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PHYSIOLOGIC DEVELOPMENT OF SPEECH MOTOR CONTROL: ARTICULATORY COORDINATION OF LIPS AND JAW

by

Jordan R. Green

A dissertation submitted in partial fulfillment
of the requirement for the degree of

Doctor of Philosophy

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Approved by _____
Chairperson of Supervisory Committee

*

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Doctoral Dissertation

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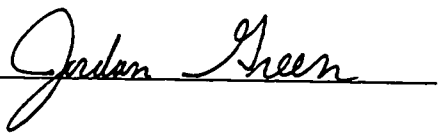
Signature 

Date 7/15/98

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ABSTRACT

Physiologic Development of Speech Motor Control: Articulatory coordination of lips and jaw

by Jordan Green

Chair of the Supervisory Committee: Associate Professor Christopher A. Moore, Ph.D.
Department of Speech and Hearing Sciences

The objective of this investigation was to describe development of lip and jaw coordination during speech. The potential influence of labiomandibular coordination on phonologic acquisition was also considered. A computer-based movement tracking system was used to transduce movement of the upper lip, lower lip, and jaw. Productions of syllables containing bilabial consonants were obtained from four age groups (i.e., one-, two-, six-years, and young adult). Two complementary analytic techniques were used to quantify interarticulator coordination, one reflecting spatial and temporal coupling of articulatory pairs and the other isolating each articulator's contribution to oral closure.

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 six. At one year of age, jaw displacement contributed the most to oral closure. The contribution of the lower lip increased gradually with age, whereas the contribution of the upper lip was greater for two-year-olds than for any other group.

Spatial and temporal coupling of movement of the upper lip, lower lip, and jaw were shown to increase with maturation. A similar developmental trend was exhibited for each measure. Coupling of upper lip and lower lip movement was rigid in even the

youngest subject groups. In contrast, coupling of lip and jaw pairs was initially weak and gradually increased with age.

The present results can be interpreted as representing 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.

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DEDICATION

This dissertation is dedicated to my family. I am indebted to my wife Kimber, who has demonstrated much love, support, and patience, throughout my doctoral studies. My parents Nancy and Stewart Green have always encouraged me to follow my passions, to trust myself, and to only learn from my mistakes. Their friendship and love is gratefully appreciated.

INTRODUCTION

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 (Enstrom, 1982; Kent, 1984; Kent & Murray, 1982; Lenneberg, 1967; Lieberman, 1977; 1984). Despite the sizable literature on the development of speech and language, there is a paucity of data describing the development of speech motor coordination and its influences on the sequence of phoneme acquisition. A better understanding of the sequence of motor acquisition for speech is essential before we can begin to comprehend delayed and abnormal speech development.

A complete description of speech acquisition will detail the mechanisms underlying phonologic development. Formulation of this description has been impeded by the logistically difficult task of collecting articulatory kinematic and electromyographic data from young children. Consequently, most of the existing literature on speech development has been based on phonetic transcription and quantitative acoustic analyses (e.g., Kent, 1976; Kent & Bauer, 1985; Nittrouer, 1993; Nittrouer, Studdert-Kennedy, & Neely, 1996; Stoel-Gammon, 1988; Stoel-Gammon & Otomo, 1986). The comments by Kent (1992) emphasize the importance of including physiologic descriptors in an account of speech motor development: "A proper understanding of motor events may be clouded by a premature phonetic attribution to infant's sound productions.... A conservative approach is to emphasize the nascent motor functions rather than the apparent (but arguable) phonetic representation underlying

infant sound productions." (p. 84). Recently, investigators have begun to develop methods for acquiring stable physiologic measurements from the speech apparatus during the first years of life (Barlow, Finan, Bradford, & Andreatta, 1993; Boliek, Hixon, Watson, & Morgan, 1996; Moore & Ruark, 1996; Ruark & Moore, 1997).

Physiologic Constraints on Speech Acquisition

The universality of speech sound acquisition across languages (Locke, 1983) suggests that the infant has a propensity for certain articulatory dynamics and configurations, and is incapable of producing later developing sounds. Locke (1993) recognized the predispositions in vocal development: "The gestures of babbling are so robust they survive retardation, neonatal brain damage, and congenital deafness" (p. 179). Contrary to this notion, Jakobson (1949; as cited in Vihman, 1996) suggested that each infant produces the complete inventory of the world's languages and that the essential process of phonemic development is the shedding of nonambient sounds. This hypothesis was later refuted by observations that babble consists of only a small repertoire of consonants and vowels (Mitchell & Kent, 1990; Smith, Brown-Sweeney, & Stoel-Gammon, 1989; Stoel-Gammon, 1985; Stoel-Gammon & Otomo, 1986).

The universals in early speech may reflect the shared experiences among humans while developing speech proficiency. Speakers share similar anatomic structures and engage in similar oral motor experiences during early development (i.e., sucking, chewing, early vocalizations). Moreover, speakers must solve common motor problems including management of reactive forces (intrinsic and extrinsic) and establishment of

supporting neuromotor organization. The question becomes how can processes in speech motor development be characterized and how do they influence the sequence of phonologic development.

Of course, the development of speech motor control entails more than these biologic influences. Motor processes of speech are shaped by multiple intrinsic (e.g., cognitive/linguistic and sensorimotor maturation) and environmental (e.g., auditory and visual stimulation, learning, social experience) forces. Accordingly, verbal communication can be modeled as a dynamic system (Kelso, Saltzman, & Tuller, 1986). The evolution of a dynamic system will be retarded by its slowest developing components (i.e., " rate limiting" factors; Thelen, Ulrich, & Jensen, 1989). The following literature review focuses on potential anatomic and physiologic factors that may limit the rate of speech development. The focus of discussion is not intended to minimize the role of other influences, such as environmental stimulation and cognitive readiness, but is intended to motivate further investigation into the directly observable aspects of the speech developmental process.

The Problem of Early Speech Development: Anatomic and physiologic constraints on early sound production

The infant is challenged by a unique set of motor control problems during the acquisition of mature speech. A well recognized problem in early speech production is that of normalization (Kent, 1984; Lieberman, 1977). Initially, the child must (1) contend with a vocal tract that is not capable of generating the range of sounds

characteristic of adult speech (Lieberman, Crelin, & Klatt, 1970) and (2) develop motoric and "speech signal" stability as vocal tract structures undergo dramatic changes in mass and geometry (Kent, 1984; Lieberman, 1977; Lieberman, et al., 1970; Sasaki, Levine, Laitman & Crelin, 1977). Vocal tract growth yields shifts in resonances, which challenge the infant's attempts to acquire a "target acoustic output." The impact of vocal tract expansion on both emerging phonetic forms and consistency of speech motor performance is poorly understood.

The size and geometry of a newborn's supralaryngeal vocal tract contributes to its inability to produce adult sounds. In comparison to the adult vocal tract, the infant's has several distinguishing features:

1. The hyoid, epiglottis, and larynx are positioned high in the pharynx (Lieberman, 1977).
2. The tongue is completely housed in the oral cavity (Lieberman, 1977).
3. The supralaryngeal cavity between the dorsum of tongue and larynx is small (Lieberman, 1977).
4. Adenoids are inverted (Subtelny & Baker, 1953).

Combined these features make the infant vocal tract more like a "single tube system." In contrast is the adult human vocal tract where the "cross-sectional area of the oral and pharyngeal cavities can be independently manipulated ... while a midpoint constriction is maintained." (Lieberman, 1977, p. 77). The continuous nature of the newborn vocal tract considerably limits the acoustic variations available to the infant (Lieberman, 1977).

During the first six months of life, the anatomic configuration of the infant's vocal tract limits its ability to produce oral sounds (Kent & Murray, 1982). Between birth and four–to-six months of age, the epiglottis and the velum nearly form a contiguous structure (Sasaki, et al., 1977). When the child is upright, this bridge presents high resistance to oral airflow and lowers nasal resistance. This observation parallels the common report that the earliest vocalizations are predominately nasal (Oller, 1978). Thus, along with neuromuscular maturation, the repositioning of the velum in the nasopharynx assists the child in producing oral speech.

Of even greater significance to sound acquisition than the maturation of the vocal tract is the formation of the neuromuscular framework that coordinates the articulators (Lieberman, 1984). Many of the most basic questions concerning the development of speech motor control have yet to be addressed: How does the sequence of neuromotor maturation influence the sequence of sound acquisition? How does growth interact with coordination of the articulators during speech acquisition? What is the role of reflexes and other extant neural circuits in the development of oral motor control for speech? What are the motor milestones of speech?

A number of experimental findings provide indirect support for the rate limiting effects of physiologic constraints on the development of speech:

1. The sequence of acquisition of sounds and sound classes is similar across cultures (Locke, 1983).

2. Some aspects of auditory perception are established long before corresponding speech emerges (e.g., perception of the voicing contrast; Eimas, Siqueland, Jusczyk, & Vigorito, 1971).
3. Infants attempt to imitate speech as early as three to five months of age (Kuhl & Meltzoff, 1996), suggesting that production precedes linguistic need.
4. Speech performance does not stabilize until adolescence (Eguchi & Hirsh, 1969; Kent, 1976; Tingley & Allen, 1975), maturing much later than underlying cognitive/perceptual substrates.

Thus, during the first year of life, anatomic constraints limit the sound producing capabilities of the infant. Physiologic constraints may also influence the course of speech development, but little is known about the potential consequences of such limits. Accordingly, a firmer understanding of physiologic constraints on early articulatory control may change the way we conceptualize speech development.

Processes in the Development of Motor Control

Sequences in neuromotor development may differentially constrain articulatory movement, thereby influencing the sequence of phonologic development. Universalities in the sequence of motor skill development led early researchers to focus their attention on the involvement of neuromotor maturation in motor development (Gesell & Ames, 1940; McGraw, 1940, cited in Haywood, 1993). These investigators observed the skills for posture, sitting, walking, and grasping tended to develop in the same order in all infants despite significant variations in their experiences (Haywood, 1993). The parallel

question of whether speech motor skills are attained in a consistent sequential order has not been addressed directly.

The developmental processes observed in the sequence of coordination for walking and reaching may be similarly operative in early speech. The challenges the child must overcome to grasp and walk are similar to those posed by coordination of vocal tract structures for sound modulation. For instance, for effective bilabial closure, the child must learn to coordinate lip and jaw movement within narrow time constraints. The developmental sequence of motor skills has been characterized as requiring *differentiation* (i.e., the modification of a pre-existing behavior into more specialized ones) and/or *integration* (i.e., integration of new behaviors with previously stabilized ones). This question of the ability of the oromotor system to exploit extant coordinative structures is central to the understanding of speech development.

Differentiation: Speech motor control may emerge from undifferentiated to differentiated organization

Gabbard (1992) has defined differentiation in motor control:

> Differentiation is the process by which structure, function, or forms of behavior become more specialized. In general, it is the progression of motor control from gross, poorly controlled movements (like those displayed by young infants) to more precise, complex forms of motor behavior commonly exhibited by older individuals. (p. 6)

The involvement of differentiation in motor development may be manifested behaviorally as comodulation of non-target muscles or at the level of movement, the

presence of extraneous movements accompanying an intentional movement. Such associative movements have been observed to decrease with age and specific training (Connolly & Stratton, 1968; Lazarus & Todor, 1987). These associative movements have also been termed "motor overflow" and "mirror movements," and have been observed at various anatomical sites (e.g., ears, fingers, and limbs) and levels of organization (e.g., limbs, Lazarus & Todor, 1987; motor units, see Provins, 1997). The presence of these movements in early motor development have led a number of investigators to suggest that neuromotor maturation may limit the young child's ability to selectively activate some neuromuscular elements (Jeannerod, 1988).

The learning of grasping conforms to this general sequence of motor development. When a child first learns to grasp an object, the arm segments move as a unit and the hand is primarily transported by rotation of proximal joints (Jeannerod, 1988). Gradually, the child works toward gaining independent movement of the arm, hand, and fingers (Schuster & Ashburn, 1992). Trevarthen (1984) described the whole body response in pre-reaching:

> Pre-reaching, since it does not involve guidance or redirection of movements during the cycle, can be described as 'ballistic' or 'open loop'. However, a succession of pre-reaching movements, possibly involving both hands, may show tracking in conjunction with whole body orientations... Such oriented activities also involve the feet which move in quadripedal synchrony with the hands. (p. 242)

Although mature speech production requires the ability to independently move vocal tract structures, it is not known if early speech exhibits such widely distributed motor patterns. In other words, tendencies in early speech may reflect the presence of obligatory coordinative linkages that give way to simultaneous activation of the involved articulators. In this case, advancement to mature speech would require the emergence of selective discrimination of neuromuscular elements. Moreover, the development of articulatory control would follow the general-to-specific sequence that would be manifested behaviorally as gains in independent control of vocal tract structures.

Integration: Speech motor control may require the assembly of existing skills

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

It is probable that the organization of coordination for speech involves both the *integration* and the *differentiation* of vocal tract components (Fentress, 1984; Kent, 1992). Lenneberg (1967) emphasized the involvement of both maturational forces in determining the sequence of motor development:

> First, the order in the emergence of sensory and motor capacities, reflexes, and spontaneous motoric events is constant and predictable for a given species. The sequence of events is not dependent upon experience. Second, the embryological emergence of behavior in mammals cannot be characterized by one simple scheme such as gradual differentiation of a whole or assembly of independently arising component reflexes. Although some aspects of behavior do emerge as undifferentiated patterns with subsequent individuation (for instance, the movements of limbs and digits and, to some extent, of head and trunk), other aspects of behavior are best regarded as a lawful but gradual integration of reflexes that can be observed to function independently before total integration takes place. (p. 9)

Sequence of Oromotor Development

It is known that, prenatally, the control of oral structures emerges at different times (Herring, 1985). For instance, while the lip musculature is still in the premyoblast stage at eight weeks gestation (Gasser, 1967), the 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. Prenatal studies of both animals and humans suggest that the order of appearance of oral movements tends to be jaw opening, jaw closing, tongue movement, and lip movement (see Herring, 1985; Humphrey, 1970; 1971). Description of the postnatal development of orofacial control is

confounded by the varying context of the oral functions. For instance, lip control may develop adequately for sucking much earlier than for speech.

The ontogeny of oral function includes the neurophysiologic control of sucking, chewing, and speech. Although these tasks share the same motor effector structures, they emerge during different periods of postnatal development (Bosma, 1985). Bosma (1985) suggests that the appearance of new oral functions coincides with the survival needs of the infant. Bosma (1973) further suggests that pharyngeal and laryngeal functions develop ahead of oral functions, citing the early appearance of swallowing and crying in the premature infant in comparison to sucking, which does not mature until the 37th week of gestation. The suck-swallow is one of the earliest oral behaviors to appear, usually close to term (Bosma, 1985). The shift from sucking to chewing coincides with the reorganization of central motor pathways (Iriki, Nozaki, & Nakamura, 1988). For chewing, oral coordination must evolve considerably, in comparison to sucking, for the child to advance to solid foods. Although the basic coordinative infrastructure for chewing is well established as early as 12 months of age, toddlers continue to make refinements until approximately three years at which time the chewing pattern appears adult like (Green, Moore, Ruark, Rodda, Morvée, & VanWitzenberg, 1997). In contrast, children typically do not master the sounds in their ambient language until eight years (Sanders, 1972). Moreover, adult-like stability in the acoustic signal is not achieved until adolescence (Eguchi & Hirsh, 1969).

Alimentary functions such as sucking and chewing have been frequently cited as antecedent behaviors from which speech motor coordination emerges (Darley, Aronson,

& Brown, 1975; Grillner, 1982; Ling, 1976; Mysak, 1980). This notion has intuitive appeal on several grounds. First, these oral functions share the same peripheral structures (Lund, Appenteng, & Séguin, 1982). Second, alimentary functions, such as chewing, have been historically grouped with the "earliest appearing" oral behaviors both ontogenetically and phylogenetically (MacNeilage, 1997). However, the disparities among the coordinative patterns for alimentary functions and speech have prompted a number of investigators to question the plausibility of a shared neural structure (Goffman & Smith, 1994; Green et al., 1997; Moore & Ruark, 1996). The coordination demands for speech probably exceed those of alimentary functions because (1) alimentary functions involve only a subset of the oral structures engaged for speech production (Bosma, 1985), and (2) the requirements for speech coordination are non-stereotypical and highly time specified (Gracco, 1994).

Development of Motor Skills for Speech: Current models and issues

A frequently cited sequence of speech acquisition is the one developed by Oller (1978). His basic taxonomy of early speech development is presented in Table 1. Note that "speech like" syllables do not appear until four to six months, Oller's stage III. Prior to this time the infant produces a great variety of sounds, some of which have little resemblance to speech (e.g., trills, coos; see Kent & Murray, 1982). At about six months, syllable primitives emerge as the infant engages the articulators to modulate the glottal tone. During Oller's stages III-V, rhythmic oscillations of the mandible produce primitive syllable trains commonly referred to as "reduplicated" or "canonical"

babbling. A number of researchers have suggested that such repetitive oscillatory movements, which are observed across many parts of the effector system between six and nine months, may assist in the transition from uncoordinated to coordinated movement (Kent, 1984; 1992; Thelen, 1991).

Table 1. Stages of normal speech development within the first year of life.

Stage (age in months)	I (0-1)	II(2-3)	III(4-6)	IV-V (7-12)
Vocal output	Quasi Resonant Nucleus "reflexive vocalizations"	GOO "Cooing"	Fully Resonant Nuclei and Marginal Babble	Reduplicated and Variegated Babbling

Adapted from Oller, 1978

A model proposed by MacNeilage and Davis (1990a; 1990b; Davis & MacNeilage, 1994; 1995) complements Oller's taxonomy, linking the pattern of sound acquisition to the underlying physiologic processes. The core of their model of speech development is the "Frames, then Content" metaphor, which was designed to explain how primitive syllables evolve into mature speech. In their model, "frames" are the most primitive articulatory pattern and are produced by the cyclic depression and elevation of the mandible. The emergence of speech-like vocalizations or babble coincides with the successive repetition of these primitive frames. Vocalizations become increasingly more complex or "adult like" as subsyllable organization develops within the frame structure.

These authors posit that infants produce variegated babbling by modulating the basic frame, a first step toward development of segmental properties. "Content" refers to this more complex subsyllable organization. In this view, old forms (i.e., "frames") are modified to create forms that are more complex. MacNeilage and Davis (1990a) draw support from the observation that voiceless phonemes appear to develop from alterations of the voiced form. MacNeilage and Davis' (1990a; 1990b) and Oller's (1978) proposals provide a conceptualization of speech motor development though lack empirical physiologic testing.

Physiologic Interpretations

MacNeilage and Davis' (1990a; 1990b) and Oller's (1978) characterizations of speech development can be viewed as integrative models of articulatory control. Each model proposes that early speech is produced primarily with a limited set of articulators and that development of mature speech coincides with increases in the number of involved articulators. Part of MacNeilage and Davis' (1990a) Frame-Content hypothesis proposes that early speech is produced exclusively using mandibular movement: ".... in the course of developing the capacity for simulating the alternation of sound levels that is characteristic of speech, the child develops *one* behavior that is a universal motor base for subsequent speech - the open-close alternation of the mandible." (p. 461) and "babbling episodes with labial stop consonants [p] and [m] may be produced without any specific positioning of the lips themselves. The fact that the lower lip 'rides' on the mandible may be sufficient to produce lip closure when the mandible is elevated." (p. 461).

It is alternatively possible that MacNeilage and Davis' "frame" is a manifestation of an undifferentiated motor program distributed across multiple articulators; other articulators may be equally responsible for producing early syllable primitives. Limited independence of functional components is a hallmark of early skilled movement (Provins, 1997) and may constrain early speech attempts as well. Anecdotal support for the presence of shared or widely distributed motor organization in early speech comes from the infant's emergent phonemic inventory. First, there is the frequent occurrence of voiced stops in early speech (Stoel-Gammon, 1985). Inter-articulator coordination for a voiced stop is "ballistic," unlike those classes of speech sounds that require a high degree of spatial and temporal specification (e.g., aspirated voiceless stops; Kewley-Port & Preston, 1974) and appear much later (Macken & Barton, 1980). Second, nasal consonants occur infrequently in early speech (Stoel-Gammon, 1985). This preference for oral sounds might be taken to suggest that velar closure is part of a motor program that is widely distributed across the speech apparatus. Alternatively, a developmental process might be hypothesized in which there is a more gradual increase in oral consonants in babble, reflecting a learning period with progressive gains in coordination of the velum and the supralaryngeal articulators. The infant's motivation to produce oral sounds might be attributed to a number of factors: oral sounds are acoustically rich, perceptually salient, and likely predominant in the infant's ambient language.

From studies of orofacial reflexes comes support for the notion that some of the neural pathways in the infant's oral region become more specified with maturation

(Barlow et al., 1993; Humphrey, 1970). Barlow and colleagues (1993) have demonstrated that tactile stimulation of the vermilion border in infants evokes a large reflex response (perioral reflex) across the quadrants of the orbicularis oris superior (OOS) and orbicularis oris inferior (OOI), indicating an absence of specificity between site of stimulus and effector activation. In contrast, adult subjects exhibited a localized ipsilateral response with the strongest effect recorded in the homonymous muscle. These findings raise the question: Does the development of voluntary orofacial control parallel perioral reflex development? In addition, these results provide further motivation for the exploration of widely distributed movement patterns in early speech.

Several mechanisms may limit the independent control of orofacial structures in early speech: *a widely distributed central motor program, a common source of neural drive, a simplification control strategy, or a pre-established motor pattern.* The wide distribution of the central motor plan for speech entails that the command signals do not contain the details necessary to activate only those muscles or articulators required for the task. According to Bernstein's (1996) notion of "motor constraints," motor learning involves the elimination of superfluous and redundant forces. This optimization process is an essential feature of skilled movement development (Bernstein, 1996) and can develop over a period of years (Provins, 1997). Thus, the organization of speech motor control may require the paring down of grossly defined motor programs.

Alternatively, a common source of neural drive may exert control over multiple articulators limiting the potential for independent movement of these anatomically distinct structures. To this author's knowledge, the prevalence of shared neural structures

in early speech motor control has not been considered. However, several researchers have begun to examine the possibility of shared loci of control for articulators in mature speakers (Goffman & Smith, 1994; Smith & Denny, 1990).

Another possibility is that an immature speaker may compensate for poor control by reducing the degrees of freedom of control (i.e., simplification control strategy). This compensatory strategy represents an initial solution to a motor problem and differs from the previous notion of reducing degrees of freedom for achieving optimization of a skilled movement (Bernstein, 1996). Simplification control strategies are observed, for instance, from the kinematic differences in grasping between preferred vs. non-preferred hand during the transportation of objects (Steenbergen, Marteniuk, Kalbfleisch, 1995). When grasping with the non-preferred hand, subjects tend to reduce the number of variables that needed to be independently controlled by decreasing angular motion of distal joints (shoulder and elbow) and increasing displacement of proximal segments (trunk). It is also possible that an immature speaker would reduce the complexity of articulatory control during early speech by linking portions of the speech apparatus.

Finally, the developing child may need to overcome pre-existing coordinative patterns (i.e., negative transfer) employed for tasks that share the same peripheral structures such as chewing and sucking. Transfers of learning effects occur when a pre-existing skill influences the learning of a new skill. These effects may facilitate (positive transfer) or impede (negative transfer) the learning of a new skill. Evidence for this process in motor learning is exemplified when a trained tennis player first attempts to play badminton (Magill, 1993). Individuals who play tennis will often erroneously

stiffen their wrist when learning badminton, which requires a wrist snap. Traditionally, extant 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 that the young child overcome such well-ingrained oromotor patterns.

In summary, if any of these mechanisms are operative in the immature motor system, the development of coordinative organization for speech may require increases in the ability to control vocal tract structures independently. Moreover, the presence of linked articulatory control may have predictable effects on the child's ability to produce certain phonemes under these coordinative constraints. Additional physiologic data may provide evidence of these mechanisms in early speech development.

Orofacial Control for Speech

Functionally, the upper and lower lips are distinct. Unlike the upper lip, the movement of the lower lip must be coordinated with respect to the position of the mandible. During speech, the lower lip produces greater force (Barlow & Netsell, 1986) and movement than the upper lip (Gay, 1977; Sussman, MacNeilage, & Hanson, 1973). The flexibility in articulatory control exhibited by adult speakers reflects several organizational features in the neural infrastructure mediating the perioral musculature. The perioral musculature is finely regulated with the number of muscle fibers innervated by each motor neuron estimated to be between 3:1 and 5:1 (Laurenson, 1968). This innervation ratio is much lower in contrast to other human muscles such as the medial

head of gastrocnemius where one motor neuron innervates up to 2600 fibers (Feinstein, Lindegard, Nyman, Wohlfart, 1955).

Several researchers have suggested that the upper and lower lips have different loci of neural control (Abbs & Gracco, 1984; Goffman & Smith, 1994; Smith, 1992; Wohlert & Goffman, 1994) and that there are biomechanically distinct compartments within the orbicularis oris (Abbs, Gracco, & Blair, 1984). Support for the existence of separate neural inputs to various regions of the orbicularis oris comes from (1) studies showing non-overlapping sub-nuclei in the facial nucleus of several species (e.g., Welt & Abbs, 1990, rhesus monkey; Courville, 1966; cat) and (2) studies that have reported an absence of coherence in lip EMG recorded from different quadrants of the orbicularis oris (Goffman & Smith, 1994).

Despite functional partitioning of the labial musculature, a speaker's capacity to control these muscles independently is limited (Folkins, 1978; Folkins, Linville, Garrett, & Brown, 1988). Folkins and colleagues (Folkins et al., 1988) examined the interactions in muscle activity of upper lip and lower lip during speech. Muscle activity was sampled from four different sites on the lips: midline orbicularis oris superior (OOS), midline orbicularis oris inferior (OOI), lateral OOI, and midline mentalis. Subjects were provided visual feedback reflecting activation level from one of the electrode sites (either midline OOI or midline OOS) and were instructed to manipulate the amplitude of muscle activity at that site while speaking. A volitional change in the level of activity in the target muscle produced similar modulation in the muscle activity of the other three muscles. Thus, for the speech task that was studied, elements of the perioral musculature

behaved as an interdependent, linked system. Because the correlations between OOI and OOS were not significantly higher than those of OOS and mentalis, it was suggested that these coordinative linkages are not restricted to orbicularis oris. Of interest was that only positive correlations were observed between upper lip and lower lip electrode sites, which is the opposite of what would have been predicted if the perioral musculature obeyed principles of complementary variation.

In summary, the coordinative organization of the perioral musculature allows oral structures to perform the varied actions required for speech, sucking, and chewing. Because coupled activation is obligatory among some perioral muscles, the extent to which humans can control these muscles independently is limited. However, the functional significance of these coordinative linkages may be inconsequential because isolated activation of perioral muscles is probably not essential to speech.

Development of Lip and Jaw Coordination for Speech

Few studies have described developmental changes in articulatory coordination. Research has been impeded by the absence of viable methods for obtaining physiologic measures from the articulators of young children. Several investigators (Sharkey & Folkins, 1985; Smith & Gartenberg, 1984; Smith & McLean-Muse, 1987; Watkin & Fromm, 1984) have successfully employed strain gauge devices to transduce lip and jaw movement in children, but because this method requires considerable cooperation from the subject, it is not amenable for use with very young children. Consequently, articulatory kinematic data are nonexistent from children under the age of 4 years. More

recently, several investigators have been able to record electromyographic activity from the orofacial musculature in very young children (e.g., Barlow et al., 1993; Moore & Ruark, 1996; Ruark & Moore, 1997).

By comparing the activation patterns of perioral musculature across oral tasks (e.g., chewing, speech), Moore and colleagues (Moore & Ruark, 1996; Ruark & Moore, 1997) have described traces of the coordinative infrastructure for speech in children as young as 15 months of age. Moore and Ruark (1996) studied differences in mandibular coordination during chewing, sucking, babbling, and speech in a group of normally developing 15-month-old children. They observed distinct coordinative patterns between non-speech and speech tasks. Specifically, chewing was characterized by a pattern of reciprocal activation of antagonist muscle pairs whereas speech was characterized by co-contraction of antagonist muscle pairs. Thus, as early as 15 months of age, children produce coordinative strategies for mandibular control that resemble those of the adult (Moore, Smith, & Ringel, 1988).

Ruark and Moore (1997) compared changes in upper and lower lip activity in two-year-old children across a variety of speech and non-speech tasks (e.g., chewing, rhythmic lip pursing). The degree of coupling varied across the different tasks. For instance, upper and lower lip activity was highly correlated during pursing and syllable repetitions, and less correlated during lip rounding and non-labial speech. These coordinative patterns were similar to those previously observed in adult speakers (Wohlert & Goffman, 1994). The authors interpreted these findings to suggest that, at

age two, children exhibited differential control of upper and lower lips for these different oral tasks.

Smith and Gartenberg (1984) examined differences in lip and jaw movements during speech in four children (ages: 4,6; 5,4; 6,11; and 7,0) and three adults. Unlike the adult speakers, the children did not produce systematic increases in peak velocity of lip and jaw movement from /p/ to /b/ to /m/. In both children and adults, the lower lip exhibited the greatest extent of movement, followed by jaw then upper lip. Children's speech movements were consistently slower and more variable than adults', corroborating previous observations of longer and more variable segment durations in children as compared to adults (Eguchi & Hirsh, 1969; Kent & Forner, 1980). Because children and adults produced similar magnitudes of movement across articulators, differences in movement velocity, for example, could not be explained by anatomical differences alone.

Smith and McLean-Muse (1987) examined potential developmental changes in motor equivalence. These authors recognized that few studies have empirically supported the existence of motor equivalence in speech (Hughes & Abbs, 1976), but reasoned that motor equivalence should increase with age if it is a characteristic of skilled motor abilities. Using a strain gauge apparatus, the experimenters recorded upper lip, lower lip, and jaw movements from four age groups (i.e., five-, eight-, and eleven-years-old, and adult) with six subjects in each group. Subjects produced CVC stimuli in one "normal" condition (i.e., normal speech rate) and in two perturbed conditions (i.e., fast rate, bite block condition). The data were subjected to several analytic procedures;

however, motor equivalence was not supported in any of the age groups studied. In one method, for example, Pearson product moment correlations were performed on the displacement values of articulator pairs collected from repetitions of the same utterance. Motor equivalence would have been supported if significant negative correlations between articulator pairs were observed, indicating a trading relationship among articulators. However, few subjects exhibited correlations that were significant from zero suggesting that motor equivalence was not operative in any of the age groups.

Sharkey and Folkins (1985) examined developmental changes in the variability of lower lip and jaw movement across several age groups (i.e., four-, seven-, and ten-years, and adult). These investigators measured the duration of lip opening, jaw opening, lip-open posture, jaw-open posture, and timing between the onset of lower lip lowering, and jaw lowering. Although adults' articulatory movements were significantly less variable than those of children, few significant differences in variability were found among the child groups. The variability in lower lip displacement decreased significantly between ages four and seven years, while the variability in jaw displacement did not change across any of the ages studied. This finding supports an earlier mastery of jaw control than for the lips. In contrast to the findings reported by Smith and Gartenberg (1984), no phoneme effects were found for any measure across groups.

Watkin and Fromm (1984) studied differences in the extent of upper and lower lip separation in vowels produced by eight subjects ranging in age from four to ten years. These investigators found that the relative contribution of the upper lip to labial separation decreased significantly with age from 19.4% to 8.5%. Successive repetitions

of the same stimuli became less variable with age with the greatest decrease occurring between seven and ten years of age.

Smith and Goffman (1998; Goffman & Smith, in press) studied differences in lower lip plus jaw movement among four- and seven-year-old children and a group of young adults. Smith and Goffman (1998) found no differences in the amplitude of articulatory movement among the groups, but found a significant increase in movement velocity and a decrease in overall movement duration. In contrast, Goffman and Smith (in press) reported that both movement displacements and velocity increased with age. These experiments were similar in their method with the exception that they used different speech stimuli. Therefore, the difference in their findings with respect to movement displacement may be related to differences in the intrinsic properties of the phonemes that were studied. Both studies reported a decrease in variability across all kinematic parameters with age. Calculation of the spatiotemporal index (STI) for each subject revealed that the children's movement patterns were more variable on repeated tasks than the adult subjects.

These investigators (Goffman & Smith, in press; Smith & Goffman, 1998) also designed their experiments specifically to ask the question: Do different phonemes develop from one primary form or "coordinative template?" This developmental process would be supported empirically if movement patterns for different phonemes appear similar initially but become more differentiated with maturation. Smith and Goffman (1998) found differentiated patterns in their youngest subjects, suggesting that children as young as age four produced movement trajectories that were distinguishable among

the different phonemic categories examined. Therefore, their data did not support the suggestion that the diverse movement patterns observed in adult speech are derived from a single underlying gesture or "articulatory primitive."

In summary, although the neural infrastructure for speech coordination is evident as early as 15 months, significant changes continue to occur well after age five. The findings of decreased variability and increased speed of movement with age is common across all studies and suggests that articulatory control undergoes progressive stabilization. Although the developmental sequence of articulatory control was never directly examined, several of these studies might be interpreted to suggest that (1) jaw control stabilizes earlier than lip control, and that (2) upper lip movement decreases while the lower lip assumes a more dominant role.

Purpose of Study and Statement of Problem

Although, the dominant models of early speech development (Oller, 1978; MacNeilage & Davis, 1990a; 1990b) predict specific changes in articulatory control, the developmental sequence of motor speech control has not been studied directly. Prior studies of speech motor development have been based on children aged four years and older, presumably after the coordinative organization for speech has been largely formed (Moore & Ruark, 1996, Ruark & Moore, 1997). An improved understanding of the developmental course of articulatory coordination will broaden our understanding of some of the organizational features of speech production:

1. the coordinative organizational features of mature articulatory motor control [e.g., velocity and displacement, Kuehn & Moll, (1976); velocity profiles, Gracco (1988); motor equivalence, Abbs & Gracco, (1984), speed accuracy tradeoff, Lindblom (1963); spatiotemporal stability, Smith & Goffman (1998)]
2. the sequence of speech motor development
3. the physiologic processes underlying developmental speech disorders
4. the sequence of phonemic acquisition

A reasonable beginning toward understanding the development of speech motor control is to study changes in articulatory movement. The purpose of the present investigation was to describe to describe developmental processes in labiomandibular coordination for speech. A central concern was to identify processes of development that may reflect integration and/or differentiation. The functional significance of these processes in early motor development is that they may have predictable effects on the child's ability to produce certain phonemes under these coordinative constraints, thereby accounting for preferences observed in early phonologic development.

Upper lip, lower lip, and jaw movements were recorded during the production of syllables containing bilabial consonants across age groups spanning the developmental continuum from babble to mature speech. The movement signals were subjected to two complementary analyses to quantify developmental changes in articulator coordination. One technique compared similarities in the spatial aspects of articulatory movement between articulator pairs (spatial coupling) and the degree of movement synchrony between articulatory pairs (temporal coupling). The other technique described

developmental changes in each articulator's contribution to closing the oral aperture for bilabial closure.

Beyond providing a general description of developmental shifts in coordination, these techniques provided a method to examine the presence of integration and differentiation in speech motor development. If differentiation is operative in the developmental course of articulatory control, we would expect infants to demonstrate a high degree of spatial and temporal coupling among the articulators. In addition, we might anticipate a decrease in an articulator's *contribution to oral closure* as it becomes disassociated from a tightly coupled ensemble. In this case, gains in independent control of the articulators would accompany speech motor development. Alternatively, if integration is operative, we would expect to observe the sequential appearance of articulatory movement for oral closure with age. Finally, in the absence of one of these distinct processes, we would anticipate (1) gradual increases in spatial and temporal coupling among the articulators with age, and (2) no dramatic shift in the role of each articulator for oral closure. One probable outcome is that these processes of motor skill development coexist but demonstrate differential degrees of involvement depending on the stage of speech motor development.

EXPERIMENTAL DESIGN AND METHODS

Subjects

A cross-sectional approach was employed to study several stages in speech development. Forty-six subjects comprised four subject groups: 6 infants (3 females, 3 males) between 11 and 13 months of age, 10 toddlers (5 females, 5 males) between 23 and 29 months, 10 children (5 females, 5 males) between 6 and 7 years, and 10 adults (5 females, 5 males) between 27 and 35 years. Seventeen additional subjects (15 infants and 2 two-year-olds) failed to produce the target utterances during the experiment.

The age groups studied were selected based on published findings on the development of the voicing contrast. Advances in the voicing contrast are expected to grossly reflect the development of speech motor control. One-year-old subjects were intended to represent an early phase in speech development that is predominated by voiced phonemes. Two-year-old subjects were intended to represent the period when the voicing contrast emerges (Engstrand & Williams, 1996; Macken & Barton, 1980). The six-year-old subjects were intended to represent the period when voice onset times (VOT) for voiceless and voiced stops are produced with little or no overlap, but with elevated levels of variability (Eguchi & Hirsh, 1969; Gandour, Holasuit Petty, Dardarananda, Dechongkit, & Mukngoen, 1986; Kent, 1976). Finally, the adult group reflected the mature pattern of coordination.

All participants were monolingual, native speakers of American-English and were pre-screened by interview of either the adult subject or the child's parent. All

participants had negative histories of speech, language, hearing, or vision problems, and developmental or neurological disorders.

Speech Samples

The target speech utterances sampled were "baba," "papa," and "mama." Sampling was limited to bilabial consonants for several reasons:

1) Phonetic inventories of early vocalizations demonstrate that the voiced bilabial consonants occur frequently in early speech (Stoel-Gammon, 1988; Stoel-Gammon & Otomo, 1986).
2) The production of bilabial consonants involves the coordination of articulators that are accessible for movement transduction and therefore amenable to study.
3) The production of a bilabial consonant involves a rigidly specified goal (bilabial closure) with relatively high degree of spatial and temporal coupling among the lips and jaw.

Elicitation techniques were designed to accommodate the different age groups. Samples from the young children were elicited during play activities involving the child, the caretaker, and the experimenter. Adult and six-year-old subjects were asked to read the target words from a poster in a pseudo-random order with a slight pause between each production at their normal conversational rate and loudness. The experimenter provided verbal exemplars throughout each experimental session to encourage the subjects to stress the first syllable of the target utterance and to speak at a normal conversational rate and loudness.

Approximately 45 speech samples were obtained (15 repetitions x 3 phonemes) from the adult and six-year-old subjects. The younger subjects (infant and two-year-old) produced only a subset of these utterances because children this young (1) vary in their willingness to speak in an unfamiliar environment, (2) vary in their vocal imitative skills, and (3) do not typically produce the voiceless bilabial stop (i.e., /p/) until around age two (Stoel-Gammon, 1985). Consistent with those characteristics, the two-year-old subjects in the present experiment varied considerably in their ability to produce the voicing contrast accurately, the predominant error being the substitution of [b] for /p/.

The utterances produced by the infants and two-year-old subjects included both spontaneous and imitative tokens. The two-year-old subjects had little difficulty imitating the models provided by the experimenter or parent. In contrast, only two of the six infant subjects unmistakably imitated utterances modeled by the experimenter or parent during data collection. The inclusionary criteria for the analysis of the infant's utterances specified (1) that complete lip closure was observed on the videorecording during the consonant embedded in a CV with the mouth initially open, or a VCV or CVCV utterance, or a sequence of canonical babble, and (2) that the utterance was produced during a normal mode of phonation (e.g., not during whisper) and at conversational loudness level, as judged by the experimenter. Additionally, utterances associated with "normal" dysfluencies (i.e., block or hesitation), coughs, or mispronunciations were not included in the study. Few tokens were rejected for these reasons.

Data Collection and Recording Conditions

Experimental sessions lasted about one hour for the one- and two-year-old subjects and approximately twenty minutes for the six-year-old and adult subjects. Data were collected in a large sound-treated booth equipped for audio and video recording. Subjects two-years-old and under were seated in either the caretaker's lap or in a highchair with the tray pushed in to minimize extraneous movement. Each child's utterances were transduced using a wireless remote microphone (Telex, FMR-25) attached to his/her shirt collar, and were recorded by a digital audio recorder (Panasonic, SV-3700). A full-face video recording of each subject was used to capture lip and jaw movement using an infrared camera (Burle, TC351A) coupled to a videorecorder (Panasonic, AG-1980).

Three single flat, circular reflective markers (~2 mm in diameter) were placed at the midline on the margin of the vermilion border of the upper lip (UL), lower lip (LL), and just superior to the mental protuberance of the mandible (J). Two reference markers (~2 mm in diameter), also placed midline, one on the tip of the nose and one on the nasion, were used to correct for head movement that would otherwise be included in the articulatory movement signals. These two markers translated the origin to the nasion marker and aligned the axis to the line defined by these two markers. A 4-cm reference marker, placed on the subject's forehead, was used to calibrate the movement signals. If a child exhibited any concern with this large reference marker, it was replaced with a smaller one (~ 1 cm).

Several precautionary measures were taken to reduce optical distortion while 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. The experimenter encouraged younger children to position their face perpendicular to the camera lens by holding a toy directly above the camera while eliciting samples. Speech samples accompanied by significant forward or backward rotation of the head were excluded from this analysis because significant rotation about the Z plane (sagittal) distorts the relative position between objects in a two dimensional coordinate system (i.e., x, y).

Digitization and Signal Conditioning

Bilabial consonants were identified from the combined audio and video recordings. Upper lip, lower lip, and jaw positions were extracted automatically from the videorecordings using a computer-based movement tracking system (Motus, version 2, Peak Performance). Vertical positions of the upper lip, lower lip and jaw were sampled at 60 samples per second.

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 in 16 successive steps of 5 mm each was measured for the experimental conditions (e.g., videocamera, approximate zoom factor, lighting, and reflective stickers). The average error for the position extracted by the movement tracking system was .1mm (SD = .05), which was within the limits of the experimenter's ability to

position the micrometer manually. The accuracy of this movement tracking system was assessed to be better than .1mm.

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 the jaw signal. An example of a kinematic record from an adult subject is presented in Figure 1.

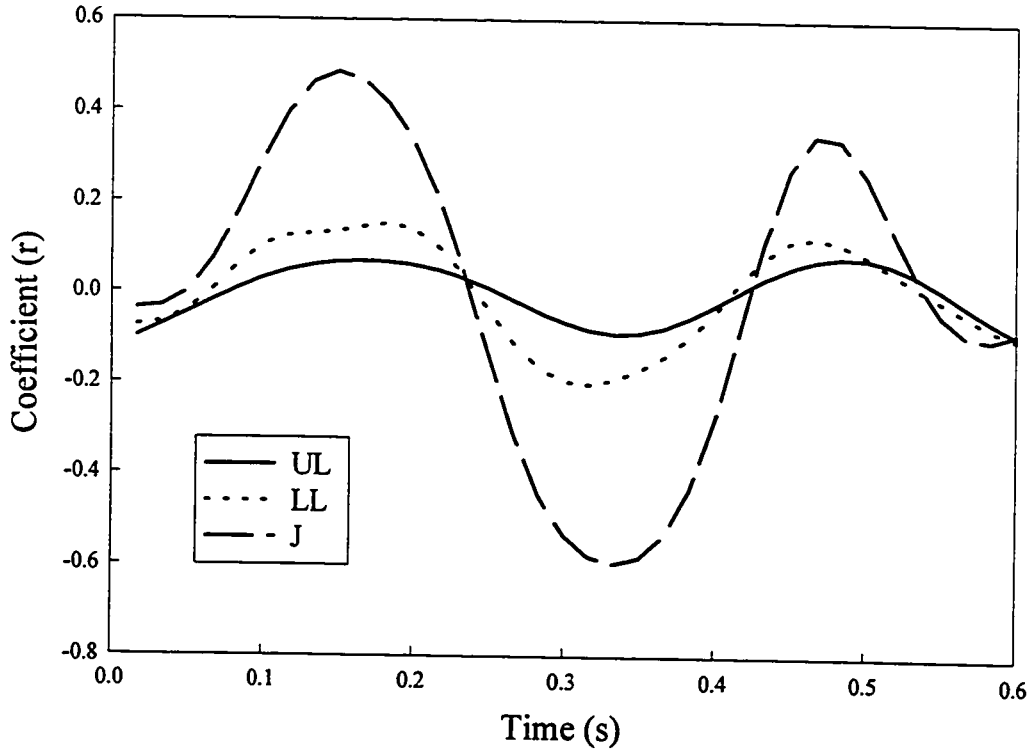


Figure 1. The treated kinematic traces from upper lip (UL), lower lip (LL), and jaw (J) produced by an adult subject saying "baba." For ease of interpretation, each signal has been centered about its mean and the UL signal has been inverted.

Quantitative Analyses of the Kinematic Traces

The kinematic tracings from upper lip, lower lip, and jaw were subjected to two complementary analytic techniques. Custom routines written for Matlab (The MathWorks Inc., version 5.1) were developed (1) to compute crosscorrelation functions across movement records and (2) to measure each articulator's contribution to oral closure during speech. These two separate analyses yielded three indices of coordination:

(1) *maximum or minimum coefficient from crosscorrelation function* - an index of the similarity in spatial aspects of movement trajectories (spatial coupling)

(2) *lag to coefficient* - an index of the degree of movement synchrony (temporal coupling)

(3) *percentage contribution to oral closure* – an index reflecting the relative contribution of each articulator to closing the oral aperture during bilabial closure for speech.

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 x LL, UL x J, LL x J). One strength of this method for quantifying inter-articulator coordination is that it is inherently normalized to differences in magnitude of the movement; thus, changes in inter-articulator

coordination are reflected independent of differences in relative vocal tract size among subjects.

The movement waveforms were trimmed prior to analysis with the assistance of a custom algorithm. The waveforms from each articulator and the velocity trace of the jaw (the time derivative of the jaw position) were displayed simultaneously on a computer monitor. An algorithm automatically indicated utterance boundaries as instances of zero velocity occurring in the jaw velocity signal. Jaw velocity was used because jaw movements tended to be more predictable and well-defined (i.e., characterized by two rising and falling gestures across the CVCV utterance) than were upper or lower lip movements across the age groups. If the subject's jaw was lowered before speaking, the initial zero velocity would be associated with the beginning of the closing phase for a CVCV utterance. If the subject's jaw was elevated before producing the utterance, the initial zero velocity point was associated with the release of the initial bilabial consonant. The end of the segment was the zero velocity occurring at the termination of jaw lowering for the vowel. In the event that zero velocity was not apparent in the jaw velocity signal, the experimenter would identify the onset and offset manually based on a visual display of the movement.

Figure 2 shows a single crosscorrelation function computed on the movement traces displayed in Figure 1. For ease of interpretation, the upper lip signal was inverted prior to analysis and each signal was centered about its mean. The most prominent peak (positive or negative) was identified from each crosscorrelation function using a custom algorithm written for Matlab. This routine required the investigator to place a cursor at

the most prominent peak or trough in the crosscorrelation function in a ~ 200 ms window centered on zero lag. The algorithm identified the maximum or minimum *coefficient* value in this window. The *coefficient* and its *lag* value were automatically exported to a database.

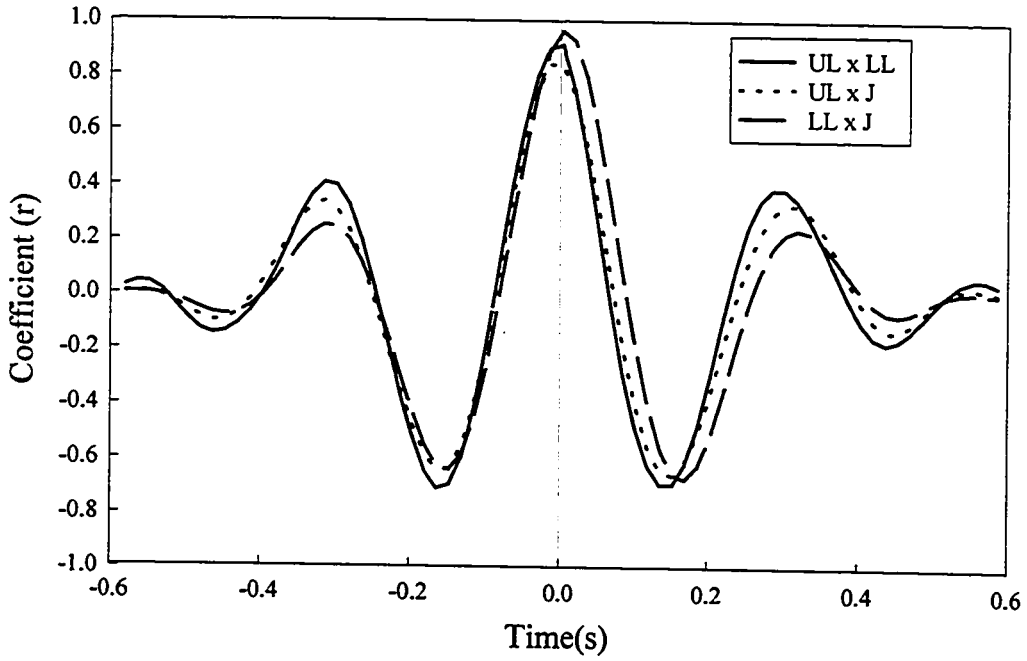


Figure 2. Pairwise crosscorrelation functions computed on the signals presented in Figure 1. The dashed vertical line denotes zero lag.

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 in 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 a

prominent negative peak in the crosscorrelation function that represents the correlation between the opening gesture of one signal and the closing gesture of another. One drawback of this approach is that differences in inter-articulator timing that are greater than half the window width (approximately 100 ms) cannot be detected. Approximately 8% of all tokens were rejected because of this criterion. This proportion did not differ significantly across age groups.

In this analysis, articulators that exhibit rigid temporal and spatial coupling yield high correlations and near-zero *lag* values. The magnitude of the correlation coefficient reflects the degree of spatial coupling and the value of the *lag* reflects the degree of temporal coupling (e.g., movement synchrony) within the articulatory pair. For the speech stimuli being examined, adult subjects usually produce spatially and temporally coupled articulatory movements. If the articulators differ significantly in their direction and pattern of movement, the signals will not be correlated. Thus, a significant deviation from the "mature pattern" would reflect inter-articulator dyscoordination and would produce coefficients closer to zero and/or greater *lag* values.

Articulatory Contribution to Oral Closure

Developmental shifts in articulatory control were examined by comparing changes in the relative *contribution* of the upper lip, lower lip and jaw for oral closure across age groups. This analysis was designed to complement the crosscorrelation methods by providing information on age-related changes in the extent of movement displacement. The information provided by the crosscorrelation analysis is limited because small articulatory displacements can be highly coupled although their functional

significance may be minimal. For instance, the upper lip and lower lip may be highly coupled but their movement may be relatively unimportant to the goal of oral closure (i.e., jaw movement may predominate oral closure).

Custom algorithms were designed to compute each articulator's relative *contribution to oral closure*. These routines required only that the experimenter grossly identify the onset and offset of the movements associated with each syllable. Once the syllable was roughly identified, calculating each articulator's relative *contribution to oral closure* involved four steps:

Step 1: Identification of each articulator's position during oral closure: (e.g., $UL_{closure}$)

For each syllable, the positions of the upper lip, lower lip, and jaw were recorded when the distance between the lips was at a minimum (i.e., position during oral closure).

Step 2. Identification of each articulator's position during maximum performance task: (e.g., $UL_{reference}$)

The position of each articulator was recorded in its maximum open position. These "reference" positions were intended to represent the functional boundaries of the oral aperture in their maximum open position. To capture these positions, the experimenter verbally and/or gesturally cued each subject to produce a smile and a yawn like gesture. The lower lip and jaw reference positions were recorded during the yawn and the upper lip's position was recorded during the smile. In some instances, the maximum open positions were recorded from spontaneous yawns, loud cries, or smiles in the younger children. Five of the younger subjects

(3 one- and 2 two-year-olds) were excluded from this analysis because they did not produce acceptable maximum open positions during the session. If available, several maximum opening positions were recorded and the greatest opening excursion observed was deemed the reference position for each articulator.

Step 3. Calculate each articulator's position in the oral aperture: (e.g., UL_{co})

For each syllable, the position of each articulator during the reference posture (i.e., maximum opening) was subtracted from its position during oral closure. These values represented the extent that each articulator occluded the oral aperture. See Equation 1.

Equation (1)

$$UL_{co} = UL_{reference} - UL_{closure}$$

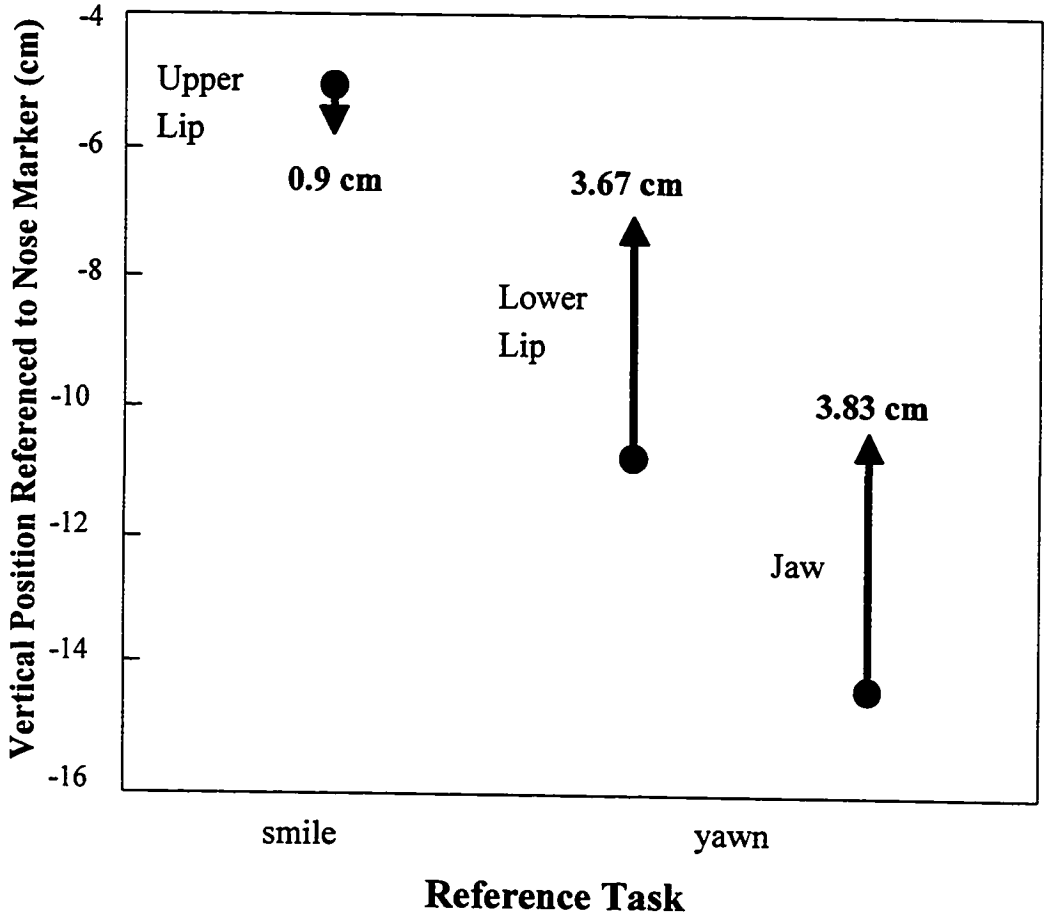
Step 4. Calculate each articulator's relative contribution to oral closure: (e.g., $\%UL_{co}$)

Finally, to calculate each articulator's relative *contribution to oral closure*, each value calculated in Step 3 was individually divided by the summed positions of upper lip, lower lip, and jaw (also calculated individually in Step 3). See Equation 2.

Equation (2)

$$\%UL_{co} = UL_{co} \div (UL_{co} + LL_{co} + J_{co}) \times 100$$

This transformation was performed on each syllable. Figure 3 demonstrates graphically how each articulators relative *contribution to oral closure* was calculated. This technique had several advantages over more traditional measures of movement displacement because (1) it minimizes jaw movement variability related to



Calculations of Relative Contribution to Oral Closure:

$\%UL_{co} = UL_{co} / (UL_{co} + LL_{co} + J_{co}) \times 100$
$= 0.9cm / (0.9cm + 3.67cm + 3.83cm) \times 100 = \mathbf{11\%}$

$\%LL_{co} = LL_{co} / (UL_{co} + LL_{co} + J_{co}) \times 100$
$= 3.67cm / (0.9cm + 3.67cm + 3.83cm) \times 100 = \mathbf{44\ \%}$

$\%J_{co} = J_{co} / (UL_{co} + LL_{co} + J_{co}) \times 100$
$= 3.83cm / (0.9cm + 3.67cm + 3.83cm) \times 100 = \mathbf{46\%}$

Figure 3. Calculation of relative contribution to oral closure. The length of each vector corresponds to each articulator's contribution to closing the oral aperture during oral closure. The end of the arrow represents the position of that articulator during oral closure. The circle represents the position of that articulator during 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 articulators value was divided by the sum of UL, LL and J values for each syllable and multiplied by 100.

vowel context (Sussman et al., 1973), and (2) it did not require precise identification of onset and offset of each articulatory gesture, which can be unreliable in the irregular movement traces exhibited in young children

Statistical Treatment

Developmental changes in upper lip, lower lip, and jaw coordination for speech were characterized by three coordinative indices: maximum or minimum *coefficient*, *lag to coefficient*, and *relative contribution to oral closure*. Before collapsing the data, *lags* were converted to absolute values because their direction was not of interest in the present design. Developmental trends were examined by computing the average of each coordinative index for each subject. The subjects' averages were combined in each age group and subjected to a three-way ANOVA (gender x age x articulator pair). Because the coordinative indexes are expected to vary with age and/or gender, multiple pairwise comparisons were performed on all significant main effects and interactions using the Fisher LSD method (alpha level = .05).

Additionally, the data from the adult and six-year-old group were subjected to a three-way ANOVA (gender x age x phoneme) to test for potential phoneme effects. This analysis was restricted to these groups because the one- and two-year-old subjects did not produce all the phonemes.

Reliability of Measurement

One subject in each group was selected randomly for the reliability analysis. The same experimenter remeasured all the utterances produced by these subjects for the three coordinative indices, which together comprised approximately 10% of the entire set. Test-retest reliability was assessed by calculating the Pearson product moment correlation and average deviation between the first and second measurement for each coordinative index (i.e., *coefficient*, *lag*, and percent *contribution to oral closure*). Table 2 reports average differences between the first and second measurements for *coefficients* and *lags*. The average absolute difference between first and second measurements of *coefficient* and *lag* was .012 and .003 s, which was acceptable for the present analysis. It was anticipated that measurement reliability would be worse for the younger subjects because of increased instability in their movement traces leading to increased difficulty in determining token boundaries. Contrary to this expectation, the difference between measurements of *coefficients* and *lags* tended to be small across all groups, although there was a slight decrease in average deviation between measurements with age for both *coefficient* and *lag* values. Pearson product moment correlations between the first and second measurement 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* relied heavily on computer algorithms and required that the experimenter only grossly define the syllable boundary.

This measure was reproducible with 100% accuracy. Generally, the implementation of computer algorithms wherever possible enhanced measurement reliability.

Table 2. Test-retest reliability for measurement of coefficient and lag from crosscorrelation analysis.

Age Group	Average Deviation	
	Coefficient (r)	Lag (s)
One	0.023	0.0074
Two	0.010	0.0023
Six	0.013	0.0017
Adult	0.003	0.0004
Average for Study	0.012	0.0030

RESULTS

The primary purpose of the present study was to provide a description of developmental changes in lip and jaw coordination during production of syllables containing bilabial consonants. Developmental changes in articulatory coordination were characterized by two distinct analyses examining (1) the strength of spatial and temporal coupling among the upper lip, lower lip, and jaw movements, and (2) the relative contribution of each articulator for oral closure. Beyond providing a general description of age-related changes in coordination, these data were evaluated to elucidate the coordinative constraints on early speech motor control.

Data Corpus

A total of 1098 utterances were analyzed, including: 54 from the one-year-olds, 256 from the two-year-olds, 429 from the six-year-olds, 422 from the adults. The number of bilabial utterances produced by each subject varied considerably depending on their age (see Figure 4). All utterances were CVCV combinations produced in isolation with the exception of nine from the one-year-old group. Five of these utterances were VCV (or CV with mouth in initially in open position) combinations and four were CVCV combinations extracted from continuous canonical babble.

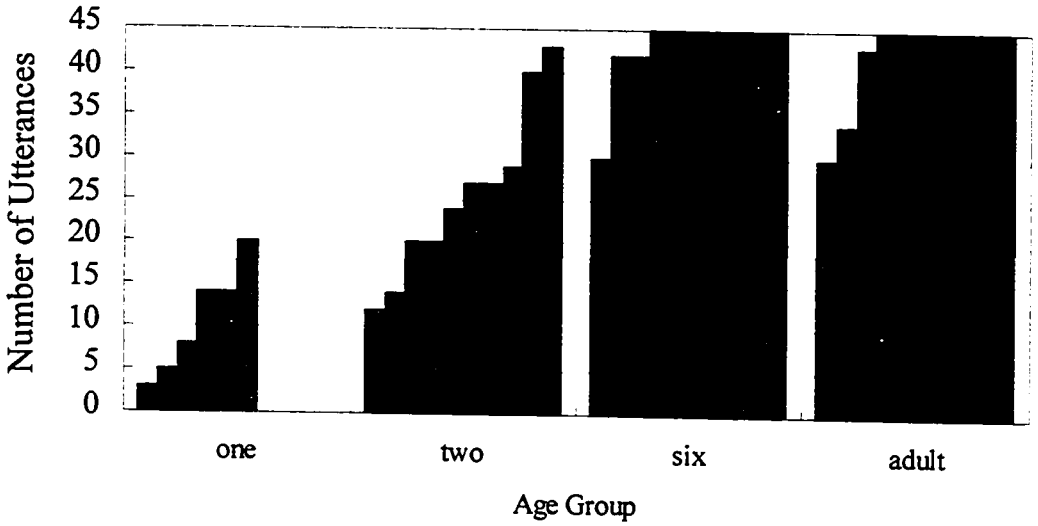


Figure 4. Number of utterances per subject in each age group. Each bar represents the number of utterances for one subject. The data are ordered from smallest to largest number of utterances.

Phoneme Effects

Phonemes were not evenly represented among the age groups. None of the one-year-olds produced utterances that contained a [p] exemplar. In addition, two of the two-year-olds did not produce examples of the /p/, and half of the children in this group produced five or fewer of these utterances. These findings were anticipated, as the voiceless bilabial stop (i.e., /p/) emerges around age two (Stoel-Gammon, 1985).

This imbalance in the data set required evaluation of potential phoneme effects on the three coordinative indices (i.e., *coefficient*, *lag*, and *contribution to oral closure*).

Only the data from the six-year-olds and adults could be included in this analysis because only these subjects consistently produce all three bilabials (i.e., /b/, /p/, /m/). The results of a three-way analysis of variance on repeated measures (phoneme x pair x gender) indicated that there were no statistically significant phoneme effects for *coefficient*, *lag*, or *contribution to oral closure*. Based on these results, the data for each subject were collapsed across phonemes to yield a single average for each coordinative index.

Qualitative Observations

Figure 5 includes a kinematic record from one subject from each age group producing "baba." For ease of interpretation, each kinematic signal was centered about its mean and the upper lip signal was inverted. While generalizations cannot be made based on single productions, these examples illustrate differences in the coordinative organization exhibited among age groups that are supported by findings revealed in the quantitative analyses. Adult subjects uniformly produced the movement sequences with high levels of inter-articulator coupling. Movement trajectories in these subjects were characterized by a predominant single rising and falling pattern for each syllable.

In contrast to the adult pattern, one-year-old children typically exhibited pronounced jaw movements accompanied by excessive compression of lip tissues during oral closure. As displayed in Figure 5, this compression was associated with oppositional movements (180 degrees out of phase) between the lips and jaw. These

deflections in the movement trajectories at oral closure were much larger in one-year-olds than in any other age group. In two-year-old subjects, jaw movement appeared to decrease as upper and lower lip movement increased. The upper and lower lip movement trajectories were often similar in form (e.g., "mirror movements") and frequently characterized by a single rising-falling across both syllables. The movement patterns of six-year-olds were similar to those of adults, but were generally more variable.

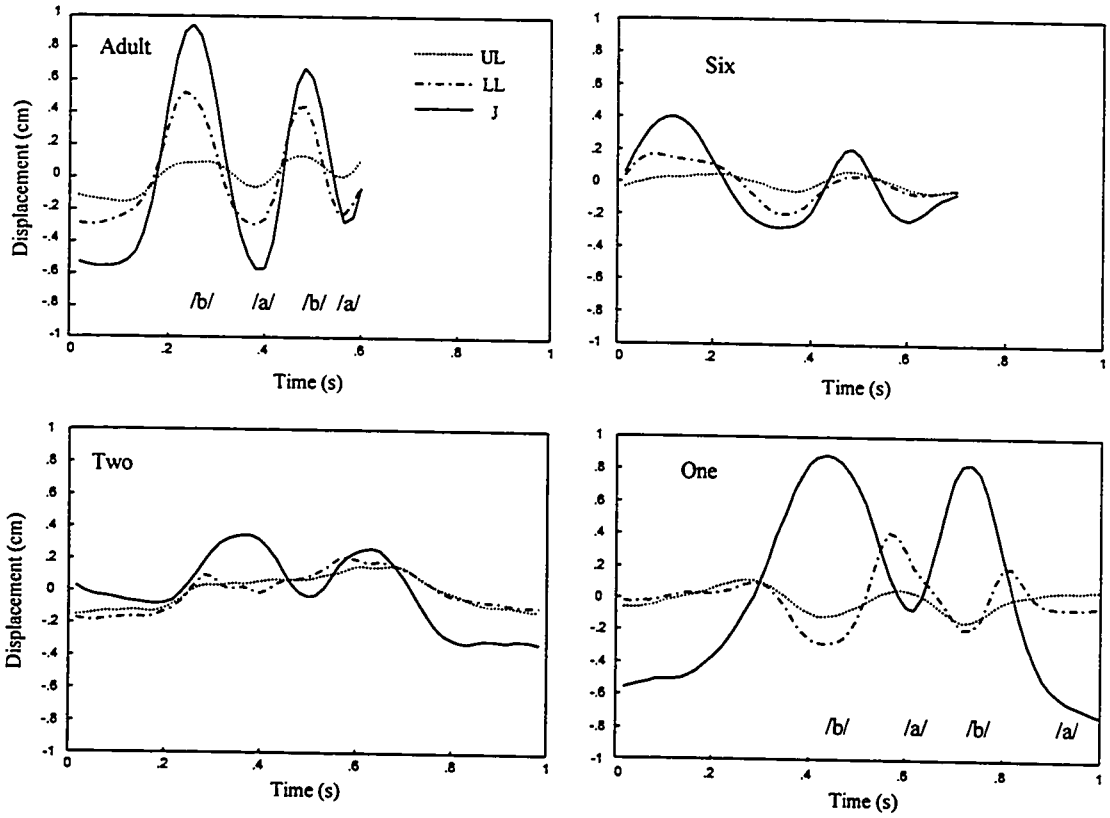


Figure 5. Representative kinematic records from a subject in each age group based on a single trial. Traces are centered about their means and the upper lip is inverted for ease of interpretation.

Crosscorrelation Analysis

Developmental changes in spatial and temporal coupling among upper lip, lower lip, and jaw were quantified by subjecting the movement traces to a pairwise crosscorrelation analysis. Peak *coefficients* were abstracted from each crosscorrelation function and were interpreted to reflect spatial coupling between articulatory pairs. In addition, the *lag of the peak coefficient* was recorded and indicated the degree of movement synchrony between articulatory pairs. The peak *coefficients* and *lag* values exhibited by the youngest subjects were of special interest. If spatial and temporal coupling are low (low *coefficients* and high *lag* values) in these groups, we might conclude that movement synergies are not features of early speech motor organization.

Spatial Coupling

Spatial coupling increased significantly with age [$F(3,84) = 28.41, p < .001$]. Figure 6 shows the mean peak *coefficients* values obtained at each age for each articulator pair. The mean *coefficients* and standard deviations are presented in Table 3. Gender was the only main effect that was not significant. The only significant interaction was articulator pair by age [$F(6,84) = 3.0, p < .01$].

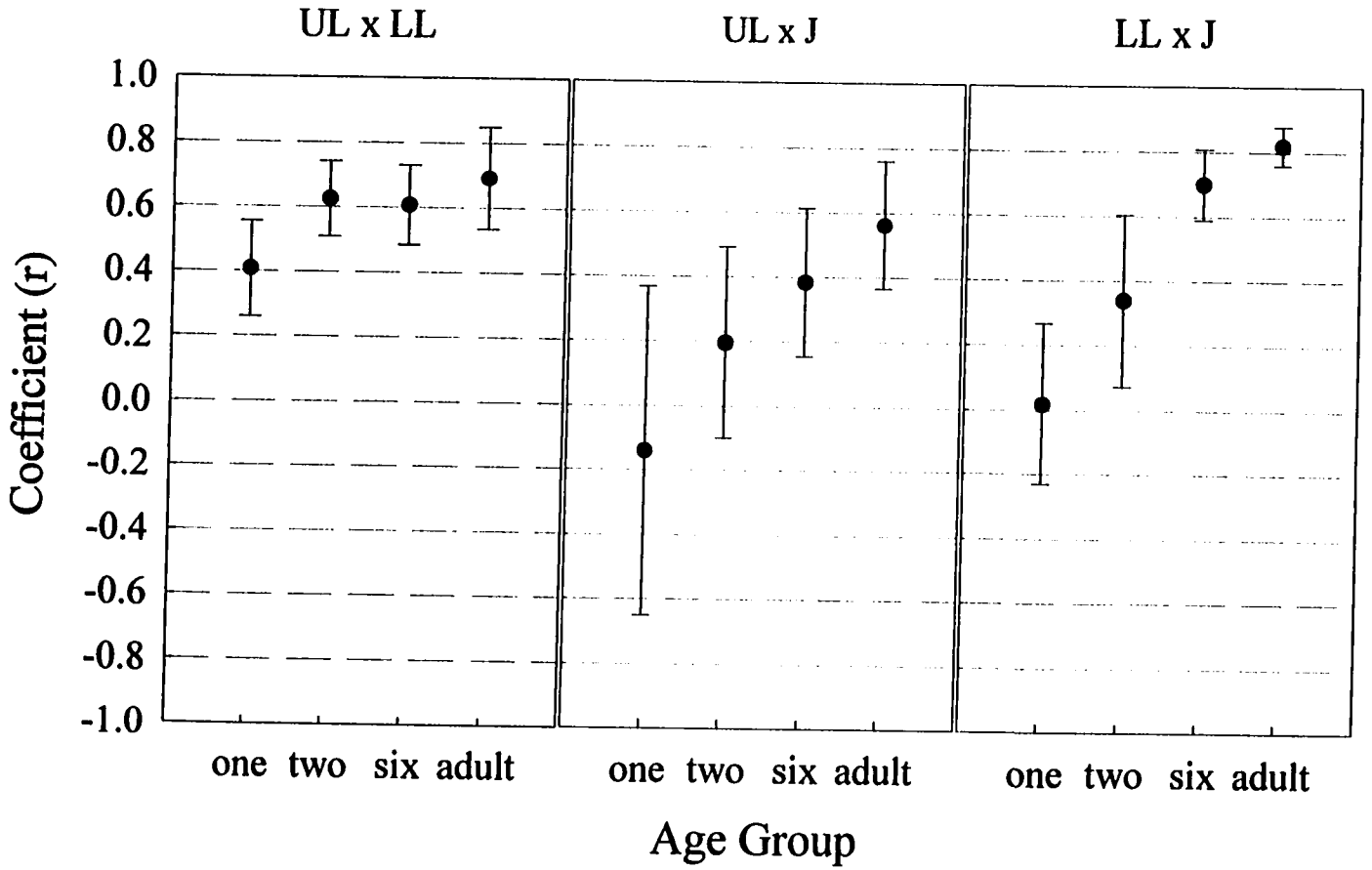


Figure 6. Average coefficients and standard deviations obtained from pairwise crosscorrelations for upper lip and lower lip (UL x LL), upper lip and jaw (UL x J), and lower lip x jaw (LL x J) by age. Error bars represent average standard deviation between subjects in each age group.

Table 3. Mean coefficient (r) values for articulator pairs across age groups. Standard deviations of the means are in the parentheses.

	Pair		
Age Group	UL x LL	UL x J	LL x J
One	0.41 (0.15)	-0.18 (0.55)	0.00 (0.27)
Two	0.63 (0.12)	0.20 (0.30)	0.34 (0.26)
Six	0.61 (0.12)	0.38 (0.23)	0.73 (0.09)
Adult	0.69 (0.16)	0.56 (0.20)	0.82 (0.06)

Note: (UL = upper lip, LL = Lower Lip, and J = Jaw)

Multiple comparisons of the interaction of articulator pair and age revealed different developmental progressions for UL x LL, UL x J, and LL x J[1]. Only the one-year-olds exhibited significantly less UL x LL coupling than the adults. As demonstrated in Figure 6, UL x LL coupling was relatively high for the younger age groups. In contrast, UL x J and LL x J *coefficients* were centered near zero at age one year, reflecting the unpredictability of coordination between these articulators. Coupling between these articulators increased gradually with age, although several

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[1] All multiple pairwise comparisons were performed using the Fisher LSD method (alpha level = .05).

adjacent age groups did not differ significantly in these measures. Specifically, six-year-olds did not differ significantly from adults for LL x J, and from two-year-olds and adults for UL x J.

Age-related coordinative characteristics were revealed by differences in the relative degree of spatial coupling among articulator pairs within each age group. Table 4 highlights the age-related changes in spatial coupling that occurred for all three articulator pairs based on the results of the multiple comparisons analysis. One- and two-year-old children exhibited greater spatial coupling between the lips than between the lips and jaw (i.e., UL x LL > UL x J and LL x J). In contrast, spatial coupling between the UL x LL was not significantly different from that of UL x LL and LL x J for adult subjects. In six-year-olds and adults, UL x J coupling was lower than for LL x J coupling (i.e., UL x J < LL x J).

Table 4. Results of pairwise comparisons of age by articulatory pair.

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

Movement Synchrony

Overall, the developmental trends in movement synchrony paralleled those observed for spatial coupling. Lags between articulatory pairs, as measured by the *lag-to-peak coefficient*, became shorter with age [$F(3,84) = 5.43, p < .01$]. Figure 7 displays the averages and standard deviations of *lag* values across the age groups for UL x LL, UL x J, and LL x J, respectively. The mean values and standard deviations are presented in Table 5. Temporal resolution was ± 8.8 ms, which was determined by the videorecording rate (i.e., 60 frames per second). Similar to the coefficient analysis, gender was the only main effect that did not exhibit statistically significant differences. No interactions between variables were observed.

Table 5. Mean absolute lags (in milliseconds) for articulator pairs as a function of age. Standard deviations of the means are in the parentheses.

	Pair		
Age	UL x LL	UL x J	LL x J
One	18 (6)	29 (31)	23 (12)
Two	12 (6)	21 (6)	18 (7)
Six	14 (5)	20 (5)	11 (4)
Adult	14 (2)	18 (8)	8 (4)

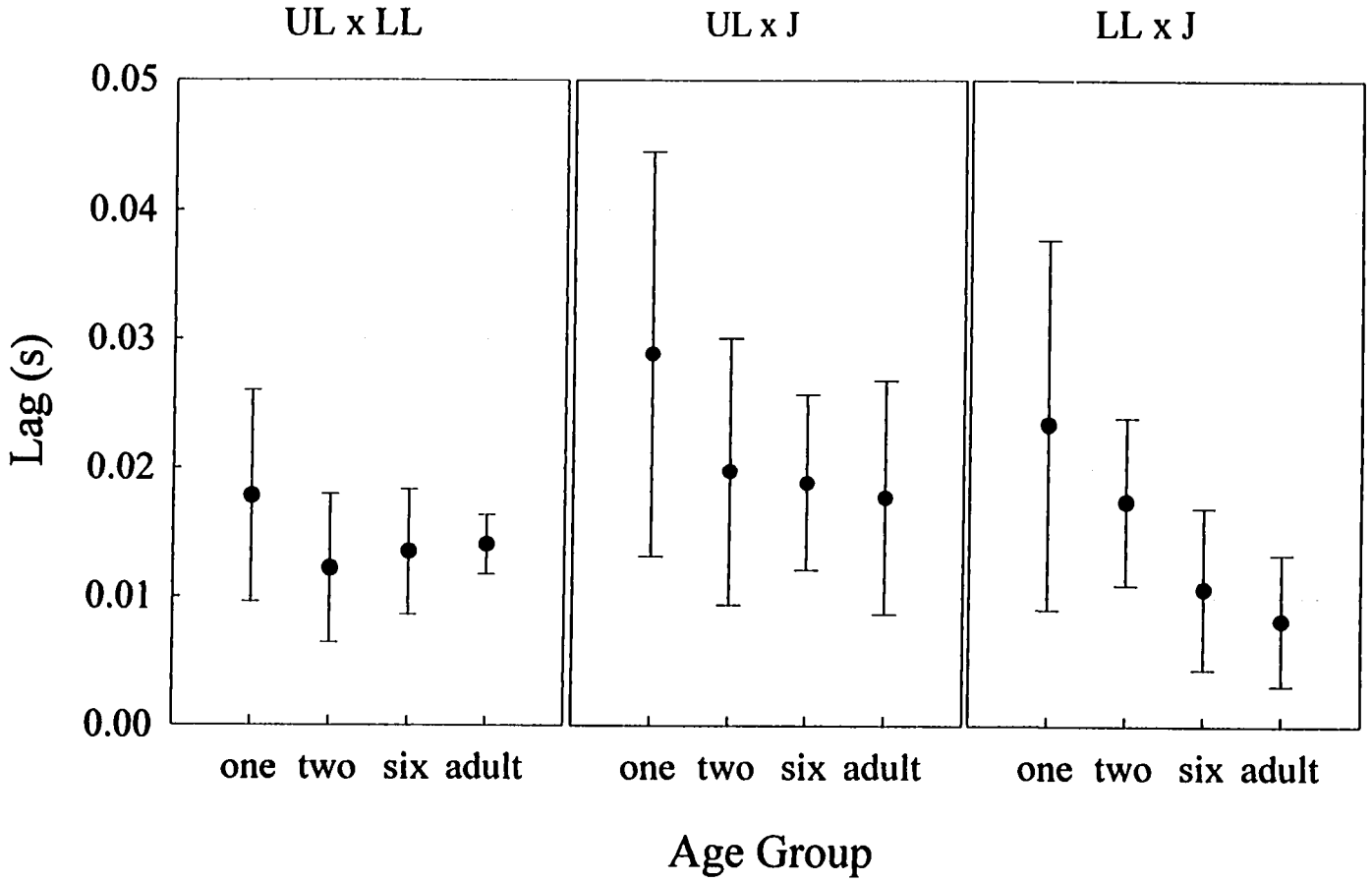

Figure7. Average absolute lag values and standard deviations obtained from pairwise crosscorrelations for UL x LL, UL x J, and LL x J for each age group. Smaller lag values represent increased interarticulator synchrony. Error bars represent average standard deviation between subjects in each age group.

Overall, age related differences in *lag* values were relatively small. Multiple comparisons revealed that there was no age effect for UL x LL. In contrast, UL x J and LL x J articulatory *lags* decreased with age. The multiple comparisons revealed longer *lags* for one-year-olds than for six-year-olds and adults. In addition, LL x J *lags* were significantly longer for two-year-olds than for adults.

Movement synchrony differed among articulator pairs [$F(2, 84) = 7.54, p < .001$]. As in the coefficient analysis, age-related coordinative preferences were revealed by differences in the relative degree of synchrony among articulator pairs within each age group. Table 6 highlights the age-related changes in movement synchrony that occurred for all three articulator pairs based on the results of the multiple comparisons analysis. Both one- and two-year-old subjects exhibited greater synchrony for UL x LL than for UL x J and LL x J (i.e., UL x LL > UL x J and LL x J). In contrast,

Table 6. Results of pairwise comparisons for articulator pair for lag values (ms). Smaller values indicate greater movement synchrony.

	Age			
Comparison	One	Two	Six	Adult
UL x LL vs. UL x J	18 < 29	12 < 21	14 ≈ 20	14 ≈ 18
UL x LL vs. LL x J	18 ≈ 23	12 ≈ 18	14 ≈ 11	14 ≈ 8
LL x J vs. UL x J	23 ≈ 29	18 ≈ 21	11 < 20	8 < 18

six-year-old and adult subjects exhibited significantly greater movement synchrony for UL x LL and LL x J than for UL x J (i.e., UL x LL and LL x J > UL x J).

Taken together, these results demonstrate two distinct processes in the development of lip and jaw coordination for speech. First, young children exhibit relatively high levels of coupling for UL and LL. The magnitude of this coupling was surprising, especially when compared to the poor coordination of lip and jaw movement exhibited at these young ages. These findings are consistent with the possibility of linked control between these articulators. In contrast to the changes in UL x LL coordination, coupling of lip and jaw pairs (i.e., UL x J and LL x J) gradually improved with age. This sequence reflected improvements in inter-articulatory coordination in the absence of early movement synergies in lip and jaw articulator pairs.

The relatively high degree of spatial and temporal coupling between upper and lower lips observed in one-year-olds might suggest synchronous neural drive. However, as demonstrated in Figure 5, the jaw produced these passive displacements of the lips which probably yielded *coefficients* that were spuriously high and *lags* that were spuriously low at this age.

Contribution to Oral Closure

Developmental changes in each articulator's *contribution to oral closure* were examined. As in the crosscorrelational analysis, the coordinative patterns of the young children were of special interest. Integration of motor capabilities in speech motor

development would be supported if the jaw was shown to contribute most to oral closure in early speech with the lips becoming more involved with age. This sequence is consistent with a hypothesis advanced by MacNeilage and Davis (1990a, 1990b). On the other hand, differentiation would be supported by increases in the independent control of individual articulators. In the present design, this shift in coordination may be accompanied by a decrease in an articulator's *contribution to oral closure* as it becomes disassociated from tightly coupled ensemble.

Several developmental changes in labiomandibular coordination for oral closure were exhibited. The percentage *contribution to oral closure* differed significantly for each articulator with age [Articulator x Age, $F(6, 92) = 11.34, p < .001$]. Figure 8 displays the means and standard deviations by age group for UL, LL, and J. The mean values and standard deviations are presented in Table 7. There were no statistically significant gender effects for these measures.

Table 7. Mean percentage contribution to oral closure as a function of age and articulator. Standard deviations of the means are in the parentheses.

	Articulator		
Age	UL	LL	J
One	8 (5)	26 (13)	66 (15)
Two	16 (10)	34 (9)	50 (8)
Six	9 (4)	44 (6)	47 (4)
Adult	8 (3)	46 (3)	46 (2)

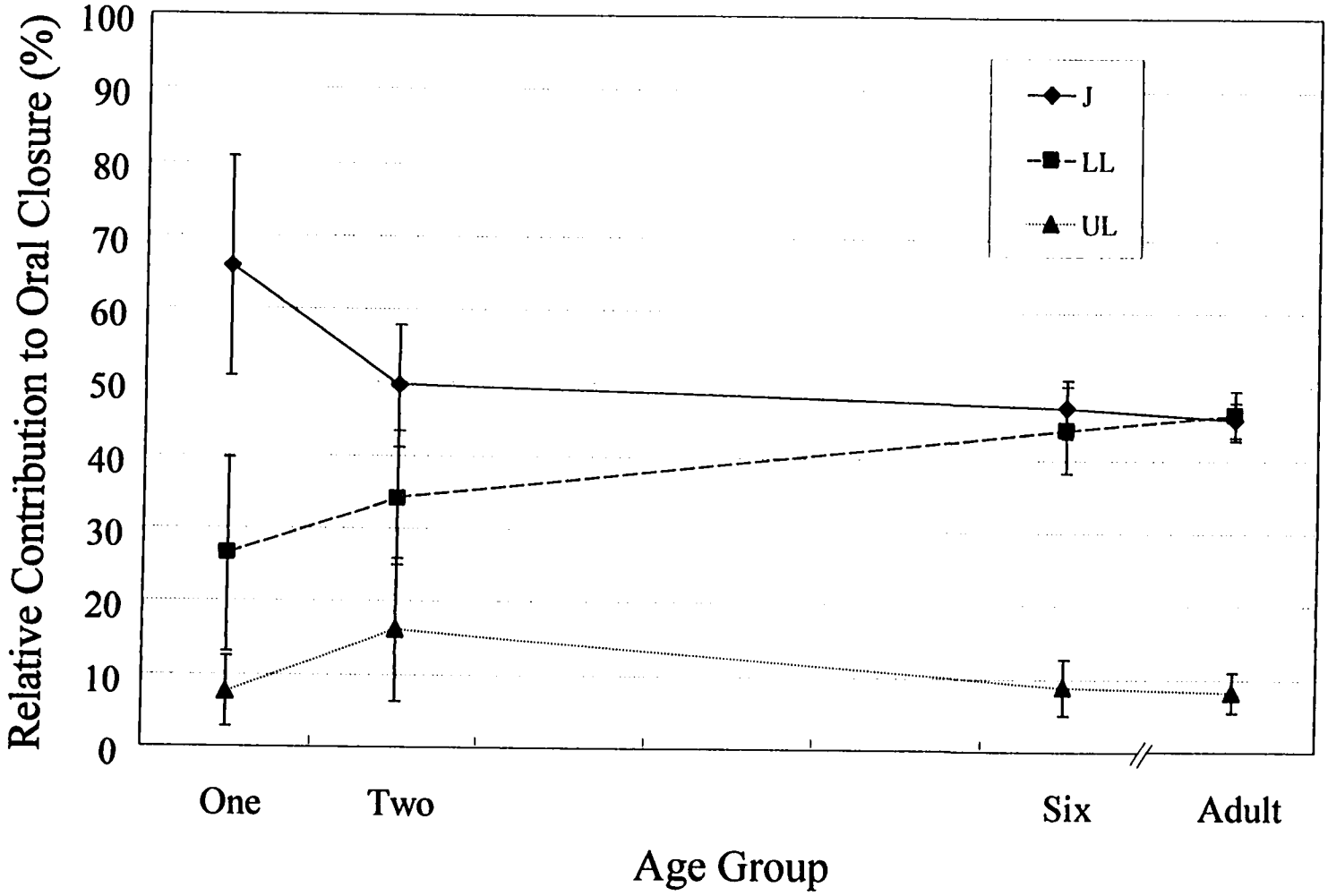

Figure 8. Relative contribution to oral closure for each articulator by age. Error bars represent average standard deviation between subjects in each age group.

Multiple comparisons of the articulator by age interaction revealed specific age-related changes in the relative *contribution* of each articulator. *Contribution* of J to oral closure decreased significantly between one and two years of age. This decrease was associated with a significant increase in *contribution* from UL and LL in two-year-old subjects. The *contribution* of UL decreased after age two, but LL *contribution* continued to increase. The adult and six-year-old subjects exhibited a similar pattern for oral closure. For these groups, LL and J *contributions* were comparable, and the involvement from UL was small in comparison to either of these articulators.

Age-related coordinative preferences in articulatory movement were revealed by differences in the *contribution to oral closure* within each age group. Table 8 highlights the age-related changes that occurred for all three articulators based on the results of the multiple comparisons analysis. In one- and two-year-old children, jaw movement contributed most to oral closure, followed by LL, then UL. In contrast, six-year-old children and adults used the LL and J equally to close the oral aperture, and the UL contributed significantly less than either of these articulators.

Table 8. Results of pairwise comparisons for articulator for relative contribution to oral closure (%).

Comparison	**Age**			
	One	Two	Six	Adult
J vs. LL	66 > 26	50 > 34	47 ≈ 44	46 ≈ 46
J vs. UL	66 > 8	50 > 16	47 > 9	46 > 8
LL vs. UL	26 > 8	34 > 16	44 > 9	46 > 8

In summary, these findings suggest that an essential aspect of speech motor development for these movement sequences is increasing lower lip independence of movement. The predominant role of the jaw in early articulation and the gradual increase in lower lip *contribution* suggests an integrative process operating in the development of speech motor control. On the other hand, the high degree of UL x LL coupling at two years of age, and the decrease in the upper lip's involvement between two and six years suggests a differentiating process in the development of speech motor control.

DISCUSSION

The Development of Articulatory Coordination: Integration, differentiation, and refinement

The objective of this investigation was to describe age-related changes in lip and jaw coordination for bilabial closure during speech. Movement of the upper lip, lower lip, and jaw were recorded during the production of syllables containing bilabial consonants in four age groups (i.e., one-, two-, and six-years, and young adult). The results revealed that the coordinative organization of articulatory gestures shifts dramatically during the first several years of life and continues to be refined past age six.

The findings might be interpreted to support three primary phases in the development of lip and jaw coordination for speech. Each phase is characterized by processes in the development of coordination that exhibit integration, differentiation, and refinement. Although distinct developmental changes occurred at each hypothetical phase, they probably overlap considerably or coexist. An integrative process in the organization of early speech might entail the sequential development of articulatory control, which in the present experiment reflects the assimilation of lip movement into an established movement pattern predominated by jaw movement. Alternatively, differentiation of articulatory coordination of upper and lower lips may be revealed as a unitary assembly in early speech, with motor development requiring increasingly independent control of these anatomically distinct structures. Finally, refinement of

motor organization may be seen in the gradual refinement of spatial and temporal control even after the age of six years. The coordinative constraints imposed by each of these mechanisms will have predictable consequences for phonologic development.

The Mature Pattern

Movement sequences by adults exhibited several features characteristic of skilled movement (see Figure 5). First, the articulators exhibited near synchronous movements and well-formed movement trajectories (i.e., characterized by a single, predominant, rising and falling pattern for each CV syllable). These features yielded high correlations and low *lags* in the present 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

The results of the oral closure and qualitative analysis suggested that the infant exerts greater control over the jaw than the lips for speech. The jaw contributed to closing the oral aperture twice as much as the lower lip did at this age. Although the spatial characteristics of jaw movement by one-year-olds were similar to those exhibited by adults, lip movements were characterized by reduced extent of movement and frequent reversals in direction unrelated to syllable boundaries. A hypothesis of delayed achievement of lip control is controversial given the wide array of lip configurations

observed during early oromotor behaviors (e.g., vocalizations, facial expressions, sucking, and chewing). However, coordination of spontaneous movements or extant behaviors may not reveal the underlying control structures for novel, more complex tasks (see Moore and Ruark, 1996 for discussion on the role of extant behaviors on speech motor development).

The developmental sequence of integration is supported in the present investigation by the augmentation of oral closure by lip movement with established jaw movement at age two. This sequence is consistent with the earlier appearance of jaw control observed in prenatal studies of orofacial movement (Humphrey, 1970; 1971). The sequential development of articulatory control for speech has received some theoretical consideration (MacNeilage & Davis, 1990a; 1990b; Nittrouer, 1993), although physiologic data are lacking.

The present observations of the predominance of jaw movement during early speech received further support from studies showing the coordinative organization for jaw control for speech to be adult-like by 15 months of age (Moore and Ruark, 1996). These observations provide some physiologic support for the model of speech development proposed by MacNeilage and Davis (1990a; 1990b) who suggest that the earliest articulations are predominated by jaw movements with little or no contribution from the lips.

Nittrouer (1993, 1995) suggested that children master some speech gestures earlier than other gestures. She derives her use of the term "gestures" from Browman and Goldstein's (1986) definition: " an articulatory structure or, more commonly, a

constellation of structures working together to achieve a linguistically significant pattern of action (i.e., the formation and release of a vocal-tract constriction)." (Nittrouer, 1995, p. 520). The present results suggest that in early development, 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.

The low *coefficient* and high *lag* values obtained for lip and jaw pairs suggest that the young child is not endowed with early movement synergies (e.g., a widely distributed central motor program) among these articulators. However, to definitively rule out the existence of early movement synergies would require observation of lip muscle activation patterns. Specifically, the lip musculature may be activated during oral closure, but the underlying motor organization may not be sufficient to produce the trajectories characteristic for these movement sequences. The one-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 at rest, but in others, they were tense with the lower lip elevated and the upper lip depressed. These varied patterns yielded a wide range of *coefficients* in the crosscorrelation analysis between and within subjects.

Although the infants generally produced well-formed jaw movements, the lips were often 180 degrees out of phase with the jaw, yielding negative *coefficients* in the crosscorrelation analysis. The amount of lower lip and upper lip deflection (i.e., interlabial compression) was much greater in this group than in any other. It is possible

that this pattern of interlabial compression reflects the generation of poorly controlled mandibular movement. Excessive displacement of movement in early speech may be related to a more general characteristic of immature motor control as, for instance, 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 movements.

Kent (1992) suggested that early articulatory movements are rapid and ballistic (i.e., movements that 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, which characterize, for instance, the /w/. A limited ability to regulate jaw control may explain why complete closing and opening gestures are so common in early vocalizations (Locke, 1983).

Two-Year-Olds

In two-year-old subjects, the movement of the jaw assimilated with movement of the lips. Upper lip and lower lip *contribution to oral closure* became more prominent. Further support for the hypothesis of sequential development of articulatory control comes from the observations that the two-year-old children tended to exhibit poorly defined lip movements across both syllables (see Figure 5). In some instances, upper and lower lip movements were characterized by a single rising and falling trajectory across both syllables. In contrast were the relatively well-defined movement trajectories exhibited in the jaw. Another distinguishing feature of this age group's productions was

the increased *contribution* of upper lip to oral closure. This observation parallels previous reports of decreases in the relative contribution of the upper lip to labial separation for vowel opening with age (Watkin & Fromm, 1978).

Movement of upper and lower lips appeared to be tightly coupled at age two. As a group, two-year-old children exhibited rigid spatial and temporal coupling of upper and lower lips in comparison to that of lip and jaw coupling. The functional significance of these high *coefficients* and short *lags* may vary depending on the age of the subject. In adult speakers, the upper lip, lower lip, and jaw are capable of producing highly independent movements. The high degree of coupling and synchrony of articulatory movement observed in adults, therefore, reflects highly specified, coordinated movement. In young speakers, a comparably high degree of coupling may indicate a lack of coordinative plasticity. Further support for the suggestion that these anatomically distinct structures may behave as a unit comes from the parallel increases in upper and lower lip *contribution to oral closure* at age two years (see Figure 8). Moreover, as demonstrated in Figure 5, lip movement trajectories at this age could be remarkably similar in shape and amplitude, especially when compared to the movement trajectories of the jaw.

Linked upper lip and lower lip control may be related to a more general feature of motor skill development that has appeared in the literature as *associative movements* (Todor & Lazarus, 1986) and *motor overflow* (Cohen, Taft, Mahadeviah, & Birch, 1967). Instances of linked motor control are commonly observed in early motor development where symmetrical muscles (homologous) and asymmetrical

(heterologous) muscles tend to produce associative movements (Lazarus & Todor, 1987). Dramatic examples of associative movements occur when movement can be observed in the resting contralateral extremity while its counterpart is performing a motor act (Cohen et al., 1967). Associative movements have been observed at various anatomical sites (e.g., ears, fingers, and limbs) and levels of organization (e.g., limbs, motor units; see Provins, 1997). These movements have been reported to decrease with age and with differential practice (Provins, 1997). In some clinical tests, the presence of such movements has been used as an indicator of neuromotor immaturity or motor impairment (Connolly & Stratton, 1968).

The putative coupling of lip movement is consistent with progressive differentiation with development. Development of lip control for speech using this mechanism would coincide with gains in the selection of discrete neuromuscular elements of the labial apparatus. Differentiation was supported by the present results in two-year-olds which revealed increased levels of spatial and temporal coupling for upper and lower lip, and elevated involvement of upper lip *contribution to oral closure*. The subsequent decrease in upper lip's *contribution to oral closure* may reflect its disassociation from lower lip. Linkage of upper and lower lip control may have neuroanatomic (i.e., shared neural structures), functional (i.e., simplification control strategy) or experiential (i.e., negative transfer of learning) bases. These possibilities will be considered further in the following sections.

A more rigorous test of 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"). Ruark and Moore (1997) studied upper and lower lip coupling directly using electromyography in two-year-old children during production of a variety of nonspeech (e.g., lip pursing, chewing) and speech tasks (e.g., syllables containing bilabials). These investigators observed task-specific patterns of labial coordination across the varied tasks (Ruark & Moore, 1997), a finding that might be interpreted as failing to support the dependence of upper lip and lower lip motor control. However, examination of their results reveals a relatively high-positive degree of coupling for all the speech tasks performed (i.e., average Fisher's z scores approximately ranging from .50 to .77). Thus, the interdependence of upper and lower lip control remains viable in support of a differentiating hypothesis for addressing the coordinative patterns exhibited by the two-year-old subjects.

Six-Year-Olds

At six years of age, lip and jaw coordination for the movement sequences examined continued to undergo refinement prior to reaching the mature form. Between ages two and six years, lip and jaw spatiotemporal coupling continued to increase. The qualitative observations revealed that movement patterns exhibited by six-year-olds were similar to those of adults, but were often more variable. Generally, spatial and temporal coupling in six-year-olds were decreased in comparison to those observed in adults; however, differences between these groups were small and did not reach statistical significance. A significant decrease in upper lip involvement occurred between ages two and six years in the oral closure analysis. In contrast, the involvement of upper lip, lower

lip, and jaw for oral closure was similar between six-year-old and adult subjects. Together these findings give the impression that the period between six-years and adult reflects continued refinement of movement control and optimization of coordination. These findings parallel the continuous refinement of speech performance from mid-childhood to adolescence, including reduced token-to-token variability (Sharkey & Folkins, 1985; Smith & Goffman, 1998) and shortened segment durations (Kent & Forner, 1980).

In summary, the present experiment has revealed age-related shifts in the coordinative organization of lip and jaw movement for speech. Based on these observations a developmental sequence of labiomandibular coordination for speech is proposed to involve integration, differentiation, and refinement. The first phase is characterized by the predominance of jaw control. The second phase involves gaining independent control of the upper and lower lip. The final phase is characterized by optimization of the established coordinative pattern. This characterization of speech motor development should be viewed as speculative; nonetheless, a number of hypotheses can be generated regarding the potential influence of this sequence on phonologic development.

Mechanisms: Data, theory, and speculation

The observed sequences in labiomandibular coordination support the presence of integration, differentiation, and refinement in the development of speech motor control. A deeper understanding of the present results requires a consideration of developmental

changes in articulatory motor pathways and biomechanics. However, before these changes can be attributed to processes related to development, movement sequences exhibited during motor learning that are independent of maturation also need to be considered.

Developmental Sequences and Changes in Neural Substrates

Integration and differentiation in early development of motor control may reflect differential development of neural centers. Myelination (Schuster & Ashburn, 1992) and early motor control (Stallings, 1973) proceed cephalocaudally and proximodistally, processes that are also reflected in early motor skill development. Moreover, studies of non-human animals have linked the emergence of oromotor skills such as sucking, biting, and chewing to maturational changes in the neural populations mediating orofacial movements (Herring & Wineski, 1986; Iriki, et al., 1988; Kubota, Narita, Ohkubo, Shibania, Nagae, Kubota, Odagiri, & Kawamoto, 1988; Lakars & Herring, 1980).

Several investigators have suggested that the location of a neural center is a good predictor of when it matures. 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 (1988) have provided compelling evidence that sucking appears earlier than biting because facial motor pathways mature (e.g., myelination and cell area) prior to trigeminal motor pathways in mice. Thus, in early

development, the emergence of some oromotor behaviors appears to be closely tied to the maturation of their supporting neural pathways.

These findings support the suggestion that neural maturation differentially constrains articulatory control during early development, limiting the movement solutions available to the infant and yielding the process of integration observed in the present study. Specifically, the results of the present experiment support the earlier appearance of jaw control compared to that of lip for speech. This developmental sequence may arise from the fact that the motor neuron pools mediating these articulators have distinct locations in the brainstem. This possibility would receive empirical support if the motor pathways for speech in the trigeminal nucleus mature earlier than those of the facial nucleus.

A number of characteristics of the immature neuromotor system may limit independent control of upper and lower lip. 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. That is, the subnuclei in the facial motor nucleus controlling upper and lower lip may be functionally indistinguishable in early development. 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 that neuronal selection is experience-driven (Edelman, 1987; Sporns & Edelman, 1993). Edelman's theory of neuronal group selection states 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.

Finally, a number of organizational features in efferent motor pathways crucial for skilled movement are absent in the young mammal, a fact which may underlie the immature motor patterns observed in the younger subjects in this study. In the immature motor system, there is an absence of the morphological diversity characteristic of most muscles. Muscle fibers are small (Sato, Mizuno, & Konishi, 1977), more homogeneous in fiber type (Rubenstein & Kelly, 1981), and innervated by multiple neurons (Navarrete & Vrbova, 1983). Together these features limit the graded recruitment of motor units and reduce the variety of movements and coordinative patterns generated.

In summary, several potential neural mechanisms in early oromotor development require consideration: (1) the effective neural centers mediating the articulators may mature at different times (i.e., integration), and (2) some neural centers may be functionally indistinguishable (i.e., differentiation). Because neural mechanisms cannot be identified from behavioral data (i.e., the problem of inverse kinematics), we can only speculate about their existence. Future developments in neural imaging techniques (i.e., functional magnetic resonance imaging) may afford the opportunity to specify the roles of neural maturation and experience in speech motor development.

Developmental Sequences and Changes in Biomechanics and Body Composition

The development of motor control may depend as much on the biomechanical properties of the articulators as on neuromotor development (Thelen, 1995). The neural organization subserving speech must adjust for developmental changes in the biomechanical properties of the articulators, including changes in tendon elasticity, muscle fiber characteristics, and increases in fat, bone, and muscle mass. Recent models of motor skill development have begun to emphasize the effects of such structural changes on early coordination (Thelen, 1995).

The intrinsic properties of body segments (e.g., mass) and environmental loads (e.g., gravity) may rate limit early motor skill development. In a series of experiments Thelen and colleagues (Thelen, 1983; 1986; Thelen, Bradshaw, & Ward, 1981; Thelen & Fisher, 1982) provided compelling evidence for the rate limiting effects of body mass on the development of locomotion. Their findings were in contrast to the long standing view that CNS maturation determines the age of onset for walking. The influence of biomechanics on emerging motor functions may vary considerably depending on the physiologic composition of the components involved and the task requirements (e.g., accuracy, speech, strength, endurance, and flexibility).

The upper lip, lower lip, and jaw exhibit different growth curves. The mandible is proportionately very small in the infant in relation to the skull. Growth of the mandible proceeds logarithmically while its characteristic shape remains relatively

unchanged (Kent & Vorperian, 1995). In contrast, the size, shape, and tissue composition of the lips change most dramatically during the first several years of life. The upper lip may even have a distinct developmental course from that of the lower lip (Kent & Vorperian, 1995).

It is difficult to specify how these anatomical changes along with changes in the biomechanical properties of muscle might differentially affect control of each articulator. There have been few investigations of the biomechanical properties of the articulators in adults (e.g., Abbs, 1973; Baragar & Osborn, 1984; Müller, Milenkovic, & MacLeod, 1984; Sanguineti, Laboissière, & Ostry, 1998), none in the context of speech motor development. It might be anticipated that changes in the absolute or proportional size of the child's articulators would dramatically alter the coordinative organization of speech. The potential for dramatic coordinative changes secondary to anatomical growth has been recognized by proponents of a dynamic systems approach to speech development: "even small changes in anatomy, for example, potentially can engender new attractor states." (Thelen, 1991, p. 343).

Surprisingly, the present findings and the available data do not support the view that changes in the relative size or mass of the lips and jaw alter articulatory control. For example, adults and children (as young as age four) exhibit only small differences in articulatory displacements despite dramatic differences in the sizes of their vocal tract structures (Smith & Gartenberg, 1984; Smith & Goffman, 1998). Although peak displacement was not measured directly in this study, Figure 5 shows that the jaw displacement of the one-year-old subjects was similar in magnitude to that of the adult

subjects. This observation is surprising given the proportionately small size of the mandible at one year of age. This mismatch of observations and expectations regarding biomechanical constraints suggests that additional studies are needed to better understand speech motor development.

Changes in Coordinative Organization Associated with Motor Learning

The observed changes in articulatory coordination may also reflect motor learning independent of maturation. Motor learning exhibits distinct phases (i.e., temporary motor solutions) with the accumulation of practice and experience. The adoption of a specific motor solution will depend on the complexity of the task and its relationship to pre-existing skills. Processes in motor learning such as *sequential motor learning*, *simplification control strategies*, and *negative transfer of learning* may account for some of the coordinative changes observed in the present study.

Sequential Motor Learning

The process of learning a complex motor skill typically requires proficiency with fundamental skills prior to advancing to higher levels of performance (Haywood, 1993). This view implies sequential learning of motor skills and may apply to the developmental sequences observed in the present data set. Specifically, the jaw-predominant gestures, which characterized the one-year-old's utterances, may constitute a fundamental skill underlying speech. This suggestion is consistent with the MacNeilage and Davis (1990a; 1990b; Davis & MacNeilage, 1994; 1995) "Frames, then Content" model of early speech production.

MacNeilage and Davis suggested that this jaw-predominate articulatory pattern has phylogenetic origins, and that it may be adapted from the coordinative framework previously established for chewing. However, the assertion that speech motor control is derived from alimentary functions has not received support by any of a series of recent investigations (see Moore & Ruark, 1996), which have demonstrated parallel development of the coordinative infrastructures of speech and nonspeech task. The present data do not resolve the question of the origin of these patterns, but support the suggestion that jaw oscillations are fundamental developmental movements in the sequence of speech motor control.

Simplification Control Strategy: Constraining the degrees of freedom

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. We have described this process as *simplification control strategies,* to distinguish it from the processes of motor skill acquisition in which constraint of redundant degrees of freedom reflects optimization of control. Bernstein's suggestion has received empirical support from studies showing that separate body segments act as a unit when learning a new motor skill (e.g., handwriting, Newell & van Emmerik, 1989; racquetball, Southard & Higgins, 1987). These studies have shown that the ability to control each segment separately is achieved through practice and is accompanied by improved skill performance (Southard & Higgins, 1987).

The upper lip, lower lip, and jaw form a redundant three-component system with respect to oral closure. Any one of these articulators can effectively occlude the oral

aperture. In the context of speech motor control, Bernstein's (1996) notion might be interpreted to suggest that during speech development children simplify an already existing set of articulatory goals to achieve more effective or efficient articulation. Thus, the rigid coordinative linkage of upper and lower lips in the present study may reflect the child's attempt to constrain the number of controlled elements. Conversely, the young child may have to rely on a reduced set of functional articulators and may recruit only those articulators over which he/she can achieve the greatest control (Kent, 1992). This possibility may especially apply to the early predominance of jaw movement in comparison to that of the lips.

Negative Transfer of Learning

The tightly coupled lip movements of early speech may be the result of negative transfer of learning. Transfer of learning effects occur when a pre-existing skill influences the learning of a new skill (Magill, 1993). Effective sucking requires high levels of interlabial coupling to form the oral seal. Therefore, it is possible that upper and lower lip coordinative patterns established for feeding influence initial attempts to coordinate these structures for speech. 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.

In summary, speech motor development entails the sequential emergence of articulatory control. The present results probably reflect extensive changes in the neuromotor pathways controlling the articulators and in their biomechanical composition. More general principles of skilled movement acquisition may also account

for some of the changes observed. Additional studies are required to reveal the relative importance of each of these factors.

Physiologic Constraints and Phonologic Acquisition

Several researchers have advanced a "physiological and human factors" orientation to phonology (Diver, 1979; Tobin, 1997), which suggest that constraints in the articulatory production and the auditory perceptual systems produce lawful relations in phonology. Universal phonologic patterns are viewed as emergents of the human communication system (Lindblom, 1992). One basic assumption of this approach is that some sounds are inherently more difficult to produce than others, and sounds or sound combinations that require less effort appear more frequently in the world's languages (Tobin, 1997). Tobin (1997) summarizes the human factors orientation to phonology:

> "The explanation of the general skewing- relying on the physiological and human factors orientations – which is based on the relative degree of ease or difficulty of the control of musculature, can even be applied further to explain the subskewings within the larger skewings, thus providing us with a single linguistic generalization that will account for all the data in the simplest way possible..." (p 37).

Tobin (1997) has extended this approach to speech development to explain the nonrandom distribution of phonemes produced by young children. The human factors orientation suggests that young children favor or disfavor certain phonemes because of inherent differences in ease of production (Tobin, 1997). Articulatory ease may account

for preferences in place, voice, and manner of articulation exhibited in young children (e.g., the prevalence of voiced bilabial stops in early speech; Stoel-Gammon, 1988). Unfortunately, there is no straightforward method to characterize sounds in terms of their articulatory complexity or ease or articulation. Such an attempt would have to include many factors relating both to perception and to production. Contemporary arguments are largely circular: later appearing phonemes must be more difficult because they appear later. From a developmental motor control perspective articulatory ease might be affected by a number of factors:

1. *The degree of specification of spatial and temporal movement parameters.* Phonemes are probably not equivalent in their coordinative demands. Some phonemes must be produced using a very narrowly specified articulatory gesture (e.g., /s/), while others can be specified quite generally (e.g., /b/).
2. *The biomechanical composition of the articulators.* The differences in the biomechanical properties of articulators interact with their function in an immature motor system. As illustrated by Thelen (1995), biomechanical properties can sharply constrain movement of some components of a motor system in early development. Furthermore, articulators with greater degrees of freedom will require either greater control specification or constraint from the motor system (i.e., tongue versus velum).
3. *The pre-existing neuromuscular organization.* There may be developmental predispositions in coordinative organization of oromotor control, that are determined by neuromotor maturation. Of course, the capacity of the system may facilitate or impede the learning of speech gestures.

Several investigators (Locke, 1993; MacNeilage & Davis, 1995) have suggested that early syllables are predominantly characterized by complete closing and opening gestures, and few narrow constrictions. These observations agree with Tobin's (1997) hypothesis 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 to 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). These observations form the impression 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).

The findings of the present study agree with and extend this proposal. Several features of articulatory coordination observed in the one- and two-year-old children suggest that, from a physiologic perspective, articulatory ease may change as a function of age. The observed coordinative features that may limit sound producing capabilities during the first several years of life include: (1) the prevalence of jaw movement, (2) poor lip and jaw coupling, (3) poor lip control, and (4) the potential for linked control of upper and lower lips. These coordinative constraints may explain why voiced stops predominate in the first year of life, and why labiodental fricatives do not emerge until around two years (Stoel-Gammon, 1985), attaining mastery at age four (Sanders, 1972).

The coordinative requirements of voiced stops apparently do not exceed the capabilities of the immature articulatory system. Stops consonants can be produced using relatively ballistic jaw control without active contribution from the lips or tongue (MacNeilage & Davis, 1995). In contrast, articulation of the labiodental /f/, for instance, requires graded lower lip and jaw control to produce a slight constriction between the upper central incisors and the lower lip.

In summary, the observed developmental changes in articulatory control support the role of physiologic constraints in the sequence of phonologic development. Accordingly, immature speech may reflect the child's exploitation of the articulators over which they have the most control. If this is the case, the divergence from babble to speech may entail the breaking away from preferred coordinative patterns in favor of those in the ambient language.

Methodological Limitations

The present techniques have provided a means by which the spatial and temporal aspects of articulatory movement in young children can be quantified. These methods were developed to address these specific experimental questions, but will be further refined for future investigations and applications.

There are a number of methodological factors that may have influenced these results and require further attention. The use of a single skin-based marker to represent articulatory movement has a number of potential problems. Because the movement markers are attached to the skin, mechanical interactions may occur. This potential

interaction between movement markers can become especially problematic when lower lip movement is derived by subtracting the jaw signal from the lower lip signal, as was done in the present study. In addition, although jaw movements were "removed" during this transformation, jaw occlusal forces continued to influence the lower lip and upper lip signals. However, the varying coordinative patterns in the data suggest that mechanical interactions between movement markers were not extensive. Specifically, if mechanical linkages were significantly influencing the position of the movement markers, we would have expected the correlation values to be uniformly high in the crosscorrelation analysis (Löfqvist, & Gracco, 1997), which was in contrast to the wide range of correlation values observed.

Another possible weakness was the effects of rotation of the head in the Z plane on movement measurements. Forward rotation of the head decreases the relative amplitudes of movements among the markers with the jaw signal being most affected. Accordingly, utterances associated with significant forward or backward head rotation were not included in the present study (see Method). Forward rotations of the head were more common than backward rotations because children tended to orient toward toys place on their lap tray. Head rotation was only a concern for the one- and two-year-old subjects as older subjects were able to comply with instructions to maintain an upright position with minimal head rotation. Throughout each experimental session, the child's head position was guided to an orientation by placing a toy just above the camera while eliciting utterances. The present results did not suggest any systematic influence of head rotation. In fact, one-year-old subjects produced relatively greater jaw movements than

any other group, a trend opposite to that which would result from artifactual forward rotation.

The coordinate system derived for the analysis of oral closure was designed to reveal developmental shifts in each articulator's role during speech, while limiting the influence of contextual variation. In the future, this measure will provide a means to examine developmental changes in articulatory coordination across a variety of speech contexts. Of course, each coordinate system has its own weaknesses and strengths. The greatest disadvantage of the present system is that passive contributions of the articulators cannot be discerned from active displacements. For instance, the position of the upper lip at rest was calculated to be contributing to oral closure because its reference position obtained during a smile was higher than its rest position. Ideally, we would like to measure only the movement of active components, which will reflect control strategies for oral closure. Consequently, individual differences in orofacial morphology among the subjects may have been reflected in the measurement of relative *contribution to oral closure.*

Finally, another potential problem for this analysis was achieving the reference postures in the young subjects. We could not be entirely confident that the young children were producing the greatest degree of oral opening possible. 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

A better understanding of the sequence of speech motor control is essential before we can begin to comprehend delayed and abnormal speech development. Unlike speech motor control, developmental milestones and critical periods have been identified for other motor skills and systems. These normative descriptions have been clinically indispensable (locomotion, Ames, 1937; Gesell & Ames, 1940; reaching, Halverson, 1931, all cited in Haywood, 1993). 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. For instance, the present results might be taken to suggest that limited mandibular control in early speech is a negative prognostic factor for later speech motor delays. While 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.

Future Research

These preliminary findings raise a host of new questions with respect to the development of speech motor control. One important next step will be to provide a more complete description of the one- and two-year-old's articulatory kinematics. Thus, future studies will focus on describing early movement characteristics of the jaw and lips in

terms of displacement, velocity, and acceleration to gain a better understanding of the control exerted in early articulation. Another avenue of inquiry includes a more detailed examination of the associative movements of the lips at around two years of age.

Finally, because the experimental approach adopted was only concerned with group differences, futures studies must consider individual differences in the sequence of speech motor development. Because children tend to vary considerably in their motor development, longitudinal designs will provide a more suitable means for describing individual differences in the developmental process.

SUMMARY

The objective of this investigation was to describe development of lip and jaw coordination for production of syllables containing bilabial consonants. Movement of the upper lip, lower lip, and jaw were recorded during the production of "baba," "papa," and "mama" in four age groups (i.e., one-, two-, six-years, and adult). Two complementary analytic techniques were used to quantify interarticulator coordination, one reflecting spatial and temporal coupling of articulatory pairs and the other isolating each articulator's contribution to oral closure.

The coordinative organization of articulatory gestures changes dramatically during the first several years of life and continues to undergo refinement past age six. The present results can be interpreted as representing 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. These constraints will have predictable consequences for the sequence of phonologic development.

Integrative processes in speech motor development were supported by the observation that one-year-olds relied heavily on jaw movement for oral closure. In contrast to the early predominance of jaw movement, lower lip's contribution to oral closure was initially small and increased gradually with age. This developmental sequence in early speech supports the hypothesis that speech motor development requires assimilation of lower lip movement into established mandibular synergies. The

predominance of jaw movement in early speech may explain the frequent occurrence of stops in early speech.

Differentiating processes may also be operative during speech motor development. The present data suggest that the attainment of independent control of the upper and lower lips might be one phase in early speech motor development. The presence of linked lip control will have predictable effects on the child's ability to produce certain phonemes under these coordinative constraints. For instance, young children may have difficulty isolating upper lip and lower lip movement to produce the labiodental fricative /f/.

Other developmental changes in interarticulator coordination reflected refinement of coordination. The qualitative observations revealed that movement patterns exhibited by six-year-olds were similar to those of adults, but were often more variable. Moreover, lip and jaw spatiotemporal coupling gradually increased with age.

Future studies will focus on further describing developmental sequences of articulatory control. One important step will be to gain a better understanding of the control exerted in early articulation by examining early movement characteristics of the jaw and lips in terms of displacement, velocity, and acceleration.

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APPENDIX

Code Generated for Experiments

Program for Crosscorrelation Analysis: Kincorr5

KINCORR5

```
%Kinematic analysis program for Peak Motus to perform
crosscorrelations
%kinematic signals of UL, LL, and J.
%UL signal is inverted prior to analysis and singals are
centered prior to correlation
%Designed for 3 movement and 2 reference markers
%Output Matrix is "data1" use with Excel-link
%Contains ULxLL Coef, ULxJ Coef, LLxJ Ceof, ULxLL Lag, ULxJ
Lag, LLxJ Lag.

close
clear

files = input (' Enter number of files to be measured: ',
's')
files = str2num(files);


KinTraces = [];
VelocityTraces = [];
Jaw_DAll =[];
KinJaw =[];
KinMatTemp = [];
CrossMAX = [];
CrossLag = [];
LagTotal = [];
CoefTotal = [];
AllMovement = [];

fs = 60; % sampling freqency
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%    For Graphic Windows
scrsz = get(0, 'ScreenSize');
color = ['green  ';'red    '; 'cyan   ';'magenta';'yellow
'];

%_______GLOBAL VARIABLES DECLARATION _____________________

global tmp2

cols = 3;

points = cols * 2; %%%%%%%%%%%% number of points to be
measured per cycle %%%%%%%

winsize = fs * 10;   % make window 10 second long

begwin = 1;
endwin = winsize;

data = []; ydata = []; Movement = []; peak = []; Peak_Data
= []; Duration_Data = [];
Peak_Diff_Data = [];DataMat = []; Time_Data =
[];Peak_Diff_Open = [];
Peak_Diff_Close = [];Peak_Diff_Time_C = [];Peak_Diff_Time_O
= [];

Max_Segment_Length = 60;



   for ii = 1:files % Loop 1
   %============  Get filename and load data
%Tunable path
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

invert = -1;


path1 = ['c:\my
documents\dissertation\data\adult\rs_a\*.*'];
path2 = ['e:\jordan\dissert\data\6yrs\h_6\*.*'];
path3 = ['e:\jordan\dissert\data\2yrs\mb_2\*.*'];
```

```
path4 = ['e:\jordan\dissert\data\1yr\hm_1\*.*'];
path5 = ['a:\']
path = path1;

[filename, pathname] = uigetfile(path,ii,100,100);

   file = [pathname filename];
        getfiles = (['DataMat',num2str(ii) ,'=
csvread(file);']);
   eval(getfiles);
        ii
   sizeit = (['[mrows chans] =
size(DataMat',num2str(ii),');']);
   eval(sizeit);


   %%  Format the file to create matrix with only the y
vectors
   %-----------------------------------------------------
------

   emptymat = (['KinMat',num2str(ii),' = [];']); % Create
empty matrix
   eval(emptymat);

   %Get all y vectors

        for iii = 1:5  %% Temporary
          place = (['place_hold =
DataMat',num2str(ii),'(:,(iii * 3)-1);']);
     eval(place);

       %Put all y vectors into one matrix

     Kin = (['KinMat',num2str(ii) ,'= [KinMat',
num2str(ii),', place_hold];']);
     eval(Kin);
   end

   DelRef = (['KinMat',num2str(ii),'(:,1:2) = [];']);
   eval(DelRef)      %Delete Reference Point coordinates

        DataMatCorrect = [];
```

```
        CenterKinMat = [];
        Segment = [];
        Peak_Time =[];
        Cent_Jaw = [];

%================  Subtract Lower Lip from Jaw to get
Lower Lip

centjaw = (['Center_Jaw = KinMat', num2str(ii),'(:,3) -
mean(KinMat',num2str(ii),'(:,3));']);
eval(centjaw);

Correction_Jaw_Mark = Center_Jaw;

%step1 = (['Correction_Jaw_Mark = Center_Jaw -
min(Center_Jaw);']); %Get correction factor for Jaw
%eval(step1);

step2 = (['KinMat',num2str(ii),'(:,2) =
KinMat',num2str(ii),'(:,2) - Correction_Jaw_Mark;']);
eval(step2);

%Invert all signals - need to adjust for Peak Motus
translation

step3 =(['KinMat',num2str(ii),'(:,:) =
KinMat',num2str(ii),' * invert;']);  %Invert all signals -
need to correct for Peak Motus translation
eval(step3);

%>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>>> Define Segment

%%%% Plot Kinematic signal and associated velocity trace --
to get gesture boundaries

tempkin = (['tempk = KinMat',num2str(ii),'(:,:);']);
eval(tempkin);

tempjaw = (['tempj = KinMat',num2str(ii),'(:,3);']);
eval(tempjaw);

%Calculate derivative
```

```
tempjaw_d = (['tempj_d = diff(KinMat',
num2str(ii),'(:,3));']);
eval(tempjaw_d);

hold on

%>>>>>>>>>>>>>>> PLOT INITIAL WINDOW for user to choose
movement of interest >>>>>>>>>
% Instructions Window
     instructions = uicontrol(gcf,...
        'Style','text',...
        'BackgroundColor', color(2, : ),...
        'String', 'IDENTIFY SEGMENT BOUNDARIES: based on
zero crossing of velocity trace',...
        'Position',[0 scrsz(4)-70 1300 100]);

%%%%%%%%%%    ZeroCrossing %%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Find Zero Crossing in Velocity Signal to estimate onset
and offset of movement %%%%%

TEMP = tempj_d; %rename for ZeroCrossing program
winsize_z = 1;
begwin_z = 1;
NumWindows = length(TEMP) - 1;
endwin_z = 2;
Movement = [];

for searchwin = 1:NumWindows  % L4 - Find zero crossings in
9 windows across signal

    AboveMat = find(TEMP(begwin_z:endwin_z)>0);
    BelowMat = find(TEMP(begwin_z:endwin_z)<0);

  if isempty(AboveMat) ==0 & isempty(BelowMat) == 0  % I2
-- If zero Crossing

     AboveMatTime = (begwin_z - 1) + AboveMat ;       %
Re-esablish the index
     AboveMatValue = TEMP(AboveMatTime);    % Get
corresponding value from data matrix
```

```
        BelowMatTime= (begwin_z - 1) + BelowMat;          %
Re-esablish the index
      BelowMatValue=TEMP(BelowMatTime);       % Get
corresponding value from data matrix


                if AboveMatTime > BelowMatTime, %%%%% I4
Positive Slope Zero Crossing --Closing Gesture

             Point1 = BelowMatValue;
             Point2 = AboveMatValue;

        if abs(Point1) < abs(Point2),
           ZeroPoint = BelowMatTime;
                else
           ZeroPoint = AboveMatTime;
                       end

                     else
                       Point1 = AboveMatValue;
            Point2 = BelowMatValue;

        if abs(Point1) > abs(Point2),
           ZeroPoint = BelowMatTime;
                else
           ZeroPoint = AboveMatTime;
                end


            end %I4

      Movement = [Movement,ZeroPoint];  %The estimated
movement onset and offset points

 end % I2

begwin_z = endwin_z;

endwin_z = begwin_z + winsize_z;


end % L4
```

```
AllMovement = [AllMovement Movement];

endloop = 0; %Initiate loop for measurements of beginning
and end points of movement

%%%%%%% END Zero Crossing Algorithm

plot(tempk);hold on; plot(tempj_d * 10);grid %Plot initial
window for boundary marking

%%%%%%%%%%%%%%%%%%%%%%%%%%%% Plot lines perpendicular to
zero crossings

hold on;
for plotzero = 1:length(Movement)
   v = axis;
   y = [v(3) v(4)];

   zero = Movement(plotzero);
   zero_x = [zero zero];

   plot(zero_x ,y,'-r');
end

%%%%%%%% User chooses gesture of interest - picks onset and
offset based on zero crossing of velocity trace

[onset junk] = ginput(1);
[offset junk] = ginput(1);

%%%%%%%%% Resize Kinematic and velocity traces

window_pad = 0; % Pad window 5 frames in front and 5 frames
in back - to get upper lip onset and offset

begwin_k = round(onset - window_pad);
endwin_k = round(offset + window_pad);

% In case chosen point for onset is less than 5.
if (begwin_k)<1,
begwin_k = 1;
end
```

```
% In case offset is greater than matrix length.
if (endwin_k)>length(tempj),
endwin_k = length(tempj)
end

ResizeK = (['KinMatGest',num2str(ii),' =
KinMat',num2str(ii),'(begwin_k:endwin_k,:);']);
eval(ResizeK);

close; %% Close Figure


end  % END for Loop1

%%%%%%%% Trial Loop - Post Data Conditioning %%%%%%%%%

for j = 1:files % Loop to Measure all trials (L1)

%%%%%%%%%  GRAPHICS  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%set(gcf, ...
        %'NumberTitle','off', ...
        %'Name','Articulatory Displacement Signals', ...
        %'backingstore','off',...
        %'Units','normalized');

KinTemp = (['KinMatTemp = KinMatGest', num2str(j),';']);
eval(KinTemp)

%%%%%%%%%%%%%%% CROSS CORRELATION %%%%%%%%%%%%%%%%%%%%%

KinMatTemp(:,1) = KinMatTemp(:,1) .* (-1); %invert upper
lip signal



meanall = mean(KinMatTemp);
CenterKinMat = [];
for ii = 1:size(KinMatTemp,2)
   CenterKinMat(:,ii) = KinMatTemp(:,ii) - meanall(ii);
end

plot(CenterKinMat);  %pause
```

```
%%%%%%%%%%%%  Cross Correlations %%%%%%%%%%%%%%%%%%%%%%%%%

corout = xcorr(CenterKinMat,'coeff');      % cross-
correlation

croscorr = corout(:, [2 3 6]); %

middle = (length(croscorr) + 1)/2; % find middle element
gaxis = axis;

y = [gaxis(3) gaxis(4)];
x = [middle middle];


%%%%%%%%%%%%%%%%%%% Plot cross-correlations for testing
%%%%%%%%%%%%
[zz yy] = size(croscorr);
xsize = (-zz/2:zz/2-1);

for i = 1:cols,   % L1 = plot cross - correlation for each
channel

plot(croscorr(:,i)); axis([1 length(croscorr) -1 1]);hold
on;
vv = axis;
   yy = [vv(3) vv(4)];

   zero = Movement(plotzero);
   zero_x = [zero zero];


plot(x,yy,'-r');grid; plot(x + 6.25,yy,'-c'); plot(x -
6.25,yy,'-c'); %plot +- 100 ms border

[peak, y1, button]= ginput(1);  %%%%%%%%% User identifies
peak with left mouse button

close

bgwin = round(peak - 2);
edwin = round(peak + 2);
```

```
   if button ==  1 ,
      [g h] = max(croscorr(bgwin:edwin,i));
      h = h + (bgwin-1);

   elseif button == 3,  % Find minimum by using right mouse
button

      [g h] = min(croscorr(bgwin:edwin,i));
      h = h + (bgwin-1);

   elseif button == 122        % If crosscorrelation does
not contain prominent peak
      g = nan;  % reject token for analysis - insert nan
      h = nan;
      end

   CrossMAX = [CrossMAX, g]
   CrossLag = [CrossLag, h]
  end %L1

            %  Main "for loop"

%%%%%%%%%%%%%%%%% Lag from crosscorrelations %%%%%%%%%%%%

lagpoint = CrossLag - middle;
lagsecond = lagpoint/fs;

LagTotal = [LagTotal;lagsecond];

CrossLag
CrossLag =[];

CoefTotal = [CoefTotal;CrossMAX];

CrossMAX=[];

ZCoef = .5 * log(1 + CoefTotal);   % Transform all cross -
correlation coefficients
ZCoef2= ZCoef/(1 - CoefTotal);              % into Fisher Z.


MeanLag = Mean(LagTotal)
StdLag =  Std(LagTotal)
```

```
end

data1 = [CoefTotal, LagTotal];

FinalMeanMat = [MeanLag StdLag];

%filename = input (' Enter filename to be saved (i.e.,
blos_48): ', 's')

%file = (['save d:\jordan\chewing\lagdata\', filename,'.lag
data1 -ascii -tabs'])
%eval(file);

%file = (['save e:\lagdata\', filename,'.lag data1 -ascii -
tabs'])
%eval(file);
```

Programs for Contribution to Oral ClosureAnalysis: Oralclos and clostime

OralClos

```
%Kinematic analysis program for determining the
contribution of UL, LL and Jaw to ORAL CLosure
% This program calls the following functions: CLOSETIME.M
% Program runs multiple files but needs user to provide
path and name
%                  a reference file that was computed using
"openpos.m"

% Data for UL, LL, and J in "RelClosure"

close
clear

global path_to_file;

%TUNABLE VARIABLES

invert = 1; % Correct for Motus upgrade
```

```
path1 = 'c:\my documents\dissertation\data\adult\rj_a\p';
path2 = 'c:\my documents\dissertation\data\6yrs\lr_6\';
path3 = 'c:\my documents\dissertation\data\2yrs\mb_2\';

path_to_file = path3;

colordef black %Make background color "black" in all
figures

files = input (' Enter number of files to be measured: ',
's')
files = str2num(files);

%============  Get filename and load data
==============================

loadit = (['[filenameput, pathnameput] =
uigetfile(''',path_to_file,'\*.mat'',''Get Reference
File'',100,100);'])
eval(loadit)

ref_fileput = [pathnameput filenameput];

% Loads reference matrix (OpenMat) previously computed in
Openpos.m

getref = (['load ''', ref_fileput, ''';']);
eval(getref);

KinMatTemp = [];
Displacement = [];
RelClosure = [];
SyllableData = [];
syllable =[];
FileData = [];


fs = 60; %sampling rate

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%    For Graphic Windows
scrsz = get(0, 'ScreenSize');
```

```
color = ['green  ';'red    '; 'cyan   ';'magenta';'yellow
'];

%_______GLOBAL VARIABLES DECLARATION _____________________

global ClosureTime Open DATAMAT BEGWIN ENDWIN syllable
directions ii chans mrows

%_____________________________________________________

winsize = fs * 10;

data = []; ydata = []; Movement = []; peak = []; Peak_Data
= []; Duration_Data = [];
Peak_Diff_Data = [];DataMat = []; Time_Data =
[];Peak_Diff_Open = [];
Peak_Diff_Close = [];Peak_Diff_Time_C = [];Peak_Diff_Time_O
= [];

for ii = 1:files % Loop 1

% Make RAW Data Matrix Global for "clostime.m".

   fileglobal = (['global DataMat', num2str(ii),';']);
   eval(fileglobal);

% Make TREATED Data Matrix Global

   getglobal =(['global KinMat',num2str(ii)]);
    eval(getglobal)


% Function call - getpeak5

DIR = (['directions = ''Get File ' num2str(ii),';''']);  %
Must specify for getpeak5.m
eval(DIR)

   getpeak5
%================  Subtract Lower Lip from Jaw to get
Lower Lip only ================
```

```
centjaw = (['Center_Jaw = detrend(KinMat',
num2str(ii),'(:,3));']);
eval(centjaw);

Correction_Jaw_Mark = Center_Jaw;

step2 = (['KinMat',num2str(ii),'(:,2) =
KinMat',num2str(ii),'(:,2) - Correction_Jaw_Mark;']);
eval(step2);

%Invert all signals - need to adjust for Peak Motus
translation

step3 =(['KinMat',num2str(ii),'(:,:) =
KinMat',num2str(ii),' * invert;']);  %Invert all signals -
need to correct for Peak Motus translation
eval(step3);

>>>>>>>>>>>>>>>>>> Define Segment >>>>>>>>>>>>>>>>>>>

%%%% Plot Kinematic signal -- to get gesture boundaries

tempkin = (['tempk = KinMat',num2str(ii),'(:,:);']);
eval(tempkin);

%%%%%%%%%  filter signal %%%%%%%%%%%%%%%%%%%%%%%

fc = 25;

fcc = fc/((fs)/2);
[fb,fa] = butter(5,fcc);

FiltMat = [];
KinMatTemp = [];

for ff = 1:3
       home;
       KinMatTemp(:,ff) = filtfilt(fb,fa,tempk(:,ff));
end

%%%%%%%%%%%%%%%%%%%%%% Invert UL%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%KinMatTemp(:,1) = KinMatTemp(:,1) .* (-1); %invert upper
lip signal

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

ITL = 0;
syllable = 1;
MultiSyllable = 1;

while MultiSyllable == 1; % MS Loop - if token contains
multiple syllables
while ITL == 0 % ITL (Intra Trail Loop)

%>>>>>>>>>>>>>>> PLOT INITIAL WINDOW for user to choose
movement of interest >>>>>>>>>
% Instructions Window
     instructions = uicontrol(gcf,...
        'Style','text',...
        'BackgroundColor', color(2, : ),...
        'String', 'IDENTIFY SEGMENT THAT CONTAINS THE PEAKS
OF ALL MOVMENTS',...
        'Position',[0 scrsz(4)-70 1300 100]);

plot(KinMatTemp); grid on

%%%%%%%% User chooses gesture of interest - picks onset and
offset based on zero crossing of velocity trace

[onset y_on] = ginput(1);
[offset y_off] = ginput(1);

%%%%%%% Draw Window Around Selection

getaxis = axis;

x_window = [onset onset offset offset];
y_window = [getaxis(3) getaxis(4) getaxis(4) getaxis(3)];

line(x_window,y_window)

%%%%%%%%% Resize Kinematic and Velocity traces
```

```
window_pad = 2; % Pad window 2 points in front and 2 points
in back - to get upper lip onset and offset

BEGWIN = round(onset - window_pad);
ENDWIN = round(offset + window_pad);

% In case chosen point for onset is less than 5.
if(BEGWIN) < 1
BEGWIN = 1;
end

% In case offset is greater than matrix length.
if(ENDWIN) > length(KinMatTemp)
ENDWIN = length(KinMatTemp);
end

KinMatGest =  KinMatTemp(BEGWIN:ENDWIN,:);

%close; %% Close Figure

forward = menu('WHAT UP?','Accept - Next' ,'Re-Do', 'Accept
- Stay '); %%%%% If 'no' overwrite last cycle measured if
not satisfied
   if   forward == 1


     MultiSyllable = 0; %Token only contains one syllable
     ITL = 1; % End intratoken loop

     syl_position = menu('Postion','Final','Medial',
'Initial'); %%%%% If 'no' overwrite last cycle measured if
not satisfied
       if   syl_position == 3
         syllable = 'I';

       elseif  syl_position == 2
         syllable = 'M';

       else    syl_position == 1
         syllable = 'F';

       end
```

```
     %% Function call

     clostime  %%% Function to get time of minimum in
Interlabial Distance

   elseif forward == 2 % A chance to redefine segment

     syllable = [];
   else forward == 3

          % Indicate Syllable Position in Utterance

     syl_position = menu('Postion','Final','Medial',
'Initial'); %%%%% If 'no' overwrite last cycle measured if
not satisfied
        if   syl_position == 3
           syllable = 'I';
           MultiSyllable = 1; %Continue to loop
        elseif  syl_position == 2
           syllable = 'M';
           MultiSyllable = 1; %Continue to loop
         else    syl_position == 1
            syllable = 'F';
            MultiSyllable = 0; %End MultiSyllable Loop
        end

        %% Function call

        clostime  %%% Function to get time of minimum in
Interlabial Distance


     end

SyllableData = [SyllableData; syllable];

num2str(ii + 1)

OralClosure = OpenMat - KinMatGest(ClosureTime,:);

if OralClosure(1) < 0 % If position of articulator is more
in the open position than reference
```

```
   OralClosure(1) = 0; % ,due to labial compression, make
position contribute "0" to oral closure.
   else
   for i = 2:3
      if OralClosure(i) > 0
         OralClosure(i)= 0;
      elseif OralClosure(i) < 0;
         OralClosure(i) = abs(OralClosure(i));

      end
   end
end


SumOfClose = sum(OralClosure);

RelCloseMov = (OralClosure/SumOfClose) * 100;

Displacement = [Displacement; OralClosure]; % Store results
from multiple files
RelClosure = [RelClosure; RelCloseMov]; % Store relative
closure computations from multiple files

FileData = [FileData,ii];
     end % (ITL) Intra trial loop
  end % END MultiSyllable Loop
end  % END for Loop1

   data1 = [RelClosure];
   SyllableData;
```

Clostime

```
%
% Finds time of Maximum Oral Closure (MOC) by computing the
interlabial distance function and finding
% the minimum. Point(time) of MOC is stored in
"ClosureTime".
% No User Input Required
```

```
%
% For no interpolation set "Interp_Factor" to "1".
% Modified from LIPDIS
%
% Written by Jordan Green 6/27/97
% Modified from LIPDIS to compute artiuclatory
displacements 9/10/97

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
AllTrialMat = [];
ClosedLipMat = [];

SampRate = 60;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%    For Graphic Windows

scrsz = get(0, 'ScreenSize');
color = ['green  ';'red    '; 'cyan   ';'magenta';'yellow
'];

%_______GLOBAL VARIABLES DECLARATION _____________________

global ClosureTime ii files DATAMAT BEGWIN ENDWIN OpenMat
channel number

iii = num2str(ii);

getfile = (['global DataMat',iii;]);
   eval(getfile);

%_____________________________________________________________

   %============  Get filename and load data
==============================

   tempmat = (['WorkMat = DataMat', iii, ';']);
   eval(tempmat)

   %%  Format the file to create matrix with only the y
vectors
   %-----------------------------------------------------
------
```

```
   CloseKinMat = []; % Create empty matrix

   %Get all y vectors

        for jj = 1:5  %% Temporary

     getcolumn = (jj * 3) - 1;
     place_hold = WorkMat(:,getcolumn);

       %Put all y vectors into one matrix

     CloseKinMat = [CloseKinMat place_hold];

   end

   %Delete Reference Point coordinates

   CloseKinMat(:,1:2) = [];

%%%%%%%%%  filter signal %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for cc = 1:3
fc = 30;
fcc = fc/(SampRate/2);
[fb,fa] = butter(5,fcc);

CloseKinMat(:,cc) = filtfilt(fb,fa,CloseKinMat(:,cc));
end

%============================================================
=

%Invert all signals - just for graphic - need to adjust for
Peak Motus translation

CloseKinMat(:,:) = CloseKinMat * (-1); %    all signals -
need to correct for Peak Motus translation

%============================================================
=
Jaw_D = diff(CloseKinMat(:,3));  %Calculate derivative and
pad with zero
```

```
ul_i = CloseKinMat(:,1);

ll_i = CloseKinMat(:,2);

InterLabDis_I = abs(ul_i - ll_i);

InterLabDis_I = InterLabDis_I(BEGWIN:ENDWIN,:);

%%%%%%% Within Trial loop - Articulator %%%%%%%%%%%%%%%%%%

     KinPlot = plot(InterLabDis_I);
     xlabel('Points');ylabel('Displacement (cm)');grid on

     i = 1; %For graphics

     %Create frame at top of graph to indicate channel
being measured

     channel = ['InterLabial Distance'];
     number = ['File ' num2str(j)];
     syllable_G = ['Syllable Position: ' syllable];

     % Label articulator being measured
     ft_chan = uicontrol(gcf,...
        'BackgroundColor', color(i, : ),...
        'Style','text',...
        'String', channel(i , : ),...
        'Position',[0 scrsz(4)-70 500 100]);
     hold on

              ft_chan = uicontrol(gcf,...
        'BackgroundColor', color(i, : ),...
        'Style','text',...
        'String', number,...
        'Position',[700 scrsz(4)-70 100 75]);



         ft_chan = uicontrol(gcf,...
        'BackgroundColor', color(i, : ),...
        'Style','text',...
        'String', syllable_G,...
```

```
        'Position', [0 .80 .10 .1],...
        'Units', 'Normalized');

%================ Get Minimum and Max Oral Closure
=============================================================

     % Get MIN in InterLabial Distance

     [Min_Data min_x] = min(InterLabDis_I);

     [Peak_Data peak_x]= max(InterLabDis_I);

 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

ClosureTime = min_x;  % Global Variable for OralClos.m

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear DataMat

close
```

General Purpose Programs

```
% Getpeak5 - Get Peak Motus file that contains 5 markers (2
reference and 3 movement)
% This program loads and formats Peak Motus files
% User needs to specify
% 1) the number of files to load in "files"
% 2) directions for menu
% Output matrix is KinMat# - '#' indicating the file number
if multiple files are loaded

global files directions mrows chans path_to_file

%============  Get filename and load data
==============================

loadit = (['[filenameget, pathnameget] =
uigetfile(''',path_to_file,'\*.csv'',directions,100,100);']
)
eval(loadit)
```

```
   file = [pathnameget filenameget];
    getfiles = (['DataMat',num2str(ii) ,'=
csvread(file);']);
   eval(getfiles);

   % Make RAW Data Matrix Global for "clostime.m".

   fileglobal = (['global DataMat', num2str(ii),';']);
   eval(fileglobal);

   % Make TREATED Data Matrix Global

   getglobal =(['global KinMat',num2str(ii)]);
         eval(getglobal)

         ii
   sizeit = (['[mrows chans] =
size(DataMat',num2str(ii),');']);
   eval(sizeit);

   %%  Format the file to create matrix with only the y
vectors
   %-----------------------------------------------------
------

   emptymat = (['KinMat',num2str(ii),' = [];']); % Create
empty matrix
   eval(emptymat);

   %Get all y vectors

         for jjj = 1:5  %% Temporary

     getcolumn = (jjj * 3) -1;
           place = (['place_hold =
DataMat',num2str(ii),'(:,getcolumn);']);
     eval(place);

       %Put all y vectors into one matrix

     Kin = (['KinMat',num2str(ii) ,' = [KinMat',
num2str(ii),', place_hold];']);
     eval(Kin);
```

```
end

DelRef = (['KinMat',num2str(ii),'(:,1:2) = [];']);
eval(DelRef)      %Delete Reference Point coordinates
```

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EDUCATION

University of Washington, Seattle	predoctoral		*Sept '93 - Present*
University of Iowa, Iowa City	predoctoral		*Jan '95 - May '95*
California State University, Chico	M.A.	Speech-Language Pathology	*1991*
California State University, Chico	B.A.	Psychology	*1988*

EXPERIENCE

Children's Hospital and Health Center, San Diego, CA *April '91 - June '93*
SPEECH-LANGUAGE PATHOLOGIST/Researcher:

Clinical responsibilities included diagnosis and treatment of a variety of pediatric cognitive/communication disorders, and supervision of clinical fellows. Served as primary speech-language pathologist on Cleft Palate, Dysphagia, and Pediatric Rehabilitation Teams.

University of California, Davis Medical Center *June'91 - Dec '91*
Department of Otorhinolaryngology
TRAINEE AND RESEARCH ASSISTANT:

Selected to participate in therapy and research efforts of Dr. Rebecca Leonard Director of Speech Language Division of U.C. Davis Otorhinolaryngology Clinic.

PREDOCTORAL ACADEMIC POSITIONS

NIH Research Training Fellowship	*Sept '93 - May '95*
Research Assistantship	*June '95 - May '96*
NIH Research Training Fellowship/Teaching Assistantship	*Sept '96 – June '97*
Research Assistantship	*June '97 - Present*

PUBLICATIONS

Green, J.R., Moore, C.A., Ruark,J.L., Rodda, P.R., Morvee, W. & VanWitzenburg, M. (1997). Development of Chewing in Children from 12 to 48 Months: a longitudinal study of EMG patterns. *Journal of Neurophysiology, 77,* 2704-16.

Green, J.R., Buder, E.H., Rodda, P.R, & Moore, C. A. (1997). Reliability of measurement across several acoustic voice analysis systems. In M. Cannito, K. Yorkston, & D. Beukelman (Eds.) *Neuromotor Speech Disorders: Nature, Assessment, & Management.* Baltimore: Paul H. Brookes Publishing Co.

Minifie, F.D., Green, J.R., Smith, J., Huang, D.Z. Inter-judge variability in perception of voice qualities. *Proceedings of The International Congress of Phonetic Sciences, Stockholm, Sweden, 1995, 758-761.*

Minifie, F.D., Huang, D.A., & Green, J.R. Relationship between acoustic measures of vocal perturbation and perceptual judgments of breathiness, harshness, and hoarseness. *Proceedings of The International Conference on Spoken Language Processing. Yokohama, Japan, 1994, 1999-2002.*

CONTRIBUTED PRESENTATIONS

Green, J.R., Moore, C.A., Higashikawa, M. & Steeve, R. (1998). Development of Lip and Jaw Coordination for Production of Bilabial Consonants. Conference on Motor Speech, Tucson, AZ, Jan. 29 – 4.

Green, J.R., Moore, C.A., & Rodda, P.R. (1997). Longitudinal Study of Chewing in Children Aged 12 to 48 Months. ASHA's Annual Convention, Boston, MA, November 20-23.

Green, J.R., Buder, E.H., Rodda, P.R., & Moore, C.A. (1996). Reliability of measurement across several acoustic voice analysis systems. Conference on Motor Speech. Amelia Island, Florida, February 22-25.

Minifie, F.D., Green,J.R., Smith, J., Huang, D.Z. (1995). Inter-judge variability in perception of voice qualities. International Congress of Phonetic Sciences, Stockholm, Sweden, Aug. 13-19.

Minifie, F.D., Huang, D.A., & Green, J.R. (1994). Relationship between acoustic measures of vocal perturbation and perceptual judgments of breathiness, harshness, and hoarseness. International Conference on Spoken Language Processing. Yokohama, Japan, September 18-22.

RESEARCH AWARDS

Children's Hospital and Health Center. " Speech Duration Variances Between Cleft Palate Children With Nasal Emissions and Non Cleft Palate Children" (Total direct costs: $ 4104.00) principle investigator, *1992-1993.*

TEACHING EXPERIENCE

Teaching Assistantship (University of Washington) *Sept '96 - June '97*
Speech Science (SPHSC 300)

Departmental Tutor (California State University Chico) *Aug '89 - Dec '89*
Provided assistance to students in areas of speech science, speech perception, and acoustics.

Guest Lectures

University of Washington

Topic: *Source Filter Theory* *1998*
Class: *Speech Science (Instructor: Chris Moore)*

Topic: *Cleft lip and palate* *1996*
Class: *Neurological Bases of Speech and Language (Instructor: Edythe Strand)*

Topic: *Speech acoustics* *1996*
Class: *Speech Science (Instructor: Chris Moore)*

Topic: *Signal processing for speech analysis* *1996*

Class: *Speech Science (Instructor: Chris Moore)*
Topic: *Central nervous system demonstration* *1995*
Class: *Neurological Bases of Speech and Language (Instructor: Edythe Strand)*
Topic: *Experimental design (Instructor: Fred Minifie)* *1994 & 1995*
Class: *Research Methods in Speech and Hearing Sciences*
Topic: *Lectured to graduates and undergraduates on the role of the basal ganglia in motor control.* *1994*
Class: *Neurological Bases of Speech and Language (Instructor: Edythe Strand)*

Children's Hospital and Health Center, San Diego

Topic: Speech Duration Variances Between Cleft Palate Children With Nasal Emissions and Non Cleft Palate Children *1993*

Topic: Treatment of Speech Motor Disorders in Children *1992*

California State University Chico

Topic: Clinical applications of Mac Speech Lab *1990*
Class: Organic Disorders (Instructor: Bob Hall)

CREDENTIALS

Certificate of Clinical Competence

ORGANIZATIONS

American Speech and Hearing Association
Acoustical Society of America