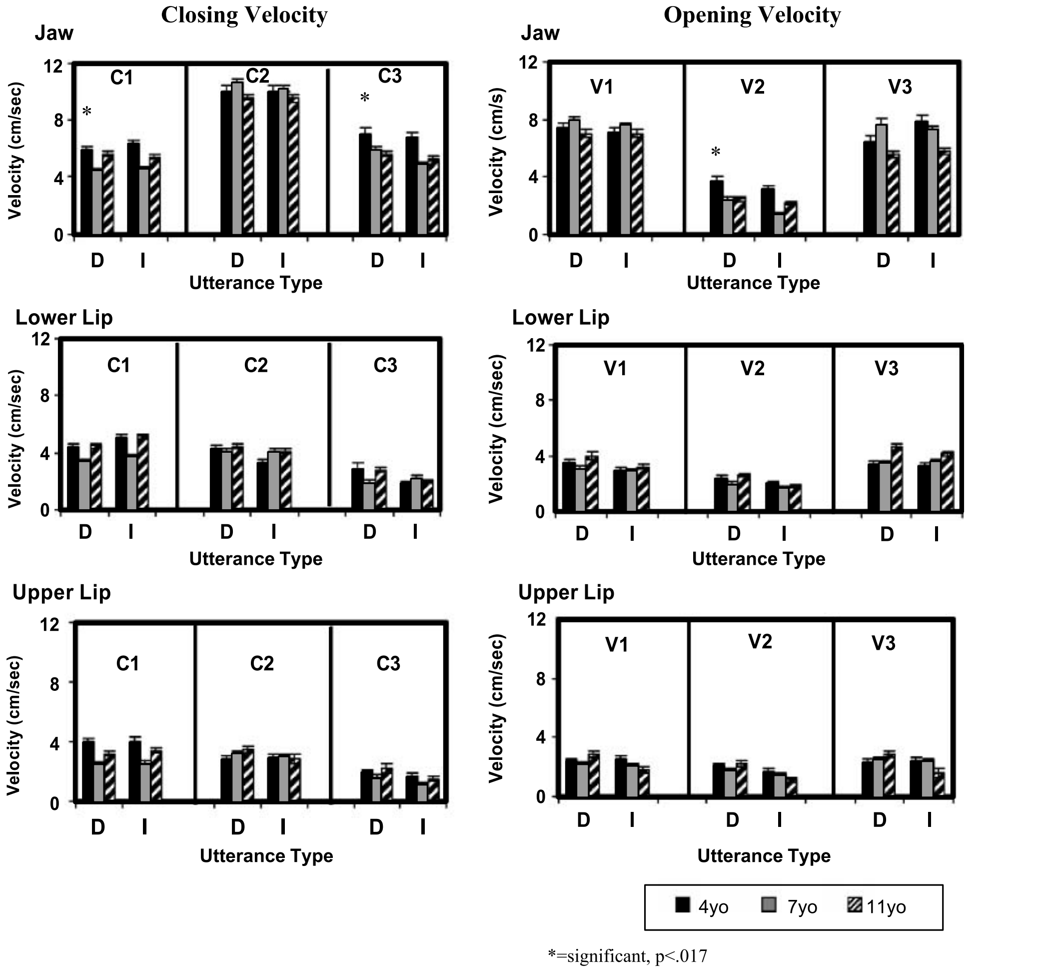
to lip and jaw movement in 7- and 11-year-olds but not in 4-year-olds. The increase in duration in the 4-year-olds also suggests that younger children may require more time to refine temporal patterns in their speech. Higher levels of motor planning may be required to achieve temporal changes (Perkell, 1986), which may be more difficult for younger children. Increased motor planning demands may also be associated with the need for refined coordination of the articulatory, laryngeal, and respiratory subsystems in order to produce a distinction between declaratives and interrogatives.

Spatial control of articulator movements in the production of declaratives versus interrogatives appears to be in place by 4 years of age. Jaw movement, in particular, was greater in declaratives than in interrogatives. The relationship between this kinematic finding and the acoustic changes that have been associated with interrogative productions (increased intensity and fundamental frequency) is interesting and should be explored further. Children may reduce the excursion of their jaw movements to more easily facilitate coordination with the respiratory and phonatory changes required to modify intensity and fundamental frequency.

Articulator Movement Changes and Linguistic Structure

Articulator movement patterns varied across different linguistic structures. Lip and jaw movement differences were found across consonant and vowel contexts, suggesting that syntactic structure and/or linguistic meaning has an impact on articulator movement. Oral closing movements were characterized by differences between word-initial and word-final phonemes. In the 4-year-old

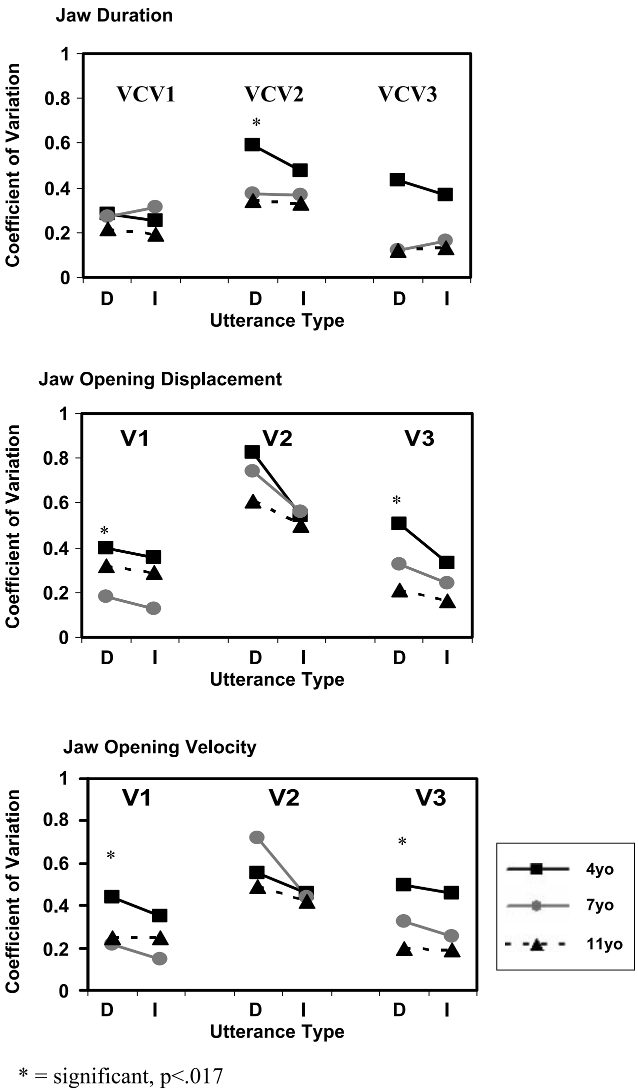
Figure 4. The mean peak velocity and standard errors of jaw, lower lip, and upper lip closing and opening movements between the consonant (C1, C2, C3) and vowel (V1, V2, V3) targets in the productions of declaratives (D) and interrogatives (I).



group, word-initial consonants, C1 and C3, were produced with greater displacements than in the 7- and 11-year-old children. In oral opening movements, there were notable differences in the production of the vowel "a" (V2), as compared with vowels embedded in a CVC syllable structure. Across ages, smaller lip and jaw displacements and velocities were associated with the production of V2, the interconsonantal unstressed function word "a," as compared with vowels embedded in content words. Thus, children at different developmental ages may differentiate their oral opening and closing movements according to linguistic structure. This pattern was consistent across declarative and interrogative forms. These results are particularly interesting in light of other findings that have shown that adults produce kinematic differences across different syntactic contexts but that children do not (Goffman, 2004). In their study, the adults produced rhythmically distinct lower lip movements across different syntactic sequences (content and function + content). The children, on the other hand, produced similar movement sequences across the utterances. In the present study, the syntactic structure of all target utterances included a function + content combination ("a bot" and "a pot") but differed in prosodic organization when produced as declarative and interrogative forms. Our results provide kinematic evidence that children as young as 4 years of age mark a prosodic contrast through changes in articulator movement but not to the extent that older children do. Presumably, while children's representations of different prosodic categories may still be forming at 4 years of age, they are in place by at least 7 years of age.

A possible explanation for the difference between our findings and those reported by Goffman (2004) relates to the linguistic meaning of the targets in each study. The targets in the present study included both real words ("a pot") and nonwords ("a bot"), whereas only nonword targets were used in the Goffman (2004) study. Any influence of linguistic meaning on articulator movement

Figure 5. The mean variability of duration, opening displacement, and opening velocity in jaw movement between productions of declaratives (D) and interrogatives (I).



may have had an impact on the results of these studies. Further research is warranted to examine whether linguistic meaning has an impact on the motor planning and production associated with articulatory control.

Within a framework of changing prosodic organization, it is also important to consider the relationship of lexical stress on our findings. Each target utterance included a strong–weak–strong sequence ("Bob a bot" and "Pop a pot"). Given the evidence that articulator movements increase in stressed utterances (Kelso, Vatikiotis-Bateson, Saltzman, & Kay, 1985; Kollia, Gracco, & Harris, 1995; Van Summers, 1987), we would anticipate lip and jaw movements to decrease in weak syllables ("a") and to increase in stressed ones ("Bob, bot, Pop, pot"). The 4-year-old children in the present study produced the unstressed syllable V2 with greater displacement and velocity, as compared with the older groups of children. Our findings suggest that children may not modify their articulator movement patterns to mark a change in stress until 7 years of age.

Articulator Movement Variability and Prosodic Development

Young children have been observed to produce more variable articulator movements than older children and adults (Green et al., 2000; Grigos, Saxman, & Gordon, 2005; Sharkey & Folkins, 1985; A. Smith & Goffman, 1998; B. L. Smith, 1995). In the present study, there were no variability differences in articulator movement between declaratives and interrogatives. Although changing prosodic demands were not directly associated with articulator movement variability, notable decreases in variability were found between the 4- and 7-year-olds. Increased variability in the 4-year-olds may represent a generalized need for flexibility in the speech motor system to produce a distinction between prosodic contrasts.

Developmental changes in movement variability may also be influenced by linguistic structure. Articulator movements associated with the production of vowels embedded in a CVC syllable structure, for example, were more variable in the 4-year-olds than in the older children. Changes in linguistic complexity associated with an increase in syllable structure may place additional motor control demands on the 4-year-old children but not on older children. At a developmental age where speech and language skills are still undergoing considerable maturation, greater articulator movement variability in the 4-year-olds may be a response to increased cognitive and motor demands. The relationship between linguistic complexity and articulatory control in children should be more closely examined in future studies.

Conclusions

A relationship between prosodic control and oral articulator movement is supported by the results of the present study. Prosodic acquisition appears to be associated with changes in articulator movement. By 4 years of age, spatial aspects of lip and jaw movement are differentiated between declaratives and interrogatives. Temporal control, however, continues to mature until 7 years of age. These findings suggest that refinement of the motor patterns associated with this prosodic contrast evolves throughout childhood. Changes in lexical stress, syllable structure, and linguistic meaning may further influence children's articulator movement patterns. In summary, linguistic and cognitive demands influence articulatory kinematics and prosodic control in children. These findings warrant further exploration into the temporal and spatial movement patterns associated with the production of prosodic contrasts in children with phonological impairments and motor speech disorders.

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References

Bloom, L. (1973). *One word at a time*. The Hague, The Netherlands: Mouton.

Cruttenden, A. (1981). Falls and rises: Meanings and universals. *Journal of Linguistics, 17,* 77–91.

Crystal, D. (1979). Prosodic development. In P. Fletcher & M. Garman (Eds.), *Language acquisition* (pp. 33–48). Cambridge, United Kingdom: Cambridge University Press.

Crystal, D. (1982). *Clinical linguistics*. Vienna: Springer-Verlag.

Dromey, C., & Ramig, L. O. (1998). Intentional changes in sound pressure level and rate: Their impact on measures of respiration, phonation and articulation. *Journal of Speech, Language, and Hearing Research, 41,* 1003–1018.

Gerken, L. (1991). The metrical basis for children's subjectless sentences. *Journal of Memory and Language, 30,* 431–451.

Gerken, L., & McIntosh, B. J. (1993). Interplay of function morphemes and prosody in early language. *Developmental Psychology, 29,* 448–457.

Goffman, L. (1999). Prosodic influences on speech production in children with specific language impairment and speech deficits: Kinematic, acoustic and transcription evidence. *Journal of Speech, Language, and Hearing Research, 42,* 1499–1517.

Goffman, L. (2004). Kinematic differentiation of prosodic categories in normal and disordered language development. *Journal of Speech, Language, and Hearing Research, 47,* 1088–1102.

Goffman, L., & Malin, C. (1999). Metrical effects on speech movements in children and adults. *Journal of Speech, Language, and Hearing Research, 42,* 1003–1015.

Green, J. R., Moore, C. A., Higashikawa, M., & Steeve, R. W. (2000). The physiologic development of speech motor control: Lip and jaw coordination. *Journal of Speech, Language, and Hearing Research, 43,* 239–255.

Grigos, M. I., Saxman, J. H., & Gordon, A. M. (2005). Speech motor development during acquisition of the voicing contrast. *Journal of Speech, Language, and Hearing Research, 48,* 739–752.

Hirst, D., & Di Cristo, A. (1998). A survey of intonation systems. In D. Hirst & A. Di Cristo (Eds.), *Intonation systems* (pp. 1–45). Cambridge, United Kingdom: Cambridge University Press.

Judd, C. M., & McClelland, G. H. (1989). *Data analysis: A model comparison approach*. Orlando, FL: Harcourt Brace Jovanovich.

Kelso, J. A. S., Vatikiotis-Bateson, E., Saltzman, E. L., & Kay, B. (1985). A qualitative dynamic analysis of reiterant speech production: Phase portraits, kinematics and dynamic modeling. *Journal of the Acoustical Society of America, 77,* 266–280.

Kent, R. D., & Bauer, H. R. (1985). Vocalizations of one-year-olds. *Journal of Child Language, 12,* 491–526.

Kent, R. D., & Murray, A. D. (1982). Acoustic features of infant vocalic utterances at 3, 6, and 9 months. *Journal of the Acoustical Society of America, 72,* 353–365.

Klein, H. B. (1981). Productive strategies for the pronunciation of early polysyllabic lexical items. *Journal of Speech and Hearing Research, 24,* 389–405.

Kollia, H. B., Gracco, V. L., & Harris, K. S. (1995). Articulatory organization of mandibular, labial, and velar movements during speech. *Journal of the Acoustical Society of America, 98,* 1313–1324.

Lieberman, P. (1967). *Intonation, perception, and language*. Cambridge, MA: MIT Press.

Loeb, D. F., & Allen, G. D. (1993). Preschoolers' imitation of intonation contours. *Journal of Speech, Language, and Hearing Research, 36,* 4–13.

MacNeilage, P. F., & Davis, B. L. (1993). Acquisition of speech production: Frames then content. In M. Jeannerod (Ed.), *Attention and performance XIII: Motor representation and control* (pp. 453–475). Hillsdale, NJ: Erlbaum.

McClean, M. D., & Tasko, S. M. (2002). Association of orofacial with laryngeal and respiratory motor output during speech. *Experimental Brain Research, 146,* 481–489.

McClean, M. D., & Tasko, S. M. (2004). Association of orofacial muscle activity and movement during changes in speech rate and intensity. *Journal of Speech, Language, and Hearing Research, 46,* 1387–1400.

Menyuk, P., & Berholtz, N. (1969). Prosodic features and children's language production. *MIT Quarterly Progress Report, 93,* 216–219.

Nathani, S., Oller, D. K., & Cobo-Lewis, A. B. (2003). Final syllable lengthening (FSL) in infant vocalizations. *Journal of Child Language, 30,* 3–25.

Perkell, J. S. (1986). On sources of invariance and variability in speech production. In J. S. Perkell & D. H. Klatt (Eds.), *Invariance and variability in speech processes* (pp. 260–263). Hillsdale, NJ: Erlbaum.

Robb, M. P., & Saxman, J. H. (1990). Syllable durations of preword and early word vocalizations. *Journal of Speech and Hearing Research, 33,* 583–593.

Schulman, R. (1989). Articulatory dynamics of loud and normal speech. *Journal of the Acoustical Society of America, 85,* 295–312.

Schwartz, R. G., & Goffman, L. (1995). Metrical patterns of words and production accuracy. *Journal of Speech, Language, and Hearing Research, 38,* 876–888.

Sharkey, S. G., & Folkins, J. W. (1985). Variability of lip and jaw movements in children and adults: Implications for the development of speech motor control. *Journal of Speech and Hearing Research, 28,* 8–15.

Smith, A., & Goffman, L. (1998). Stability and patterning of speech movement sequences in children and adults. *Journal of Speech, Language, and Hearing Research, 41,* 18–30.

Smith, B. L. (1995). Variability of lip and jaw movements in the speech of children and adults. *Phonetica, 52,* 307–316.

Snow, D. (1994). Phrase-final syllable lengthening and intonation in early child speech. *Journal of Speech and Hearing Research, 37,* 831–840.

Snow, D. (1998). Prosodic markers of syntactic boundaries in the speech of 4-year-old children with normal and disordered language development. *Journal of Speech, Language, and Hearing Research, 41,* 1158–1170.

Van Summers, W. (1987). Effects of stress and final consonant voicing on vowel production: Articulatory and acoustic analyses. *Journal of the Acoustical Society of America, 82,* 847–863.

Westbury, J. R., Lindstrom, M. J., & McClean, M. D. (2002). Tongues and lips without jaws: A comparison of methods for decoupling speech movements. *Journal of Speech, Language, and Hearing Research, 45,* 651–662.

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