The Physiologic Development of Speech Motor Control: Lip and Jaw Coordination

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This investigation was designed to describe the development of lip and jaw coordination during speech and to evaluate the potential influence of speech motor development on phonologic development. Productions of syllables containing bilabial consonants were observed from speakers in four age groups (i.e., 1-year-olds, 2-year-olds, 6-year-olds, and young adults). A video-based movement tracking system was used to transduce movement of the upper lip, lower lip, and jaw. The coordinative organization of these articulatory gestures was shown to change dramatically during the first several years of life and to continue to undergo refinement past age 6. The present results are consistent with three primary phases in the development of lip and jaw coordination for speech: integration, differentiation, and refinement. Each of these developmental processes entails the existence of distinct coordinative constraints on early articulatory movement. It is suggested that these constraints will have predictable consequences for the sequence of phonologic development.

KEY WORDS: speech development, motor control, articulatory movement, lips, jaw

The transition from prelinguistic vocalizations to adult speech represents mastery of coordination of multiple speech subsystems. This remarkable behavioral accomplishment emerges in the context of rapid changes in musculoskeletal growth and neuromotor development (Kent, 1976, 1984; Kent & Vorperian, 1995; Smith, Goffman, & Stark, 1995). Predispositions in vocal development suggest that infants have a propensity for certain articulatory dynamics and are functionally incapable of producing later-developing sounds (Locke, 1983; Piske, 1997; Tobin, 1997). Specific evidence of these predispositions is derived from universal regularities in the sequence of phonemic acquisition (Locke, 1983) and the restricted repertoire of phonemes in early speech and babble (Mitchell & Kent, 1990; Smith, Brown-Sweeney, & Stoel-Gammon, 1989; Stoel-Gammon, 1985; Stoel-Gammon & Otomo, 1986). In the present investigation, we examine the possibility that these regularities in early phonology, in part, are the result of biases in the developmental course of oromotor control and that these biases predispose young talkers to produce those phonemes that are within their coordinative capabilities.

Frequently cited models of early speech development (MacNeilage & Davis, 1990; Oller, 1978) predict specific changes in articulatory coordination, although the developmental sequence of early speech motor

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*Currently affiliated with the University of Wisconsin–Madison control has not been studied directly. Research has been impeded by the absence of viable methods for obtaining physiologic measures of articulation in young children (Smith & Gartenberg, 1984). Consequently, many of the most global questions concerning the development of speech motor control have yet to be addressed: What are the motor milestones of speech? How does the sequence of neuromotor development influence the sequence of phonemic acquisition? What are the roles of reflexes and other extant neural circuits in the development of oral motor control for speech?

Of course, the development of speech motor control entails more than just biologic influences. Motor processes of speech are shaped by multiple intrinsic (e.g., cognitive/linguistic and sensorimotor maturation) and extrinsic (e.g., auditory and visual stimulation and perceptual saliency) forces. Accordingly, verbal communication is often modeled as a dynamic system (e.g., Kelso, Saltzman, & Tuller, 1986). The evolution of a dynamic system is limited deterministically by its slowest developing component (i.e., "rate limiting" factors; Thelen, Ulrich, & Jensen, 1989). The rate limiting effects of physiologic development on phonologic acquisition have not been determined, though the relationship between immature articulatory coordination and poor intelligibility in early speech is obvious.

Figure 1 schematically illustrates how sequences in motor development may impose coordinative constraints leading to predictable phonemic biases in early speech. The course of neuromotor maturation and motor learning may differentially constrain early oromotor coordination (coordinative constraints) such that the young child is predisposed to favor some articulators and articulator ensembles. Under these coordinative constraints, the young child is required to generate a motor solution to approximate an adult model. The limited set of motor solutions available to the young talker may engender sound biases that account for the "universals" in phonologic acquisition.

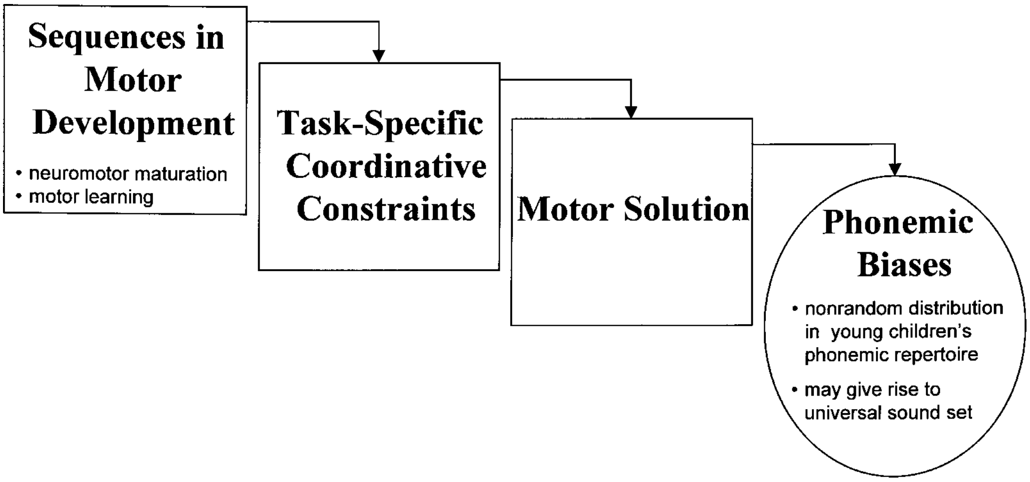
Given this construct, one important step in furthering our understanding of the sequence of phonologic development is to know (a) what coordinative constraints exist at each phase of speech motor development, and (b) how these constraints restrict the child's sound-producing capabilities.

Sequences in the Development of Motor Control

Several distinct sequences in the development of oromotor control may engender specific constraints on early articulatory coordination. Motor development may involve *differentiation* (i.e., the modification of a preexisting behavior into more specialized ones) and/or *integration* (i.e., integration of new behaviors with previously stabilized ones). In contrast to these distinct sequences is a developmental course where the initial coordinative infrastructure resembles its mature form but undergoes continual *refinement*. It is probable that the organization of coordination for speech involves *refinement* and the *integration* and *differentiation* of vocal tract components, with each sequence having a distinct effect on the child's sound-producing capabilities (Fentress, 1984; Kent, 1992; Lenneberg, 1967).

In early motor development, *differentiation* is characterized by increased independence in control of the components involved in a motor task. For instance, during early grasping, the arm segments move as a unit, with the hand being transported primarily by rotation of proximal joints (Jeannerod, 1988). Gradually, the child works toward gaining independent movement of the

Figure 1. A working model illustrating the relationship between sequences in motor development on phonologic acquisition.



arm, hand, and fingers (Schuster & Ashburn, 1992, Trevarthen, 1984).

Limited independence of anatomically distinct segments is common in immature motor systems and is manifested behaviorally as comodulation of nontarget muscles or as the presence of extraneous movements accompanying an intentional movement. Evidence of these "associative movements" has been detected at various levels of organization (e.g., limbs: Lazarus & Todor, 1987; motor units: see Provins, 1997) and anatomical sites (e.g., ears, fingers, and limbs). Associative movements have been observed to decrease with maturation and specific training (Connolly & Stratton, 1968; Lazarus & Todor, 1987).

Development of speech motor control may exhibit a similar progression, where the development of coordinative organization for speech requires increasingly independent control of vocal tract structures. Support for the notion that sensorimotor pathways in the infant's oral region become more specified with maturation is drawn from studies of orofacial reflexes (Barlow, Finan, Bradford, & Andreatta, 1993; Humphrey, 1964, 1971).

The organization of speech motor control may also involve the *integration* of new behaviors with previously stabilized behaviors. Motor control does not develop uniformly across the various motor systems. Along with somatic growth and myelination (Schuster & Ashburn, 1992), motor control generally emerges cephalocaudally and proximodistally (Stallings, 1973). For example, in the developmental sequence for posture, control is first demonstrated in the head and neck and later becomes apparent in the trunk and lower limbs. Development of speech motor control may exhibit a similar progression, where gains in articulatory control are sequential.

It is known that, prenatally, the control of oral structures emerges sequentially (Herring, 1985). For instance, while the lip musculature is still in the premyoblast stage at 8 weeks gestation (Gasser, 1967), the human fetus is already opening the jaw (Humphrey, 1964). Herring (1985) has speculated that the sequence of early oromotor development is orderly and driven by neuromuscular development. However, the varying coordinative requirements for chewing, sucking, and speech ultimately require task-specific descriptions of postnatal orofacial control (Moore & Ruark, 1996; Moore, Smith, & Ringel, 1988; Ruark & Moore, 1997). For instance, although the basic coordinative infrastructure for chewing is well established as early as 12 months of age (Green et al., 1997), children typically do not master the sounds in their ambient language until 8 years (Sanders, 1972). The coordination demands for speech probably exceed those of alimentary functions because (a) alimentary functions involve only a subset of the oral structures engaged for speech production (Bosma, 1985), and (b) the requirements for speech coordination are nonstereotypical and highly time-specified (Gracco, 1994).

Purpose of Study and Statement of Problem

The developmental sequence of labiomandibular coordination may provide evidence of integration, differentiation, and refinement in early speech development. In this preliminary study, we recorded upper lip, lower lip, and jaw movements during the production of syllables containing bilabial consonants across several age groups spanning the developmental continuum from babble to mature speech. The movement signals were subjected to two complementary analyses. One technique described developmental changes in each articulator's contribution to closing the oral aperture for bilabial closure. The other technique compared similarities between articulatory pairs in their spatial aspects of articulatory movement (*spatial coupling*) and their degree of movement synchrony (*temporal coupling*).

If the development of speech entails increasingly independent control of the articulators (i.e., differentiation), we would expect to observe a consistently high degree of interarticulator coupling in early speech: High coupling may be indicative of a lack of coordinative plasticity. Conversely, developmental differentiation of articulatory control could not be supported if young subjects failed to exhibit rigid coupling among articulators. Of course, there are alternative interpretations to observations of tight interarticulator coupling. These interpretations will vary with the speaker's age and the behavior under which coupling is observed. For example, a persistently high degree of movement coupling in the young speaker may reflect a severe limitation on the coordinative options available to the child. In contrast, because adult speakers demonstrate the ability to produce highly independent movements of upper lip, lower lip, and jaw, instances of rigid articulatory coupling exhibited in mature speakers reflects highly specified, coordinated movement.

Alternatively, if the process of integration occurs in the development of speech coordination, we would anticipate that the movement of one articulator would dominate the child's early articulatory gestures. Other articulators would be expected to be assimilated into the gesture later in development. The dominant articulator might emerge earliest because of a developmental physiologic advantage over other articulators with respect to the coordinative organization required for speech. Consistent with this conception of development is the suggestion of MacNeilage and Davis (1990a) that the jaw is the predominant articulator in early speech production (MacNeilage & Davis, 1990a). This hypothesis would be supported if the jaw's contribution to oral closure is greater than that of the lips in early speech and if the relative contribution of the upper lip and/or lower lip increases with development.

Finally, in the absence of one of these distinct developmental progressions, we would anticipate (a) no dramatic shift in the role of each articulator for oral closure, and (b) gradual increases in spatial and temporal coupling among the articulators, with age reflecting refinement. It is likely that each of these sequences in motor skill development coexist, but demonstrate differential degrees of involvement depending on the stage of speech motor development.

Experimental Design and Methods

Subjects

Several stages in speech development were sampled, spanning the continuum from babble to mature speech. Forty-six subjects made up four groups: 6 infants (mean age: 12 months, range: 12 to 14 months, *SD*: ±1 month), 10 toddlers (mean age: 26 months, range: 23 to 29 months, *SD*: ±3 months), 10 children (mean age: 6;6 [years;months], range: 6 to 7 years, *SD*: ±3 months), and 10 adults (means age: 29;5, range: 27 to 35 years, *SD*: ±4;3 years). Gender was balanced in each group. Seventeen additional subjects (15 infants and 2 two-year-olds) failed to produce the target utterances during the experiment and were therefore not included in these subject groups. Participants were native speakers of American-English and were screened during a telephone interview with either the adult subject or the child's parent. Participants had negative histories of speech, language, hearing, or vision problems and of developmental or neurological disorders.

Speech Samples

The target speech utterances sampled were "baba," "papa," and "mama," with stress placed on the first syllable of each utterance. Sampling was limited to bilabial consonants because bilabials (e.g., voiced) occur frequently in early speech (Stoel-Gammon, 1988; Stoel-Gammon & Otomo, 1986) and are produced with a high degree of labiomandibular coupling by mature speakers (Gracco, 1988).

Speech samples from the young children were elicited during play involving the child, the caretaker, and the experimenter. Adult and 6-year-old subjects read the target words from a poster in a pseudorandom order at normal conversational rate and loudness. The experimenter provided verbal exemplars throughout each experimental session.

Approximately 45 speech samples were obtained (15 repetitions × 3 phonemes) from each of the adult and 6-year-old subjects. The younger subjects (infants and 2-year-olds) produced only a subset of these utterances because children this young (a) vary in their willingness to speak in an unfamiliar environment, (b) vary in their vocal imitative skills, and (c) do not typically produce the voiceless bilabial stop (i.e., /p/) until around age 2 (Stoel-Gammon, 1985). The utterances produced by the infants and 2-year-old subjects included both spontaneous and imitative tokens. To eliminate variability from atypical productions for these speakers, utterances associated with "normal" dysfluencies (i.e., blocks or hesitations), coughs, and laughs were excluded from the data set. In addition, utterances were included in the analysis only if complete lip closure was observed on the videorecording.

Data Collection and Recording Conditions

Data were collected in a large sound-treated booth equipped for audio- and videorecording. Subjects' utterances were recorded using a digital audiorecorder (Panasonic, SV-3700) and a wireless remote microphone (Telex, FMR-25) that was attached to a subject's shirt collar. Lip and jaw displacements were extracted from full-face video recording for each subject obtained using an infrared light source and video camera (Burle, TC351A) coupled to a videorecorder (Panasonic, AG-1980). Infrared lighting was used to avoid any potential distractions from a visible light source.

Three flat, circular reflective markers (~2 mm in diameter) were placed midline on the vermilion border of the upper lip (UL) and lower lip (LL) and just superior to the mental protuberance of the mandible (J). Two reference markers (~2 mm in diameter) were also placed along the sagittal midline, one on the tip of the nose and one on the nasion, and were used to correct for extraneous head movement. These two markers translated the measurement origin to the nasion and the vertical axis to the line defined by these markers. A reference marker, placed on the subject's forehead, was used to calibrate the measurement system.

Several precautionary measures were taken to reduce optical distortion associated with videorecording. Distortion due to the shape of the camera lens was minimized by positioning the subject's face in the center of the field of view, with the camera zoom at maximum. In addition, when necessary, children were encouraged to orient their faces to the camera's line-of-sight by having them glance at a toy located just above the camera while speaking. This precaution was necessary because significant rotation about the z-axis distorts the relative sizes among objects projected onto a two-dimensional coordinate system (i.e., x, y).

Digitization and Signal Conditioning

The vertical positions of the upper lip, lower lip, and jaw were extracted automatically from the video-recordings using a computer-based movement-tracking system (Motus, version 2, 1998). We have determined that the precision of this movement tracking system is better than .1 mm (*SD* = .05) under the recording conditions described above.

The accuracy of the movement-tracking system was evaluated by measuring the position of a single marker attached to the end of a micrometer. Vertical displacement of the marker was measured in 16 successive steps of 5 mm each under conditions that paralleled subsequent experimental conditions (e.g., we used the same video-camera, zoom factor, lighting, and reflective stickers).

Following position tracking, the displacement signals were digitally low-pass filtered (f_{lp} = 15 Hz) using a zero-phase shift forward and reverse digital filter (Butterworth, 8 pole). The lower lip signal was derived by subtracting the lower lip displacement signal from that of the jaw. An example of a kinematic record from an adult subject is presented in panel A of Figure 2.

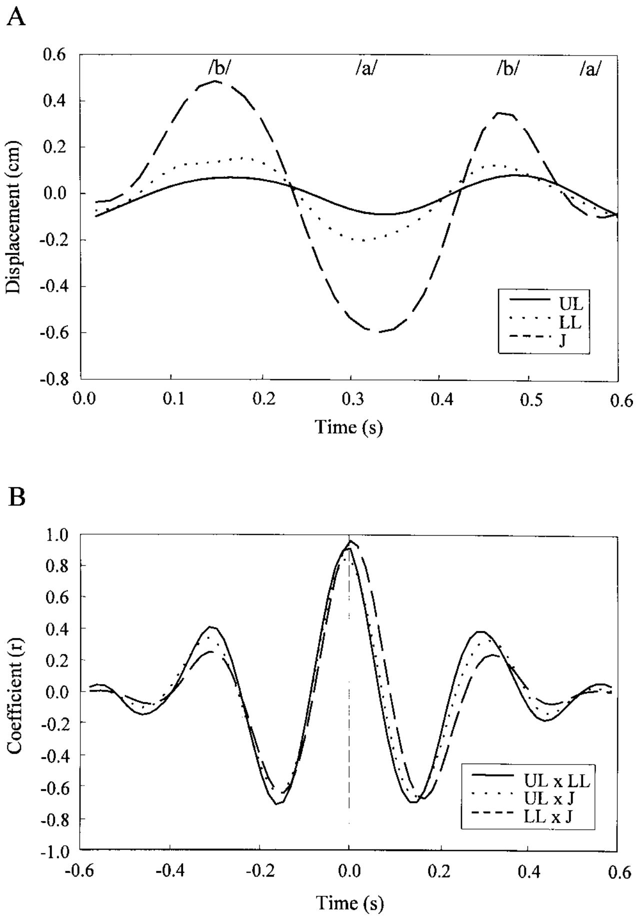
Quantitative Analyses of the Kinematic Traces

The kinematic tracings from upper lip, lower lip, and jaw were subjected to two complementary analytic techniques written for Matlab (version 5.1, The MathWorks Inc., 1998): (1) to measure each articulator's contribution to oral closure during speech, and (2) to compute crosscorrelation functions across displacement records to measure interarticulator spatial coupling and movement synchrony. These analyses, all stages of which were completed using custom Matlab algorithms, are described in the following sections.

Articulatory Contribution to Oral Closure

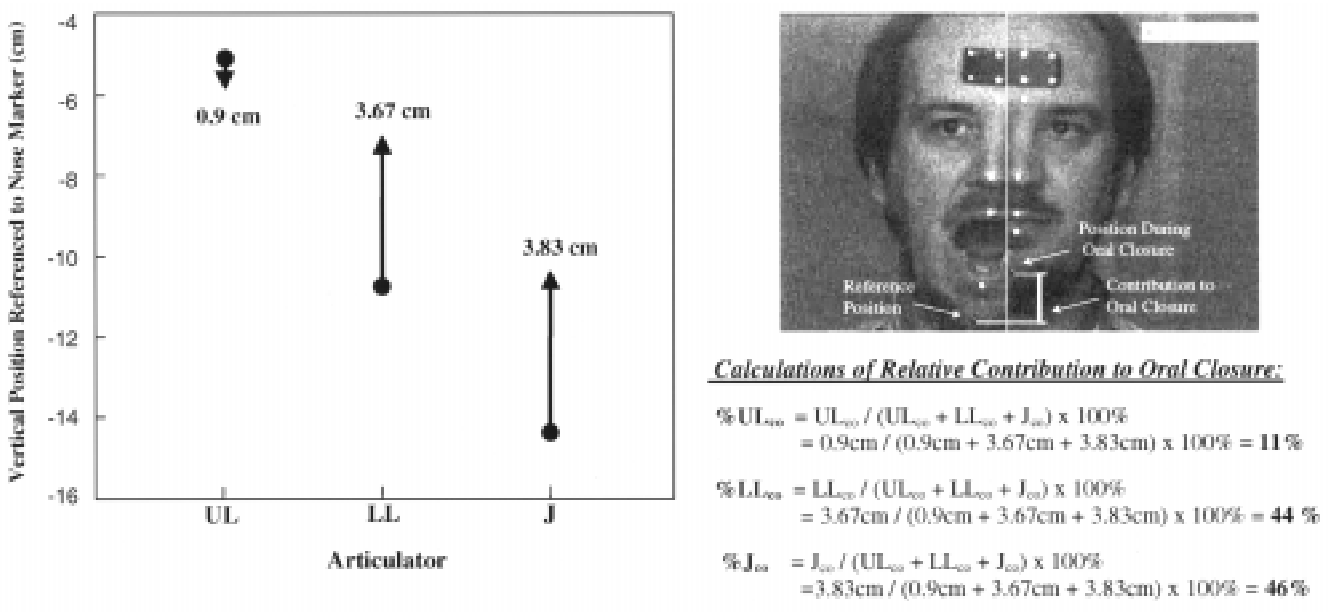
Each articulator's relative *contribution to oral closure* was calculated for each syllable by referencing its position during oral closure to its position during maximum oral opening (see Figure 3). This index reflected the relative contribution of each articulator to closing the oral aperture during bilabial closure for speech. This measure was intended to inform our conception of speech development in that—if integration were operative, for example—we expected one articulator's *contribution* to be significantly greater than the others' in early speech, with the relative *contribution* of the other articulators increasing with age. For example, if the jaw is the predominant articulator in early articulation, as suggested by MacNeilage and Davis (1990), we would anticipate that it would initially contribute most to oral closure and that the lip's contribution would increase with age.

Figure 2. Panel A shows the treated kinematic traces from upper lip (UL), lower lip (LL), and jaw (J) produced by an adult subject saying "baba." For ease of interpretation, each signal has been centered about its mean, and the UL signal has been inverted. Panel B shows pairwise crosscorrelation functions computed on the signals presented in the upper panel. In this analysis, the degree of spatial coupling is indicated by the value of the *coefficient*, and the degree of temporal coupling is indicated by the value of the *lag*. High *coefficient* values and *lags* near zero indicate a high degree of spatial and temporal interarticulator coupling.



Each articulator's position during oral closure was recorded when the distance between the lips was at a minimum for each CV syllable. The reference position was recorded when each articulator was at its maximum open posture. Generally, the lower lip and jaw reference positions were recorded during a yawn, and the upper lip's position was recorded during a smile. To capture

Figure 3. Calculation of relative *contribution to oral closure* for upper lip (UL), lower lip (LL), and jaw (J). The length of each vector corresponds to each articulator's *contribution* to closing the oral aperture. The end of the arrow represents the position of the articulator during oral closure. The circle represents the position of the articulator in its open position (maximum performance task). For each syllable, each articulator's *contribution* was computed by referencing its position during oral closure to its maximum opening position. To calculate relative *contribution to oral closure*, each articulator's value (e.g., UL) was divided by the sum of UL, LL, and J values for each syllable. Note that the rounding of percentages introduces small errors such that the sum of percentages may minimally exceed 100%.



these reference positions, the experimenter verbally and/or gesturally cued each subject to produce a smile and a yawn-like gesture. However, in some instances the maximum open positions were recorded from spontaneous yawns, loud cries, or smiles in the younger children. If available, several maximum opening positions were recorded, and the greatest opening excursion observed was deemed the reference position for a given articulator. Five of the younger subjects (three 1- and two 2-year-olds) were excluded from this analysis because they did not imitatively or spontaneously produce a large oral opening that could be used as a reference position during the data-collection session.

For each syllable (i.e., /ba/, /pa/, and /ma/), the position of each articulator during the reference posture (i.e., maximum opening position) was subtracted from its position during oral closure. These values represented the extent that each articulator occluded the oral aperture. Finally, to calculate each articulator's relative *contribution to oral closure*, the value for upper lip, lower lip, and jaw (calculated in the previous step) were individually divided by the sum of the values computed for all three articulators.

This technique had two advantages over more traditional measures of movement displacement: (1) minimization of the effect of jaw movement variability related to vowel context (Sussman, MacNeilage, & Hanson, 1973), and (2) elimination of the need to precisely identify the onset and offset of each articulatory gesture, which can be unreliable in the irregular movement traces exhibited in young children.

Articulatory Coupling and Synchrony

Peak *coefficients* (negative or positive) and their associated *lags* were derived from the crosscorrelation functions computed between the treated displacement traces of all possible articulatory pairs (i.e., UL × LL, UL × J, LL × J). This analysis was performed to examine the degree of temporal and spatial coupling in early interarticulator coordination. Weak interarticulator coupling was inferred from low peak crosscorrelation *coefficients* and long *lags*; strong interarticulator coupling was inferred from high crosscorrelation *coefficients* and short *lags*. Interpretation of these results was in the context of developmental changes. For example, strong coupling early in speech development with later weakening may reflect gradually increasing independence of control of individual articulators. Because this correlation-based method inherently normalized intersubject differences in movement magnitude, measured changes in interarticulator coordination were independent of differences in vocal tract size.

Before analysis, each signal was centered about its mean, and, for ease of interpretation, the upper lip signal was inverted. The onset and offset of articulatory movement for each utterance were defined as points of zero velocity in the jaw position signal. These determinations of jaw movement onset and offset were used for all the articulators, as jaw displacement waveforms were more predictable and well-defined across age groups (i.e., characterized by two rising and falling gestures across the CVCV utterance) than upper or lower lip displacement waveforms.

Panel B of Figure 2 shows a single crosscorrelation function computed on the displacement traces displayed in the upper panel (Panel A). From each crosscorrelation function, the most prominent peak (positive or negative) within a ~200-ms window centered on zero *lag* was identified from each crosscorrelation function. Temporal resolution was ±8.8 ms, which was determined by the videorecording rate (i.e., 60 frames per second). If the crosscorrelation function did not contain a prominent peak within the 200-ms window, the *coefficient* and *lag* for that articulatory pair were omitted from the final data corpus. This precautionary measure reduced the possibility of erroneously selecting peaks from the crosscorrelation function that were greater in duration than a unidirectional movement (i.e., lip elevation for /p/). For instance, it would be erroneous to select from the crosscorrelation function a prominent negative peak, which may represent the correlation between the opening gesture of one signal and the closing gesture of another. Approximately 8% of all tokens were rejected by this criterion. This proportion did not differ significantly across age groups.

Statistical Treatment

Phonemes were not evenly represented among the age groups. None of the 1-year-olds produced utterances that contained a [p] exemplar. In addition, two of the 2-year-olds did not produce examples of the /p/, and half of the children in this group produced five or fewer of these utterances. This imbalance in the data set required evaluation of potential phoneme effects on the three coordinative indices (i.e., *contribution to oral closure, coefficient*, and *lag*). The results of a three-way analysis of variance on repeated measures (phoneme × pair × gender) indicated that there were no statistically significant phoneme effects for *coefficient* [$F(2, 168) = .26$, $p = .77$], *lag* [$F(2, 168) = 2.26$, $p = .11$], or *contribution to oral closure* [$F(2, 150) = .18$, $p = .84$]. Given these results, the data for each subject were collapsed across phonemes to yield a single average for each coordinative index.

Developmental trends were examined by computing the average of each coordinative index for each subject (i.e., *contribution to oral closure, coefficient*, and *lag*). For ease of interpretation, *lag* values were converted to negative before collapsing the data. This transformation allowed the direction of the developmental trend for *lag* to parallel those of *coefficient* (i.e., generally, development reflected by increases in each metric). The subjects' averages were combined in each age group and subjected to a three-way ANOVA (gender × age × articulator pair). For each coordinative index, multiple comparisons of the articulator-by-age interaction were performed among all age groups using the Bonferroni procedure with an alpha level of .05. There were no statistically significant gender effects for any of the measures: *coefficient* [$F(1, 107) = .66$, $p < .42$], *lag* [$F(1, 169) = 3.66$, $p < .06$], *contribution to oral closure* [$F(1, 92) = .001$, $p < .99$].

Reliability of Measurement

One subject in each group was selected randomly for analysis of reliability. The same experimenter remeasured all the utterances produced by these subjects for the three coordinative indices (i.e., *contribution to oral closure*, *coefficient*, and *lag*), which together constituted approximately 10% of the entire set. The average absolute difference between first and second measurements of *coefficient* and *lag* was .012 and 3 ms, respectively, which were acceptable for the present analysis. Pearson product moment correlations between the first and second measurements for each of the three indices ranged from 0.96 to 0.99, indicating that the difference between the two measurements was negligible. Measures of percent *contribution to oral closure* were reproducible with 100% accuracy because this analysis relied heavily on computer algorithms.

Results

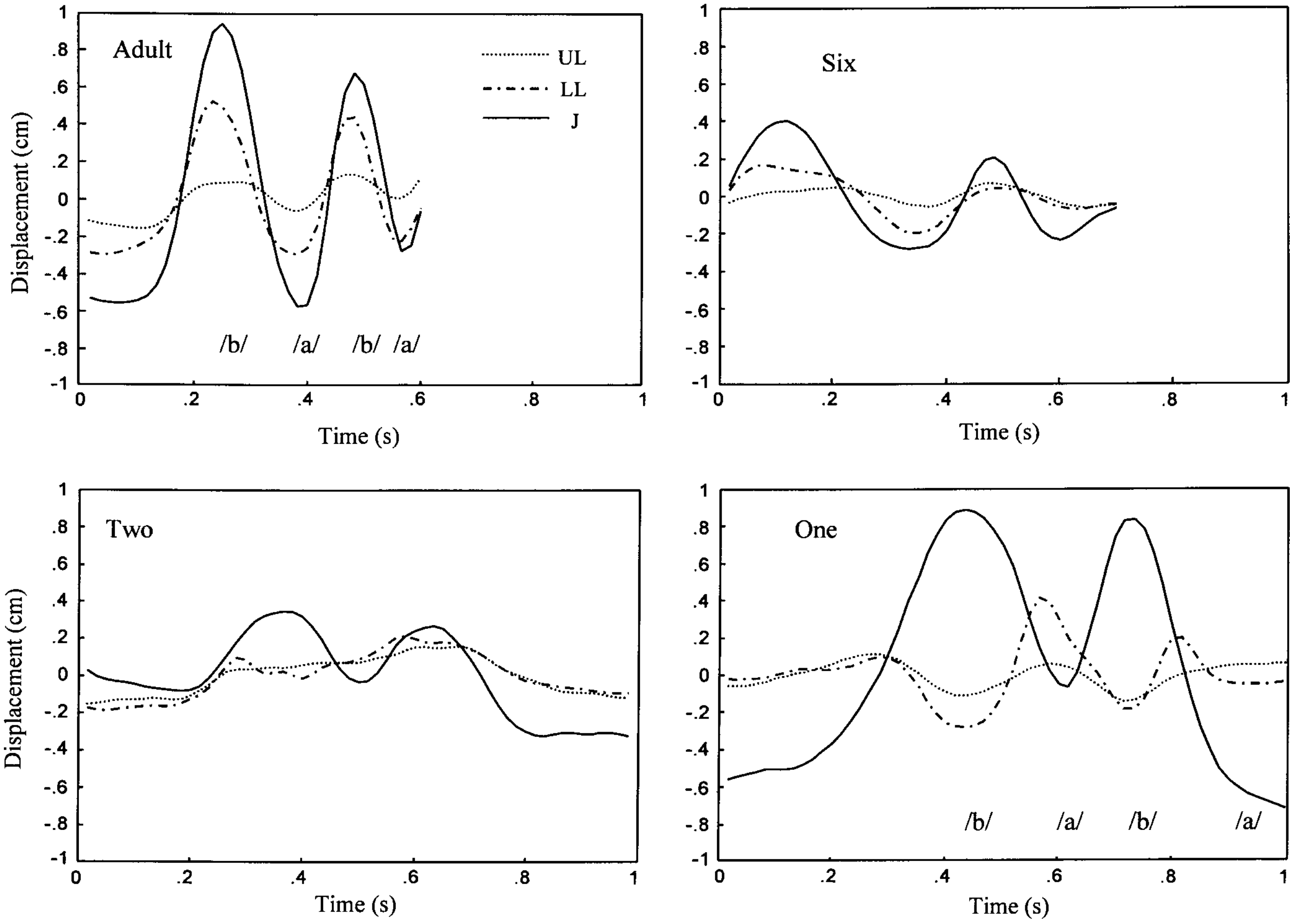
Data Corpus

A total of 1,161 utterances were analyzed, including 54 from the 1-year-olds, 256 from the 2-year-olds, 429 from the 6-year-olds, and 422 from the adults. All utterances were CVCV combinations produced in isolation with the exception of 9 from the 1-year-old group. Five of these utterances were spontaneous productions of VCV combinations (e.g., /aba/) or CV with mouth initially in an open position, and 4 were CVCV combinations extracted from continuous canonical babble.

Qualitative Observations

Figure 4 includes a kinematic record from one subject from each age group producing "baba," and Figure 5 shows the associated video clips from which the movement traces were derived. These examples illustrate

Figure 4. Representative kinematic records for the upper lip (UL), lower lip (LL), and jaw (J) from a subject in each age group based on a single trial. For ease of interpretation, each kinematic signal was centered about its mean, and the upper lip signal was inverted.



differences in the coordinative organization exhibited among age groups that were analyzed quantitatively and described in this investigation. Adult subjects uniformly produced these movement sequences with high levels of interarticulator coupling. As illustrated in Figure 4 (panel: Adult), displacement trajectories in these subjects were characterized by a predominant single rising and falling pattern for each syllable.

In contrast to the adult pattern, in many instances, 1-year-old children exhibited pronounced jaw displacements accompanied by excessive compression of lip tissues during oral closure. As displayed in Figures 4 (panel: One) and 5 (panel 1c), this compression was associated with oppositional movement (180 degrees out of phase) of the lips and jaw. These deflections at oral closure were much larger than those observed in any other age group. In general, the 1-year-old subjects exhibited a variety of lip configurations for oral closure within a single data collection session. In some instances, the lips appeared to be in their resting position during closure, but in others they were held in a static position with the lower lip elevated and the upper lip depressed. Thus, closure was often accompanied by jaw movement alone at this age. In 2-year-old subjects (Figure 4, panel: Two; Figure 5, panels 2a–2e), the upper and lower lip displacements increased relative to those produced by the 1-year-olds, and jaw displacements appeared to decrease. Again, the 1-year-olds' large lip displacements appeared to be generated by jaw movement during oral closure. For the 2-year-olds, the upper and lower lip displacement trajectories were often similar in form (e.g., "mirror movements") and frequently were characterized by a single rise-fall sequence extending across both syllables. The displacement patterns of 6-year-olds (Figure 4, panel: Six) were similar to those of adults, but were more variable.

Contribution to Oral Closure

Several developmental changes in labiomandibular coordination for oral closure were observed. The percentage *contribution to oral closure* differed significantly for

Figure 5. These video clips were selected from the movement sequences presented in Figure 4 to illustrate the distinct movement patterns for oral closure observed among 1-year-old, 2-year-old, 6-year-old, and adult subjects.

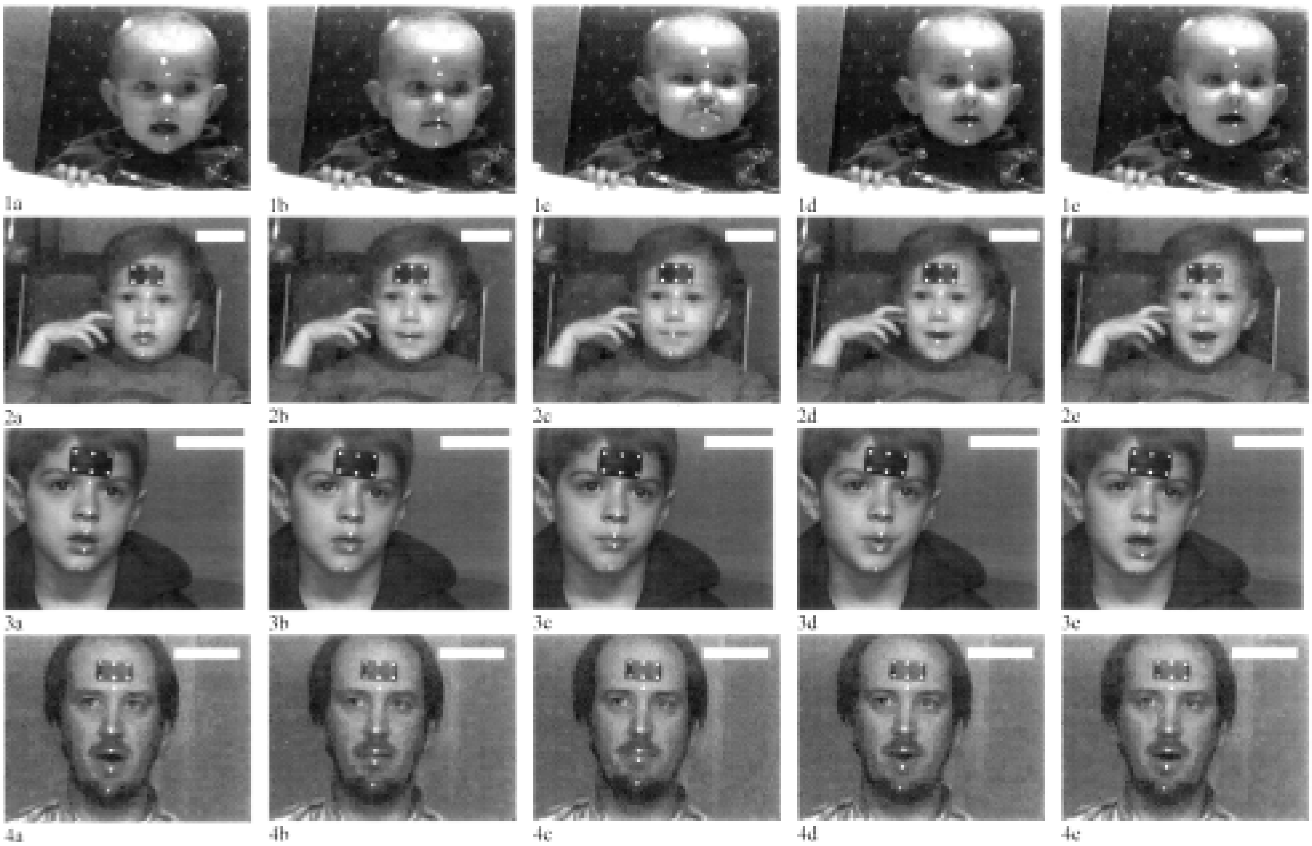
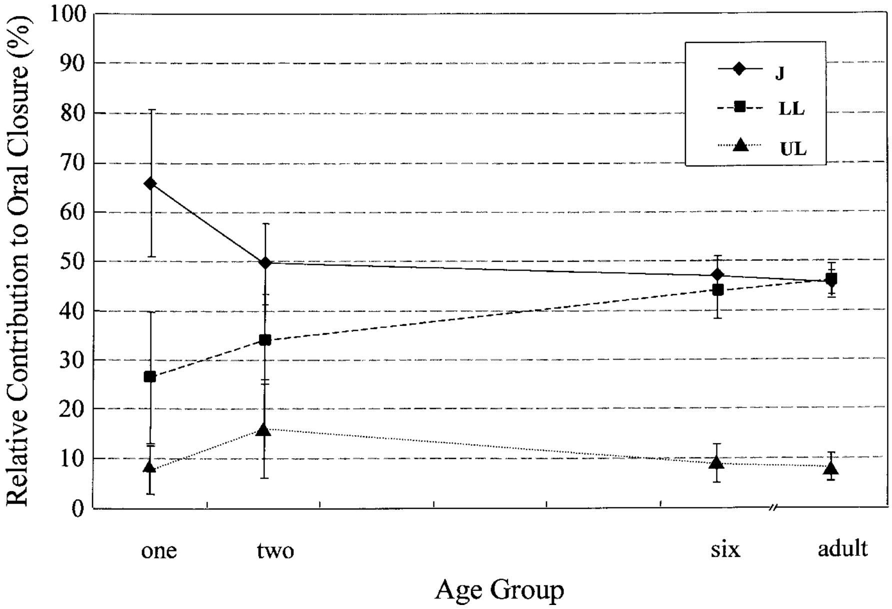


Figure 6. Relative *contribution to oral closure* for each articulator by age. Error bars represent average standard deviation between subjects in each age group.



each articulator across age groups [Articulator × Age: $F(6, 92) = 11.34$, $p < .001$]. Figure 6 displays the means and standard deviations by age group for UL, LL, and J.

Multiple comparisons of the articulator-by-age interaction using the Bonferroni procedure revealed specific age-related changes in the relative *contribution* of each articulator. *Contribution* of the jaw was significantly greater in 1-year-olds than any other group. Thus, a significant decrease in the jaw's *contribution* occurred between ages 1 and 2 years. The LL's *contribution* increased significantly between ages 2 and 6 years. The increase in UL's *contribution,* noted in Figure 6, at age 2 failed to reach statistical significance.

Age-related coordinative biases in articulatory displacement were revealed by differences in the *contribution to oral closure* within each age group. The multiple comparisons analysis indicated that in 1- and 2-year-old children, jaw displacement contributed most to oral closure, followed by LL, then UL. In contrast, 6-year-old children and adults' LL and J contributed similarly to closing the oral aperture, and the UL contributed significantly less than either of these articulators.

Crosscorrelation Analysis

Crosscorrelations were performed on kinematic traces to examine developmental changes in inter-articulator spatial coupling and synchrony. The peak *coefficients* and *lag* values exhibited by the youngest subjects were of special interest. Specifically, high spatial and temporal coupling (high *coefficients* and low *lags*) in early speech might reflect poor independent articulatory control, a state consistent with the initial stage of differentiation. Conversely, low spatial and temporal coupling (low *coefficients* and high *lag* values) in these groups would not support the existence of preexisting movement ensembles in early speech motor organization.

Spatial Coupling

Spatial coupling increased significantly with age [$F(3, 84) = 28.41$, $p < .001$]. Figure 7 shows the averages and standard deviations of peak *coefficient*s values obtained at each age for each articulator pair. The only significant interaction was articulator pair by age [$F(6, 84) = 3.0$, $p < .01$].

Multiple comparisons of the interaction of articulator pair and age revealed different developmental progressions for UL × LL, UL × J, and LL × J. As shown in Figure 7, UL × LL coupling was relatively high for the younger age groups. In contrast, coordination between lip and jaw pairs was very weak at age 1 year as UL × J and LL × J *coefficient*s were centered near zero. Coupling between these articulators increased gradually with age, although several adjacent age groups did not differ significantly on these measures. Specifically, 6-year-olds did not differ significantly from 2-year-olds nor from adults for UL × J, nor from adults for LL × J.

Age-related coordinative characteristics were revealed by differences in the relative degree of spatial coupling among articulator pairs within each age group. Table 1 highlights the age-related changes in spatial coupling that

Figure 7. Average *coefficients* and standard deviations obtained from pairwise crosscorrelations for upper lip and lower lip (UL x LL), upper lip and jaw (UL x J), and lower lip x jaw (LL x J) by age. Error bars represent average standard deviation between subjects in each age group. *Coefficient* values close to one reflect a high degree of spatial coupling.

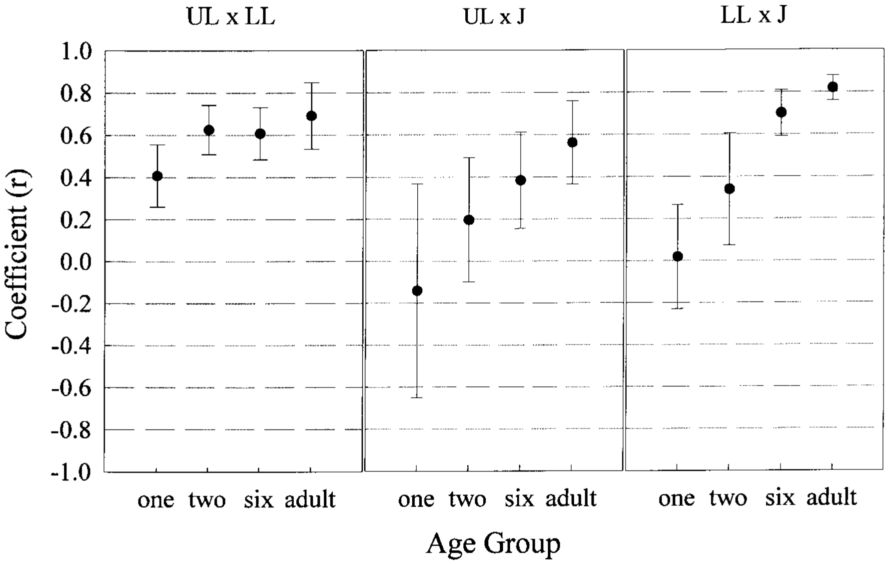


Table 1. Results of pairwise comparisons of *coefficient* values. Larger values indicate greater movement coupling. ≈ denotes differences between means that did not achieve statistical significance.

Comparison	Age			
	One	Two	Six	Adult
UL × LL vs. UL × J	0.4 > –0.2	0.6 > 0.2	0.6 > 0.4	0.7 ≈ 0.6
UL × LL vs. LL × J	0.4 > 0.0	0.6 > 0.3	0.6 ≈ 0.7	0.7 ≈ 0.8
LL × J vs. UL × J	0.0 ≈ –0.2	0.3 ≈ 0.2	0.7 > 0.4	0.8 > 0.6

occurred for all three articulator pairs based on the results of the multiple comparisons analysis. One- and 2-year-old children exhibited greater spatial coupling between the lips than between the lips and jaw. In contrast, for adult subjects, spatial coupling for UL × LL was not significantly different from that of UL × J and LL × J (i.e., UL × LL [UL × J and LL × J]). In 6-year-olds and adults, UL × J coupling was lower than for LL × J coupling.

Movement Synchrony (Temporal Coupling)

Similar to the coefficient analysis, movement synchrony, as measured by the *lag-to-peak coefficient*, increased with age [$F(3, 84) = 5.43$, $p < .01$]. Figure 8 displays the averages and standard deviations of *lag* values across the age groups for UL × LL, UL × J, and LL × J, respectively. Across age groups, movement synchrony was greater in UL × LL and LL × J than in UL × J [$F(2, 84) = 7.54$, $p < .001$]. Average *lag* values did not exceed 29 ms for any age group, indicating that, overall, articulatory movements were tightly coupled.

The multiple comparisons revealed longer *lags* for 1-year-olds than for 6-year-olds and adults for LL × J. In contrast, there was no age effect for UL × LL or UL × J. The relative degree of synchrony among articulator pairs did not differ significantly among any age groups.

Discussion

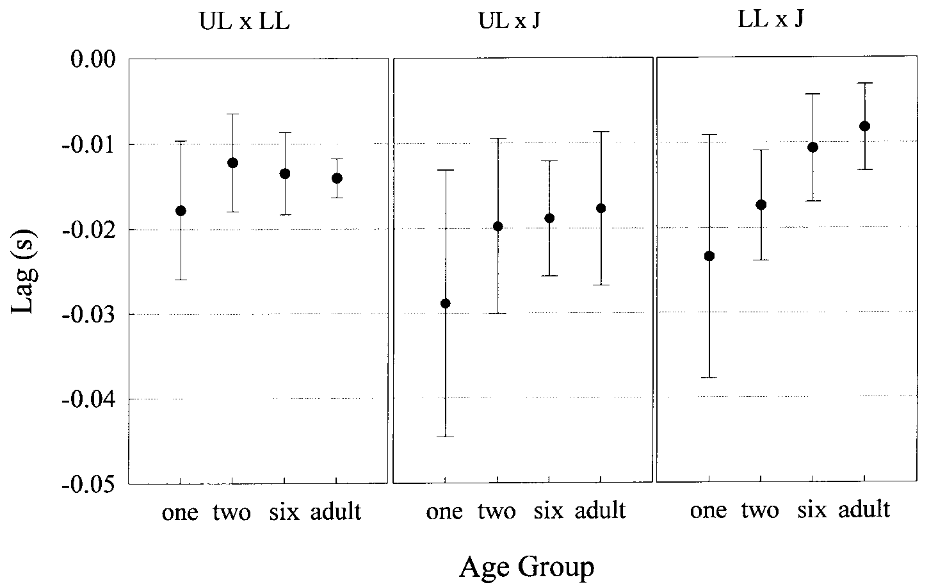
The Development of Articulatory Coordination: Integration, Differentiation, and Refinement

The coordinative organization of the articulatory gestures studied shifted dramatically during the first several years of life and continued to be refined past age 6. The present findings might be interpreted to support three primary phases in the development of lip and jaw coordination for speech, integration, differentiation, and refinement. Although distinct developmental changes occurred at each hypothetical phase, we do not assume that these phases were mutually exclusive. The coordinative constraints imposed by each of these developmental sequences may have predictable consequences for phonologic development.

The Mature Pattern

The adults' movement patterns exhibited several features characteristic of skilled movement (see Figure 4). The articulators exhibited near-synchronous movement

Figure 8. Average absolute *lag* values and standard deviations obtained from pairwise crosscorrelations for UL x LL, UL x J, and LL x J for each age group. Error bars represent average standard deviation between subjects in each age group. *Lag* values close to zero reflect high levels of temporal coupling.



and well-formed movement trajectories, which were characterized by a single, predominant, rising and falling pattern for each CV syllable. These features yielded high *coefficients* and short *lags* in the crosscorrelation analysis and were consistent with previous descriptions of adult articulatory control for bilabial stops (Gracco, 1988; Löfqvist & Gracco, 1997). Additionally, the lower lip and jaw were comparably involved in closing the oral aperture in adult subjects, and the upper lip contributed significantly less than either of these articulators.

One-Year-Olds

Coordinative integration in the development of early speech production was supported by the assimilation of lower lip movement into the established jaw movement pattern, which was observed for oral closure between the ages of 1 and 2 years. This finding provides physiologic support for MacNeilage and Davis's (1990) suggestion that the earliest articulations are dominated by jaw movement with little or no contribution from the lips. This developmental sequence is also consistent with observations of the early jaw movement in prenatal development of orofacial control (Humphrey, 1971) and is further supported by studies showing the coordinative organization for jaw control during speech to be adult-like by 15 months of age (Moore & Ruark, 1996). The reduced lip and jaw spatial and temporal coupling observed in the present study suggest that the young child is not endowed with predetermined movement synergies (e.g., a widely distributed central motor program or shared neural control) among these articulators.

Nittrouer (1993, 1995) suggested that children master some vocal tract ensembles or speech gestures earlier than others. The present results support this assertion and further suggest that the formation of articulatory gestures must operate within the coordinative constraints imposed on individual articulators by the motor system. Therefore, one important step in accounting for the emergence of speech gestures will be the description of the developmental sequence of motor control for individual articulators.

Although infants generally produced well-formed jaw movements, the lips were often compressed by elevating forces of the jaw during oral closure (see Figures 4 and 5). This pattern of interlabial compression may reflect the generation of poorly controlled mandibular force. Kent (1992) suggested that early articulatory movements are rapid and ballistic (i.e., movements are characterized by high velocity and exhibit rapid acceleration and deceleration). He differentiated these types of movements from those produced with constant velocity over a relatively long duration (e.g., /w/). A limited ability to regulate jaw movement may explain why complete closing and opening gestures are so common in early vocalizations (Locke, 1983).

Excessive displacement in early speech may be related to a more general characteristic of immature motor control—in the same way, for instance, that overshooting of the hand and arm is a feature of immature grasping (Jeannerod, 1988). This notion coincides with Bernstein's (1996) suggestion that one essential aspect in motor control development is the reduction of superfluous movement. The present findings raise the possibility that during the first year of life the *spatial* (i.e., activation of the appropriate muscles) and *temporal* (i.e., activation and deactivation in appropriate sequence) aspects of jaw control for speech may be under better control than the *magnitude* of movement (i.e., exertion of appropriate amount of inhibition or excitation).

Two-Year-Olds

The role of differentiation in the development of interarticulator coordination was suggested by the movement patterns of the 2-year-old subjects. This putative linkage between upper and lower lip control raises the possibility that further speech motor development requires increasingly independent control of these anatomically distinct structures. Qualitative impressions and crosscorrelation analyses suggested limited independent control of upper and lower lips. As demonstrated in Figure 4, lip movement trajectories at 2 years old could be remarkably similar in shape and amplitude, especially when compared to the movement trajectories of the jaw.

In comparison to lip and jaw pairs, 2-year-old children exhibited rigid spatial and temporal coupling of upper and lower lips. The functional significance of high *coefficients* and short *lags* may vary depending on the age of the subject. For instance, the high degree of interarticulator coupling in adults reflects highly specified, coordinated movement. In adult speakers, the upper and lower lips have distinct loci of neural control (Abbs & Gracco, 1984; Goffman & Smith, 1994; Smith, 1992; Wohlert & Goffman, 1994) and are capable of producing highly independent movements. However, in young speakers, a comparably high degree of coupling may indicate a lack of coordinative plasticity.

The suggestion that the lips may behave as a unit in early speech development would be strengthened if an increase in the UL's and LL's *contribution to oral closure* was followed by a decrease in UL's *contribution*. (The decrease shown for 1- and 2-year-olds in Figure 6 did not achieve statistical significance.) Earlier investigations have shown that upper-lip displacement decreases with age (Watkin & Fromm, 1984). Capturing developmental changes in UL control between ages 1 and 2 years is challenging using the present experimental design because of the rapid changes in coordinative organization occurring during this period. The present findings support the need for investigations of lip control for speech that are longitudinal or that sample at shorter age intervals.

Linked upper-lip and lower-lip control may be related to a more general feature of motor skill development, termed *associative movements* (Todor & Lazarus, 1986) or *motor overflow* (Cohen, Taft, Mahadeviah, & Birch, 1967). Limited independent control among anatomically distinct structures is commonly observed in early development where symmetrical muscles (homologous) and asymmetrical (heterologous) muscles tend to produce associative movements (Lazarus & Todor, 1987). Associative movements have been reported to decrease with maturation and with differential practice (Provins, 1997).

A more rigorous test of this speculated differentiation requires the observation of increased upper- and lower-lip coupling in speech tasks that specify independent control of those structures (e.g., as during the pronunciation of /f/ in *food*). Future studies will describe the extent of linked upper- and lower-lip control in early speech.

Six-Year-Olds

The present findings give the impression that the period between 6 years old and adult reflects continued refinement of movement control and optimization of coordination. Between ages 2 and 6 years, lip and jaw spatiotemporal coupling continued to increase. Qualitative observations revealed that movement patterns exhibited by 6-year-olds were similar to those of adults, but were found to be more variable. Generally, spatial and temporal coupling in 6-year-olds decreased in comparison to those observed in adults, although differences between these groups were small and did not reach statistical significance. The involvement of upper lip, lower lip, and jaw for oral closure was similar between 6-year-old and adult subjects. These findings parallel the continuous refinement of speech performance from midchildhood to adolescence (Goffman & Smith, in press; Sharkey & Folkins, 1985; Smith & Goffman, 1998).

Mechanisms: Data, Theory, and Speculation

The observed sequences in speech motor development reflect extensive changes in the articulator's neuromotor pathways and anatomic/biomechanical composition as well as general principles of motor learning. This discussion evaluates potential neural and motor learning correlates.

Developmental Sequences and Changes in Neural Substrates

Integration and differentiation in early development of oromotor control may reflect several neural mechanisms: (a) the effective neural centers mediating the articulators may mature at different times (i.e., entailing subsequent integration), and (b) some neural centers may be functionally indistinguishable (i.e., entailing eventual differentiation). Because neural mechanisms cannot be identified from behavioral data (i.e., the problem of inverse kinematics), we can only speculate about their existence.

Several investigators have suggested that the location of a neural center is a good predictor of when it matures. Somatic growth and myelination (Schuster & Ashburn, 1992) proceed cephalocaudally and proximodistally—processes that are also reflected in early motor skill development (Stallings, 1973). Jeannerod (1988) hypothesized that the early appearance of proximal control in the arm is associated with an inherent neural organization where proximal motor pathways have unique locations from those controlling distal segments. In addition, Kubota and colleagues (Kubota et al., 1988) have provided compelling evidence that sucking appears earlier than biting because facial motor pathways mature (e.g., myelination and cell area) before trigeminal motor pathways in mice. Because the present results indicate that articulatory control emerges earlier in the jaw than in the lips, studies should investigate whether humans exhibit a developmental pattern that is the reverse of that observed in mice, with the trigeminal motor pathways developing before facial motor pathways.

With respect to differentiation of upper- and lower-lip control, the subnuclei in the facial motor nucleus controlling upper and lower lip may be functionally indistinguishable in early development. Although there appear to be distinct sources of neural input to the upper and lower lips in mature speakers (Abbs & Gracco, 1984; Goffman & Smith, 1994; Smith, 1992; Wohlert & Goffman, 1994), the immature neuromotor system may not be endowed with this fine level of organization. This suggestion parallels the increases in specificity of perioral afferents with maturation observed by Barlow and colleagues (1993) and is consistent with the suggestion by Edelman and colleagues (Edelman, 1987; Sporns & Edelman, 1993) that the formation of distinct neuronal pathways requires specific experiences. Accordingly, speech maturation may require experience-related differentiation of subpopulations within the facial nucleus or higher neural centers.

Changes in Coordinative Organization Associated With Motor Learning

The observed changes in articulatory coordination probably also reflect motor learning, which may be represented as independent of maturation. Motor learning exhibits distinct phases (i.e., temporary motor solutions) with the accumulation of practice and experience. The transient adoption of a specific motor solution will depend on such factors as the complexity of the task and its relationship to pre-existing skills.

According to Bernstein (1996), novice performers of a complex motor task solve the degrees of freedom problem by "freezing" or "linking" some components to reduce the number of controlled elements (e.g., the wrist and fingers in handwriting: Newell & van Emmerik, 1989; the shoulder, elbow, and wrist in racquetball: Southard & Higgins, 1987). The ability to control each segment separately is achieved through practice and is accompanied by improved performance (Southard & Higgins, 1987). The rigid coordinative linkage of upper and lower lips in the present study may reflect the 2-year-old's attempt to constrain the number of controlled elements.

Bernstein's (1996) hypothesis might be interpreted to suggest that young children simplify extant articulatory goals to achieve more effective and efficient articulation. In this case, control demands may be reduced by inhibiting one or several components of an existing ensemble. Alternatively, young children may recruit only those articulators over which they have adequate control (Kent, 1992). This possibility may especially apply to the early predominance of jaw movement in comparison with that of the lips.

Another motor learning hypothesis is that the jaw-dominant pattern and the tightly coupled lip movements of early speech are the consequence of negative transfer of learning. Transfer-of-learning effects occur when a pre-existing skill influences the learning of a new skill (Magill, 1993). The labiomandibular movement patterns established for feeding may influence initial attempts to coordinate these structures for speech. In fact, features of lip and jaw coordination for sucking (i.e., both lips statically contracted while the mandible moves) are similar to those produced by the 1- and 2-year-olds in the present study during speech. Traditionally, behaviors such as chewing and sucking have been viewed as facilitating speech motor development (see Moore & Ruark, 1996). However, if negative transfer effects are operative, the advancement to mature speech may require the young child to overcome ingrained oromotor patterns. Although most negative transfer effects tend to be short-lived and are easily overcome through practice—for example when learning a sport (Magill, 1993)—this effect may be more persistent during motor skill development.

Physiologic Constraints and Phonologic Acquisition

Several researchers have advanced a "physiological and human factors" orientation to phonology (Diver, 1979; Tobin, 1997), suggesting that constraints in the articulatory production and the auditory perceptual systems produce lawful relations in phonology. In this view, universal patterns in the favoring and disfavoring of phonemes in early speech may, in part, be explained by inherent differences in ease of production (Tobin, 1997). Articulatory ease may also account for biases in place, voice, and manner of articulation exhibited in early speech (e.g., the prevalence of voiced bilabial stops in early speech; Stoel-Gammon, 1988).

Similarly, the constraint-based model presented in Figure 1 predicts that sequences in speech motor development will have predictable consequences for the sequence of phonologic development. If immature speech reflects the child's exploitation of the articulators over which they have the most control, the divergence from babble to speech may entail the breaking away from preferred coordinative patterns toward those in the ambient language. The present study is an initial description of these constraints at the level of single and multiple interacting articulators.

The observed coordinative features that may limit sound-producing capabilities during the first several years of life include (a) the prevalence of jaw movement, (b) poor lip and jaw coupling, (c) poor lip control, and (d) poor upper- and lower-lip movement independence. These coordinative constraints may explain, for instance, why bilabial stops (i.e., voiced) predominate the infant's consonantal repertoire and why labiodental fricatives do not emerge until around age 2 (Stoel-Gammon, 1985), with mastery attained at age 4 (Sanders, 1972). That is, the coordinative requirements of voiced stops apparently do not exceed the capabilities of the immature articulatory system. Stop consonants can be produced using relatively ballistic jaw control without active contribution from the lips or tongue (MacNeilage & Davis, 1990). In contrast, articulation of the labiodental /f/ requires graded and independent lower lip and jaw control to produce a slight constriction between the upper central incisors and the lower lip.

Other researchers have come to the similar conclusion that early speech motor organization is well adapted for producing stop consonants, but poorly adapted for producing phonemes that demand the exertion of graded muscle force (e.g., fricatives, liquids, affricates). Tobin (1997) suggested that one important variable in determining the articulatory ease of a phoneme is the degree of constriction. Phonemes that require a narrow constriction (e.g., labiodental fricative /f/) may require greater control and sustained effort over time in comparison with those produced with a complete closure (i.e., stops). Similarly, Kent (1992) has suggested that early articulations might be produced with relatively rapid or "ballistic" articulatory movement, differentiating this class of phonemes from those that appear later and require "fine force regulation for frication" (p. 75).

In summary, the present results suggest that an improved understanding of the constraints on early speech motor coordination will broaden our understanding of phonologic development. From a developmental motor control perspective, the biases in early phonologic development might be affected by a number of factors, including pre-existing neuromuscular organization, previous experiences, and the spatial and temporal motor requirements of a given phoneme.

Methodological Limitations

Several methodological factors may have influenced these results and require consideration. One potential problem with using skin-based markers is contamination from mechanical linkages among tracking points (e.g., LL and J). If mechanical linkages significantly influenced the position of the movement markers, we would have expected the correlation values to be uniformly high in the crosscorrelation analysis (Löfqvist & Gracco, 1997). The wide range of correlation values observed suggests that mechanical linkages were minimal.

Another potential problem for this analysis was achieving the reference postures in the young subjects. We could not be confident that the young children were producing the greatest possible degree of oral opening. Despite these limitations, we were encouraged by the observation that this measure reflected the age-related differences that were clearly observed in the raw kinematic traces.

Clinical Implications

Developmental milestones and critical periods have been identified for a wide range of motor skills and systems (locomotion: Ames, 1937; Gesell & Ames, 1940; reaching: Halverson, 1931, all cited in Haywood, 1993). These normative descriptions have been clinically indispensable. Similar descriptions are needed for the motor milestones of speech. The developmental sequence observed in the present study may lead to a descriptive framework in which speech motor delays can be detected at an earlier stage of development. The present results, for example, might be taken to suggest that limited mandibular control in early speech is a negative prognostic factor for later speech motor delays. Although it is premature to make such specific recommendations, an improved understanding of the fundamental motor patterns for speech will dramatically strengthen differential diagnosis and treatment of developmental speech disorders (Smith et al., 1995).

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