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]ct[**Development of Neural Control of Orofacial Movements for Speech**
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]ha[1 Introduction

The purpose of this chapter is to provide an integrative overview of studies of the development of the neuromotor processes involved in controlling articulatory movements for speech. Such a review is not currently available and seems warranted given the appearance over the past decade of a number of studies of prespeech and speech motor processes in infants, preschoolers, school-age children, and adolescents. There has been considerable interest in the processes underlying speech motor development in infancy and childhood for many years, but until recently, most investigators relied solely on measurements of the speech acoustic signal to infer underlying physiological processes. While many important insights into speech motor development arose from this work (e.g., Kent, 1976; Nittrouer, 1993), direct measurements of articulatory movements in children and infants provide a new avenue to expand our knowledge of speech motor development. Fortunately over the past decade, a variety of technologies have become available which allow the noninvasive transduction of articulatory movements in children and adults. There also have been numerous advances in examining the development of respiratory and laryngeal behaviors in infants and children (e.g., Stathopoulos and Sapienza, 1993; 1997; Boliek et al., 1996; 1997; Huber et al., 1999; Moore et al., 2001; Connaghan et al., 2004). However, a comprehensive review that includes these components of the speech motor system is beyond the scope of the present chapter. When a scientist or indeed a casual observer contemplates the act of speaking, the result is usually amazement at how speakers produce this complicated and multilayered output in such an apparently effortless and rapid manner. A conceptual approach that helps to simplify the problem of speech motor control is illustrated in Figure 7.1. In a lower layer of this diagram, the groups of motoneuron pools (the neurons that innervate muscles) are shown. At this level, it is clear that for speech (or any other motor behavior) to be produced, the nervous system must generate sets of commands to drive these motoneuron pools. These command signals must be coordinated in time and space for the appropriate sequences of muscle activation to occur. Therefore, we can attempt to understand speech motor control processes by investigating where in the nervous system these neural commands to muscles are generated and how they are modified to achieve a variety of linguistic and metalinguistic goals.]Figure 7.1 near here[

Also included in Figure 7.1 are the centers involved in emotional vocalization, and another box representing central pattern generators (CPGs), networks of neurons in the brainstem that drive phylogenetically older behaviors such as mastication, respiration, and swallowing. These neural centers also have relatively direct connections to the motoneuron pools that we use for speaking. Thus, if we think of the motoneuron pools

as the soldiers that are put into action to control muscle contraction, there are several different “generals” that can command them to produce the quite distinctive behaviors of speaking, chewing, resting breathing, and laughing. Thus the speech control systems in the cortex must interact with these older neural control centers in some way. How these interactions occur is a matter of some debate (thus the question marks about these connections in Figure 7.1). Some authors suggest that the older circuits, for example, for emotional vocalization, mastication, and respiration, are engaged by the speech control system, which takes advantage of these preexisting neural connections (MacNeilage, 1998; Lund & Kolta, 2006). The speech controller is hypothesized to bias these circuits in a way that produces the muscle activation patterns for speech, rather than for chewing or laughing. Other authors (von Euler, 1982; Moore & Ruark, 1996) suggest that the cortical networks involved in speech completely bypass these brainstem centers, arguing that the muscle activation patterns are radically distinctive for speech compared to the other behaviors and that speech is organized around entirely different (linguistic) goals. Therefore they hypothesize that the emotional vocalization center and other central pattern generators are simply suppressed and bypassed when cortical networks are engaged for speech. Anyone who has tried to carry on a conversation while jogging will know, however, that when speech goals interfere with metabolic demands for oxygen, the two systems compete, and metabolic breathing wins the battle for control of the motorneuron pools. Finally, this issue of the relationship between speech cortical networks and the older CPG neural networks has also been an important one in the study of the development of speech motor control. Relevant to the present chapter, there is debate about whether speech processes develop out of preexisting oral motor behaviors, such as sucking and chewing, or whether the development of speech motor control takes an entirely independent course (Moore & Ruark, 1996; Ruark & Moore, 1997; MacNeilage, 1998).

]ha[2 The Components of Articulatory Motor Control System.

]hb[2.1 Central mechanisms for articulatory control

The cortical and subcortical networks involved in language formulation and the planning and production of speech in adults have been investigated in a large literature starting with clinical lesion studies and now greatly expanded by neuroimaging studies. Interestingly, much more imaging work has focused on language processing, for example in verb generation tasks, rather than specifically on the prespeech planning and execution of speech movements (reviewed by Indefrey & Levelt, 2000). In a recent functional magnetic resonance imaging (fMRI) study, Bohland and Guenther (2006) focused their investigation on prespeech motor planning and on execution. They investigated the preparation and production of nonsense syllable sequences varying in length and complexity. Both “go” (response preparation and execution) and “no go” (response preparation only) conditions were included, so the differences in networks involved in speech motor preparation could be distinguished from those involved in overt speech production. Activations were observed in the areas of the brain that we would predict to be activated on the basis of earlier investigations, including bilateral activation of pre- and postcentral gyri, ventral motor and sensory cortical areas, anterior superior temporal cortex, medial pre-motor areas, supplementary motor area (SMA), the basal ganglia, the cerebellum, and the thalamus. Left lateralized activations emerged in the inferior frontal

sulcus and in the anterior insula. Compared to the “no go” condition, the “go” condition resulted in significantly more bilateral activation in the primary sensorimotor areas representing lips, tongue, jaw, and larynx. This finding points to the critical role for these areas in generating the commands to the musculature for speech and integrating somatosensory feedback for online control in coordination of the articulators. Bilateral rather than a left lateralized activation is observed, because both hemispheres are involved in ongoing sensorimotor control. In contrast in the preparation only “no-go” trials, a left lateralized response was observed in the ventral motor and premotor cortices. Bohland and Guenther hypothesized that preparation for speaking “primes” motor cortical cells primarily in the left hemisphere, while overt speaking requires bilateral sensorimotor control.

Thus it is clear from studies of adults that, as shown in Figure 7.1, widely distributed cortical and subcortical networks are activated in the planning and production of speech. How and when do these widely distributed, highly specialized neural networks for speech production develop? The infant is not born with these networks in place. While functional imaging studies are more methodologically challenging, many structural imaging studies have been completed in infants and children. Advances in neuroimaging methods, especially MRI, have now opened up the area of pediatric imaging. Lenroot and Giedd (2006) provided an excellent review of brain development in children and adolescents revealed by morphometric measures of gray matter and white matter from MRI scans. They include results from their own large-scale longitudinal study of typically developing children and adolescents at the National Institute of Mental Health. Important for the present chapter is the finding that the growth of gray matter volume follows a regionally specific inverted U-shaped developmental curve. For example, in the frontal lobe, gray matter volume reaches its maximum at 11 years in girls and 12 years in boys, and temporal gray matter volume peaks at 16 years in boys and girls. In contrast, the amount of white matter in the brain generally increases throughout childhood and adolescence. Myelination and dendritic and axonal arborization continue well into middle age.

These volumetric studies have been very helpful in mapping the protracted development of the brain and the regional differences in developmental trajectories. Furthermore, these methods are now being employed to map the neural bases of a variety of developmental disorders. Jancke et al. (2007) found decreased white matter volumes and anomalous anatomy in a left-hemisphere fronto-temporal network that included both language and motor areas in a group of children (aged 4–10 years) with developmental language disorder.

Another recently developed technique based on magnetic resonance scans is diffusion tensor imaging (DTI), which allows mapping of fiber tracks essential for interregional communication in the central nervous system (CNS); Paus et al., 2001). Many different laboratories are undertaking studies of children with normal developmental histories and children with a variety of atypical histories. Using DTI, Deutsch et al. (2005) studied children with a wide range of reading performance levels. In the left temporo-parietal region they reported that the white matter structure measured using fractional anisotropy (an index of the coherent structure of fiber tracts) correlated with behavioral indices of reading, spelling, and rapid naming performance. In adults who stutter there is evidence, based on DTI, that left-hemisphere fiber tracts that connect

pre- and primary cortical motor areas are disrupted (Sommer et al., 2002). This methodology is extremely promising for future studies mapping the development of white matter tracts in normally developing children and in those with a variety of speech motor problems.

]hb[2.2 Peripheral mechanisms in articulatory control and coordination

]hc[2.2.1 **Motorneuron pools and muscles** As shown schematically in Figure 7.1, groups of motorneurons (motorneuron pools) located in columns in the brain stem innervate orofacial muscles. Muscles of the lips, jaw, and tongue are innervated by different cranial nerves: the facial, trigeminal, and hypoglossal nerves, respectively. In his review of the muscles involved in speech production, Kent (2004) emphasized the uniqueness of these muscles and their distinctiveness from limb muscles. Even within the articulatory muscle system, there is a remarkable variety of muscle types and sensory receptors. For example, the jaw-opening and closing muscles operate around a joint, while the muscles of the lips comprise a sphincter and do not have any bony attachments via tendons. The muscles of the human tongue operate as a muscular hydrostat (Smith & Kier, 1989), a class of muscles that includes trunks, tongues, and tentacles. Kent provided an excellent review of the histochemical properties of the muscles involved in speech and noted that many of these muscles have heterogeneous fiber types and varying regional distributions of the different classes of fibers. Stal et al. (2003) investigated the fiber composition of three intrinsic muscles of the human tongue – longitudinalis, verticalis, and transversus – in four anterior to posterior regions using morphological, enzyme, and immunohistochemical techniques. All three muscles show a mix of slow, intermediate, and fast fibers, but small, fast fibers predominate in the anterior region, while larger diameter, slow and intermediate fibers are predominant in the posterior region. Many cranial muscles show this reversal in pattern compared to limb muscles, in which slow fibers typically are the smallest in diameter, and fast fibers are the largest. Stal et al. note, “This muscle fibre composition of the tongue differs from those of limb, orofacial and masticatory muscles, probably reflecting genotypic as well as phenotypic functional specialization in oral function” (p. 147). Given the differences between humans and other primates in fiber types and distribution in the muscles involved in speech (e.g., Sciote et al., 2003), it seems highly likely that many of the features of the human orofacial, lingual, and mandibular muscles evolved uniquely to meet the complex, rapid, low-force, positional demands of speech (Kent, 2004).

]hc[2.2.2 **Orofacial sensory information**

Many different kinds of sensory receptors are found in the muscles, skin, and connective tissues of the articulatory system. As with the histochemical properties of the cranial muscles, the nature of sensory innervation across lips, jaw, and tongue varies remarkably. Muscles spindles are densely supplied in the jaw-closing muscles (but are absent or sparse in jaw-opening muscles) and in the intrinsic tongue muscles (see Smith, 1992, for a review). Lip muscles lack muscle spindles (Stal et al., 1990). The vermillion borders, the intraoral mucosa, and the hairy skin of the face are densely innervated with a variety of mechanoreceptors. Direct recording using microneurography in humans has demonstrated that perioral and intraoral cutaneous receptors are activated during speaking (Trulsson & Johansson, 2002). While such recordings have not been made in human jaw-

closing muscle spindle afferents, it seems highly likely based on recordings of monkey jaw muscle spindle afferents during voluntarily controlled jaw movement (Larson et al., 1983) that these receptors provide very precise information to the CNS about jaw-opening velocity and position during speech. Recordings from the low-threshold cutaneous receptors of the lips and mucosa show that in addition to being activated by direct contact with external objects, they signal contact between the lips, changes in air pressure associated with speech sounds, and deformations of the tissues resulting from movement (Trulsson & Johansson, 2002). Therefore they provide both exteroceptive and proprioceptive information.

It is clear that the CNS is receiving highly specific and dynamic exteroceptive and proprioceptive information during speech. In addition to signaling sensory information along central pathways, afferent fibers from these low-threshold mechanoreceptors also make reflex connections with cranial motorneuron pools. These pathways are illustrated in Figure 7.1. In general, the importance of these reflex pathways has been underestimated in research on speech motor control, and the clinical literature often makes the assumption that cranial reflex pathways are arranged in the same patterns classically described for antagonistic pairs of limb muscles. However, the anatomical data alone indicate that analogous circuitry (e.g., the Ia inhibitory pathway to the antagonist) is unlikely, because antagonistic pairs of cranial muscles do not show the same sensory innervation patterns (e.g., jaw-closing muscles have spindles, while jaw-opening muscles do not). Another widespread clinical impression about oral motor reflexes is that they have powerful effects in the infant, and that these effects fade with development as reflex circuits are suppressed and overtaken by cortical originating control networks. As the review below will reveal, reflex effects of some classes of low-threshold mechanoreceptors in fact increase in gain during the childhood years.

2.2.3 Oral motor reflexes

Muscle spindles in the human jaw-closing muscles have powerful excitatory effects on both their muscle of origin and bilaterally to all other jaw-closing muscles (Smith, Moore, & Pratt, 1985). Precise characteristics of the jaw-stretch reflex response in normal adults, including effects of varying frequency and amplitude of step and sinusoidal stretches, have been documented (Cooker et al., 1980). Very small step stretches to the mandible produce very large electromyographic (EMG) and jaw-closing force responses at a very short latency, 8–10 ms. In a recent study (Finan & Smith, 2005) the same techniques were applied to assess stretch reflex responses in two groups of typically developing children (age 5–6 and 9–10 years) and young adults. Latency of the responses increased with age, but the 9 to 10-year-old group showed the largest amplitude of responses and the highest reflex gain, which was significantly larger compared to both the younger children and the adult group. This suggests an inverted U-shaped growth curve for jaw-stretch reflex gain and the interesting conclusion that as children are learning and refining speech motor skills, reflex circuits actually have higher gains.

Afferent fibers from low-threshold perioral and intraoral mechanoreceptors also make reflex connections with jaw-closing and lip muscles. We undertook a series of studies of the effects of intraoral stimulation on the jaw-closing muscle system (Smith, Moore, Weber, et al., 1985; Smith et al., 1991; Wood & Smith, 1992). Reflex responses were measured as stimulus-linked changes in masseter EMGs and jaw-closing force

measured against a background static biting level. The mechanical stimuli were small (1 mm) displacements of a servo-controlled smooth metal probe, which were perceived as light, innocuous gliding changes in contact. In our initial study we applied the innocuous mechanical stimulus to eight sites on the tongue dorsum and palate in a large group of young adults. Stimulation of the palate produced primarily suppressions of EMG and drops in jaw-closing force, while stimulation of the tongue, especially in anterior placements, typically resulted in excitatory EMG responses and increased jaw-closing force. This study revealed a set of spatially organized reflex responses of the jaw-closing muscles in response to light cutaneous stimulation. Such responses could not be interpreted as primarily of protective significance.

In later studies of reflexes of the jaw-closing system produced by the same innocuous mechanical stimulus, we tested groups of 7 to 8-year-old (Smith et al., 1991) and 4 to 6-year-old children (Wood & Smith, 1992). The 7 to 8-year-old children had variable responses with some showing adultlike EMG and force responses, while others showed extremely large and long-lasting jaw-closing responses to the stimulus. These large, long duration responses observed in some of the 7- and 8-year-old children were much larger than the reflex responses we had observed in our earlier study of adults. This led us to the hypothesis that 7–8 years is a transitional period in oral motor reflex development, with the very large responses at this age perhaps a sign of a less mature pattern present in some of the children. In a follow-up study of 4 to 6-year-old children (Wood & Smith, 1992), we tested the hypothesis that the younger children would have extremely high-gain cutaneous reflexes operating on the jaw-closing system. We were surprised to find that compared to the 7 to 8-year-olds, the younger children often had no response or responses that were much smaller than those of the 7- and 8-year-old children. This result is consistent with the findings for the jaw-stretch reflex, again suggesting an inverted U-shaped growth curve and that cutaneous oral motor reflexes develop along with the acquisition of speech motor skills.

Another reflex circuit which has received attention in relation to speech production is the perioral reflex, the response of lip muscles to innocuous mechanical stimulation of the vermilion border and/or perioral hairy skin (McClellan & Clay, 1994; Smith, Moore, McFarland, et al., 1985; Smith et al., 1987; Barlow & Bradford, 1996). This short-latency response is typically a multi-component excitation of orbicularis oris to light mechanical stimulation. It is present in newborn infants (Barlow et al., 2001), and like the jaw-stretch and cutaneous jaw reflexes described above, a preliminary study of a small number of school-age children suggests that the perioral reflex response grows in amplitude over childhood (Barlow et al., 1993). In adulthood, the perioral reflex shows a highly localized spatial organization with responses highly dependent on the site of stimulation (Smith et al., 1987; Barlow & Bradford, 1996).

This review clearly leads to the conclusion that the motoneuron pools controlling the muscles involved in articulation can be powerfully affected by excitatory and inhibitory short-latency synaptic inputs arising from afferent feedback. Furthermore, rather than reflecting a set of primitive reflex circuits whose potency decreases over the childhood years, many of these brainstem reflex circuits have been shown to increase dramatically in gain in the school-age years. What role do these reflex pathways play in the control and coordination of speech movements in developing and mature oral motor systems? Unless a particular reflex pathway is suppressed during an ongoing movement,

synaptic inputs arising from the circuit would be part of the synaptic drive affecting motoneuron pool excitability during that behavior. It might be useful to think of the synaptic drive to motoneuron pools during speech as arising from an “orchestra” of neural pathways, and the final “symphony” produced depends upon the mix of sources selected (E. Luschei, personal communication). Sherrington (1906) called the motoneuron pool “the final common pathway,” because it is the site of integration of all the synaptic inputs from the various sources, and ultimately determines the activity of muscles. Returning to the question posed above about the nature of these reflex effects during speech, we must conclude that the answer is not known. One study in adults suggested that perioral reflex pathways can be activated by light mechanical stimulation of the perioral skin during speaking, and thus this pathway could contribute to the excitability of orbicularis oris (Smith, Moore, McFarland, & Weber, 1985); while another study suggested that the perioral reflex pathway is suppressed prior to the onset of speech (McClellan & Clay, 1994). The gain of the jaw-stretch reflex has not been studied prior to or during speech, however it seems likely that the high-velocity opening movements involved in speaking would produce intense activation of muscle spindle afferents, which in turn would excite jaw-closing muscles. This reflex excitation of the closing muscles during the opening phase of movement would be functionally appropriate, because jaw-opening and closing muscles show highly co-activated patterns of activity during speech (Moore et al., 1988).

In our study of cutaneous reflexes of the jaw-closing system in 4- to 6-year-olds, we included a small group of children with speech delays (Wood & Smith, 1992). Interestingly this group had smaller, less mature reflexes compared to their typically developing peers. Further work is needed to determine the significance of reflex pathways arising in low-threshold mechanoreceptors that are activated during speech, their developmental course, and their potential contributions as signs of atypical oral motor and/or speech development. Finally, while I have chosen to emphasize the nature of brainstem reflex circuits, because they are often neglected in the speech motor control literature, there is also very little information generally about how children use somatosensory and/or auditory feedback centrally to shape the neural commands for speech arising from cortical networks.

2.2.4 Anatomical restructuring of the vocal tract during development Finally, no review of peripheral components of speech motor control and its development would be complete without mentioning the structural changes the vocal tract undergoes from infancy through childhood. These changes are so dramatic that the term “anatomic restructuring” has been used to describe these physical changes (Vorperian et al., 2005). While the nature and significance of these physical changes has been generally described for many years (e.g., Bosma, 1975; Kent, 1981), more recent studies using MRI have provided detailed, quantitative descriptions of the anatomic changes in the bony and soft tissue structures of the vocal tract from infancy through adulthood. Vorperian et al. (2005) used MRI to measure lip thickness, hard- and soft-palate length, mandibular depth and length, and overall vocal tract length. They analyzed scans from 63 infants and children, from birth to 81 months, and from 12 adults. The results revealed no sexual dimorphism in the infants and children and an extremely accelerated growth rate between birth and 18 months. The various soft and bony tissues that they measured showed

distinctive growth patterns, with increasing vocal tract length predominantly due to growth of oral/anterior structures during the first 18 months, while predominantly driven by growth of pharyngeal/posterior structures in later development. This anatomic restructuring with development means that the peripheral structures to be controlled via articulatory muscle activations are changing over time, and the neural circuits providing the input to the cranial motorneuron pools must be slowly changing and adapting as these anatomic changes occur. Clearly this source of variation must be considered when interpreting results of physiologic studies of developing speech motor control processes (Vorperian et al., 2005).

]ha[3 Development of Speech Motor Processes

]hb[3.1 The emergence of early vocalizations and their relationship to preexisting behaviors

The newborn possesses a behavioral repertoire that includes breathing, sucking, crying, and a variety of spontaneous movements. The basic patterns for repetitive movements, such as those in sucking, chewing, and breathing, arise in brainstem CPGs. In a special volume of the *Journal of Communication Disorders*, Lund and Kolta (2006) and Barlow and Estep (2006) provided extremely helpful tutorials on CPGs, prepared especially for readers interested in the relationship between the various CPGs and speech production. Lund and Kolta (2006, p. 382) state, “The systems that control innate repetitive movements in humans and other animals have two basic characteristics: they contain assemblies of neurons that are capable of generating a fundamental rhythm, and they include feedback systems that adapt the rhythm to the state of the internal and external environments.” This simple statement clarifies what was once a highly debated issue, whether there are behaviors that are solely under central control versus those that require sensory information in order to switch from one phase of movement to another (Gallistel, 1980). For many years it has been clear that circuits located in the brain stem can generate basic rhythmic movements in the absence of feedback. For example, Dellow and Lund (1971) demonstrated in the rabbit that the fundamental pattern of mastication, including coordinated movement of the jaw, lips, and tongue, can be generated by a brainstem CPG after all sensory inputs have been removed. However in a variety of studies of many different species and behaviors, it also has become clear that CPG-generated behaviors would not be adaptive unless their output were highly sensitive to the changing demands of the task. Thus, even relatively “simple” behaviors such as breathing, chewing, and sucking in the infant arise from the ongoing, dynamic interaction of phylogenetically old brainstem circuits with sensory information.

Recently, the critical importance of sensory information in modulating the activity of CPG-driven motor output has been shown in both term and premature infants (Finan & Barlow, 1998; Barlow et al., 2004;). These investigators developed a servo-controlled system to produce pressure changes in the nipple of a pacifier or “motorized nipple” (also called an “actifier,” Barlow & Estep, 2006). The pattern of pressure changes was programmed to be similar to those characteristic of normal infant suck-cycle timing and amplitude. When the servo system was turned on, infants’ natural sucking behaviors became entrained to the rhythm of the actifier. It seems reasonable to assume that in the newborn, this innocuous intraoral mechanical stimulation produces activity in a wide population of mechanoreceptors located in the lips, tongue, and jaw. This highly salient,

patterned sensory inflow to the CNS modulates the activity of the brainstem CPG generating the suck behavior, resulting in the entrainment phenomenon. A basic principle of neural systems is that “cells that fire together wire together” (this catchy phrase is often used by modern neuroscientists to capture Hebb’s (1949) proposal of a fundamental neural mechanism underlying associative learning). We can postulate that this patterned, repetitive bursting behavior of the oral sensorimotor systems serves to develop and sculpt neural connections. The discovery by Barlow and his colleagues that infants respond and entrain their sucking to intraoral mechanical input has had important clinical implications. They have studied premature infants who have had long periods of oral sensory deprivation because of respiratory problems (Barlow & Estep, 2006). Within a relatively short time after these premature infants have experienced controlled oral stimulation via the actifier, an increase in natural sucking behavior occurs, which facilitates their ability to feed normally, a result which obviously has critical implications for their survival .

Many of the earliest behaviors of the human infant, then, reflect the presence at birth of brainstem CPGs. As infants develop, so do their abilities to chew, and the transition to more solid food occurs during the 5–8 month period (Sheppard & Mysak, 1984). The development of chewing has been studied both cross-sectionally (Gisel, 1991; Kiliaridis et al., 1991) and longitudinally (Green et al., 1997). The basic pattern of chewing is already well established in infants at 12 months (Green et al., 1997), but the patterns of activation of synergistic and antagonistic muscle pairs become more consistent with development. One of the most remarkable findings from the developmental chewing literature is that the duration of the masticatory cycle remains virtually unchanged (mean cycle duration approximately 0.7 seconds) from the age of 12 months into adulthood (Kiliaridis et al., 1991; Green et al., 1997). The details of the chewing cycle in terms of movements and muscle activity depend upon the nature of the food being chewed, evidence that the CPG output is modified to provide a pattern of activity appropriate for the food to be ingested.

Of course the period of transition into chewing soft and more solid foods at 5–8 months is also a time of great change in infant vocal development (Oller, 1980; Stark, 1980). It is during this time that infants show a dramatic drop in nonspeech-like vocalizations, such as cries and vegetative sounds, and an increase in speech-like vocalizations, including babbling (Nathani et al., 2006). One controversial issue concerning the motor processes underlying the emergence of babbling and more advanced forms of vocalizations in infants at this stage is the role played by preexisting neural circuitry for ingestive behaviors. MacNeilage and Davis (MacNeilage & Davis, 1990, 2000; MacNeilage, 1998), in their frame/content theory of the evolution of speech production, proposed that the fundamental organizational property of speech is the repetitive oral open–close cycle. They propose that the total open–close cycle represents a syllable, while the open and close phases represent segments, vowels and consonants respectively. Furthermore, MacNeilage (1998) argued that these communication-related frames evolved from phylogenetically old ingestive behaviors involving mandibular oscillation, such as sucking and mastication. Resisting the argument that chewing is too simple to serve as a basis for the emergence of speech production, MacNeilage noted the complexities of the masticatory cycle and its highly adaptive nature related to ongoing task demands. Thus, he proposed that the masticatory CPG is the perfect candidate for

“tinkering with” by evolutionary processes to produce the articulatory open–close cycles of human speech.

This view also has been supported by a number of neuroscientists who have studied centrally patterned behaviors, including mastication (Lund & Kolta, 2006) and locomotion (Grillner, 1982). Lund and Kolta note that the brainstem CPG for mastication receives input from cortical areas, especially from the inferior lateral region of the motor cortex. The CPG itself includes a core group of neurons with intrinsic bursting properties, and reorganization of subpopulations of these neurons, which can be produced by changes in sensory feedback and/or central drive, results in highly specific, adaptive movement patterns. Furthermore the subpopulations of neurons that comprise the CPG supply controlling inputs not only to muscles of the jaw, but also to muscles of the tongue and face; the CPG also biases reflex circuits to optimize the masticatory properties to ongoing demands. In sum, all of these features would seem to make this neural circuitry a perfect candidate for biasing by cortical networks to modulate its output to produce the rhythmic oral movements needed for dynamic control of the vocal tract during speech.

Seeking evidence in support of the frame/content theory, MacNeilage et al. (2000) compared the serial organization of infant babbling and early speech across 10 languages. Their analysis revealed four movement-related design features reflecting a “deep evolutionary heritage” operating on the pattern of infant vocalizations. These included the cyclical consonant–vowel alternation underlying the syllable (the “frame”), three within-cycle consonant–vowel co-occurrence preferences that were presumed to reflect biomechanical coupling properties of the articulators, and two other features related to consonant repetition and ease of production. In summary, MacNeilage and his colleagues have been proponents of a model of the transition from pre-speech to speech vocalizations in infants in which strong evolutionary influences provide biological constraints on the fundamental units and structure of human languages. The underlying neural substrate is hypothesized to make use of brainstem pattern generation circuitry which can be flexibly biased to produce a range of adaptive behaviors, possibly including speech (see dotted lines in Figure 7.1).

On the other hand, as shown in Figure 7.1, an alternative hypothesis is that the activity of the motorneuron pools involved in speech is driven directly from motor cortex, via pathways that bypass the brainstem CPGs for respiration and mastication. This point of view was argued strongly by von Euler (1982), a neurophysiologist who made major contributions to delineating properties of the brainstem respiratory pattern generating circuitry. He argued strongly for complete separation of the control pathways for metabolic breathing and those involved in “voluntary” breathing, including speech breathing.

The view that the neural pathways for speech motor control do not arise from nor engage evolutionarily well-established brainstem networks for ingestive behaviors is also argued by Moore and colleagues (Moore & Ruark, 1996; Green et al., 1997; Ruark & Moore, 1997; Moore, 2004). This group was among the first to tackle the very difficult experimental task of obtaining physiological data, including both kinematic and electromyographic recordings, from infants and toddlers during early vocalizations and nonspeech oral motor behaviors. Their publications provide many new insights concerning oral motor development.

Green and Wilson (2006) studied spontaneously produced orofacial movements of infants. Using a video-based system, they captured the motion of passive reflective markers attached to infants' faces to track lip and jaw movements. Their study is particularly impressive, because of the relatively large number ($n = 29$) of infants aged 1, 5, 7, 9, and 12 months who were studied cross-sectionally. Only spontaneous facial movements *without any accompanying vocalization* were analyzed. Kinematic parameters computed included movement space, average movement speed, movement duration, and spatial and temporal coupling between pairs of markers. All of the infants produced spontaneous facial movements during the recording sessions with the 5-month-olds producing, on average, the most, approximately 60. Thus these investigators had a wide repertoire of spontaneous orofacial movements to examine for most of the infants they recorded. During the first year of life, these spontaneous orofacial movements showed some systematic changes. The speed of movements increased, while the duration of the spontaneous movement epochs decreased. Based on cross-correlational analysis, coupling of movements across pairs of facial markers increased. Perhaps the most interesting finding from the study, however, was that there was no evidence for stereotypic, repetitive, spontaneous oral movements, such as a rhythmic opening and closing of the jaw. The spatial and temporal characteristics of the spontaneous movements were not patterned or rhythmic but instead were highly variable. The movement spaces also were highly variable across epochs of spontaneous behaviors. This is in contrast to, for example, the highly stereotypic, rhythmic spontaneous leg movements observed in infants labeled "stereotypies" by Thelen (1979; Thelen & Smith, 1994).

This result might be interpreted as very compelling evidence upon which to reject the frame/content theory of early infant vocal development. However, as emphasized with italics above, it is important to note that Green and Wilson (2006) only analyzed spontaneous oral movements not accompanied by vocalization. The older infants in their study would have been babbling, and presumably would have produced vocalized orofacial behaviors during the recording session. These behaviors were not analyzed in this report, but these oral movement sequences accompanied by vocalization most likely would show repetitive, rhythmic cycles of opening and closing movement. One of the most well-documented and salient features of babbling is its rhythmic syllabic structure (Kent et al., 1991). This leads to the interesting hypothesis that repetitive oral open-close movement sequences emerge only when orofacial, laryngeal, and respiratory systems are coactivated in a coordinated manner. Thus the non-vocalized, spontaneous oral motor behaviors described by Green and Wilson might be a distinctive class of spontaneous behaviors which bears little relationship to pre-speech vocalizations.

Moore and Ruark (1996) recorded jaw-opening and closing muscle activity during spontaneous episodes of chewing, sucking, babbling, and speech in seven 15-month-olds. After rectifying and smoothing the EMGs to create muscle activity envelopes for each task, they computed cross-correlations among pairs of antagonistic and synergistic jaw muscles. Surprisingly, they found that the coupling between muscle pairs was greater for later appearing behaviors such as variegated babbling and early word production. Coupling of muscle pairs for chewing and sucking was less strong. Furthermore, a qualitatively different pattern of jaw-muscle coordination was characteristic of chewing, reciprocal activation of opening and closing muscles, compared to speech, which

involves a high degree of co-activation of antagonistic jaw-muscle pairs. Thus, these authors found task-specific organization of jaw-muscle coordination in 2-year-olds, which resembled patterns observed in adults in an earlier study (Moore et al., 1988). Using a similar analysis applied to lip muscles in 2-year-olds, Ruark and Moore (1997) found that speech and nonspeech coordinative patterns of activation of lip muscles also were highly distinctive. They stated, “This level of coordinative specialization is consistent with ... the accumulation of findings suggesting that children develop speech-specific coordinative mechanisms very early in life. Although conclusive results are yet to be obtained, the present findings support the suggestion that speech emerges separately from extant oral motor behaviors, and failed to support the existence of redundancy in control mechanisms across tasks. (p. 1384).”

As Ruark and Moore stated above, the evidence is not conclusive regarding the role of brainstem CPGs in the emergence of speech. Differences in activation patterns of muscles across tasks could arise from distinctive biasing of the neural assemblies that produce rhythmical jaw-, facial-, and tongue-muscle activity during mastication. In fact, as already noted above, a cardinal feature of CPGs is their adaptability in the face of different task demands. Obviously, we cannot record from brainstem neurons to determine whether the neural networks of the CPG active during mastication are also active during speaking. However, with improved imaging techniques which are providing more and more spatial resolution, investigators may be able in the future to provide functional imaging data which can address this question.

Another approach to the issue of whether common control processes are engaged across distinctive motor behaviors, which has not been applied in pediatric populations, is to analyze the frequency content of EMGs of muscle pairs. In the respiratory system of humans (and rabbits, cats, and dogs) during metabolic breathing, there is a signature frequency of activity in brainstem neurons involved in pattern generation. This activity has been referred to as high-frequency oscillations or HFOs and occurs in the 60–110 Hz band. Activity of respiratory nerves recorded in experimental animals is highly coherent (coherence values are computed as the cross-correlation between two signals in the frequency domain) in this frequency band, and pairs of respiratory muscles in humans also show this highly coherent pattern during inspiration for metabolic breathing (Ackerson & Bruce, 1983). Smith and Denny (1990) recorded right- and left-diaphragm activity during speaking and metabolic breathing. They also recorded right- and left-masseter activity during speaking and chewing. They found that the signature band of coherent diaphragmatic muscle activity was present in metabolic breathing as expected, but that coherence in this band was greatly reduced during speaking. They interpreted this result as an indication that the respiratory CPG still contributed some synaptic drive to the respiratory motoneuron pools during speech, but that this drive was greatly reduced compared to its amplitude during metabolic breathing. They also observed a highly coherent frequency band in right- and left-masseter activity in the 40–60 Hz range during chewing. This coherent frequency band was also greatly suppressed during muscle activation for speaking. Again, results for both respiration and mastication indicated that while the CPGs for respiration and mastication are not completely bypassed, their activity is greatly reduced. Surface EMG electrodes were used in these experiments and thus they might be applicable in young children.

Finally, the unresolved issue of whether the neural control mechanisms for speech take advantage of earlier existing ingestive and/or respiratory CPG circuitry is an important one for the field of speech/language pathology. There is an intense debate about the use of nonspeech oral motor tasks as part of therapy for speech disorders in both children and adults (Luschei, 1991; Weismer & Liss, 1991; Forrest, 2002; Weismer, 2006). If the neural circuitry for speech is highly specialized and completely independent of neural control networks controlling nonspeech behaviors, some scientists and clinicians conclude that nonspeech-oriented therapies provide no rehabilitative benefit for speech, which is the target of the therapy. On the other hand, if the neural pathways involved in speech overlap those involved in nonspeech behaviors, a stronger case is made for the use of nonspeech oral motor approaches to facilitate reaching later speech and/or language therapeutic goals. In any case, all neural systems affecting the timing and amplitude of muscle activity must operate through “the final common path,” to the motorneurons and out the muscles. Therefore, any task used to activate a muscle, whether it is a speech or nonspeech task, contributes to the health of the motorneurons and the muscle cells.

]hb[3.2 Speech motor development in children

Around 18 months of age, toddlers have a vocabulary of about 50 words, and they typically begin to produce two-word utterances at about this age (Brown, 1973). By 5 years, children are producing thousands of words in multiword utterances. The astonishingly rapid growth in the capacity of the speech production system to produce a variety of words, phrases, and sentences in the preschool years arises from a vast array of developing regional and inter-regional connections in the brain. The acquisition of new words continues well into adolescence, and studies of language perception using event-related potentials (ERPs) have demonstrated that some aspects of the neural networks underlying language processing are not adultlike until late adolescence (Holcomb et al., 1992; Neville et al., 1992). Before studies of the control of articulatory movements in late childhood and adolescence were available, it was often assumed that speech motor control processes were fully mature by age 10–12 years (e.g., Tingley & Allen, 1975). Recent studies, however, in which kinematic parameters of the articulatory system were measured in older children and adolescents, have demonstrated that the developmental time course for achieving mature, adult levels of speech motor control processes extends into late adolescence (Walsh & Smith, 2002; Cheng et al., 2007). Certainly the rate of change is much slower in the later years of the growth curve compared to the dramatically rapid rates of change in the preschool years (Smith & Zelaznik, 2004); yet there are still significant differences in some motor aspects of the speech of 16-year-olds compared to that of young adults (Walsh & Smith, 2002). Here we consider the protracted developmental course to adult speech motor control processes and some of the underlying factors that contribute to it.

]hc[3.2.1 **Development of basic parameters of articulatory movement** Amplitude, duration, and velocity are three fundamental parameters that can be measured for any movement trajectory. These parameters have been assessed in studies of speech production in children and adults. Intuitively, one would expect that smaller speakers, that is, children, would produce smaller speech movements compared to adults. Also,

based on earlier acoustic and perceptual evaluations of children's speech, it is well known that children are slower speakers compared to adults. Therefore we also would predict that children would be moving at relatively low velocities, such that their speech movements are longer in duration.

Children do, in fact, produce articulatory movements for speech with lower velocities compared to adults (B. Smith and Gartenberg, 1984; B. Smith and McLean-Muse, 1986; A. Smith & Goffman, 1998), but a few early studies of small numbers of young children aged 4–7 years, who obviously have smaller orofacial structures compared to adults, suggested that young children produce oral movements for speech of equal amplitude to those of adults (B. Smith & Gartenberg, 1984; Sharkey & Folkins, 1985). Riely and Smith (2003) explored this issue directly by asking if a size principle operates in speech, e.g., that smaller speakers produce smaller articulatory movements. A size principle has been documented in locomotion, such that stride length is directly related to limb length (e.g., Beck et al., 1981), suggesting that biomechanical factors play a major role in determining the kinematic parameters of gait. Such a relationship had been reported for speech by Kuehn and Moll (1976); they found a positive relationship between oral structure size and the amplitude and velocity of speech movements for a small number of adult speakers.

In a study involving a relatively large number of participants, we (Riely & Smith, 2003) collected lip and jaw kinematic data from thirty 5-year-olds and thirty young adults (15 males and females in each of the groups). Following the guidelines of Farkas (1994), we also made anthropometric measures of a number of orofacial structures. A measure of the range of amplitude and velocity of oral movements was calculated from the entire movement trajectory for two short sentences, and standard peak measures of amplitude and velocity were made from selected single movements within the movement sequences for the sentences. The results of the study clearly indicated that there is not a size principle operating in speech production. There were the expected significant differences between 5-year-olds and young adults in the size of oral structures. While there was a trend for adult speech movement amplitudes to be larger than those of the 5-year-olds, this difference was not significant for the amplitude range measure, nor for the amplitude measures from single movements. There were no differences in movement amplitude for men and women or girls and boys. Furthermore, in within-group analyses, we did not find significant correlations in each age group between the speech kinematic variables and oral structure size measures. The velocity of the 5-year-olds' speech movements was much lower than that of adults, about 50–70 percent of adult values. Thus, we concluded that 5-year-olds' speech movements reflect a large-amplitude, low-velocity style, which would be consistent with a motor control system that requires more time to plan movement sequences and one that has greater reliance on sensory feedback. We can also infer that biomechanical properties of the articulatory system do not account for fundamental differences in speech movement characteristics of young children and adults.

How long during development do children continue to use this low-velocity, relatively high-amplitude speech movement style? Earlier studies of small numbers of school-age children suggested that speech movements continue to be slow and relatively large during these years (Smith & Goffman, 1998), although the data are mixed, with B. Smith and McLean-Muse (1986) reporting that young children and adults had equal

amplitudes and velocities of lip and jaw movements for speech. We (Walsh & Smith, 2002) recorded upper-lip, lower-lip, and jaw motion in four subject groups ($n = 30/\text{group}$, 15 females and 15 males in each group) of 12-, 14-, 16-year-olds, and young adults (aged 21–22).¹ Participants produced a six-syllable sentence in a repetition task. We observed significant trends for increasing velocity and displacement of articulator movement beyond 16 years (see Figure 7.2), and there was also a significant decrease in total utterance duration, as well a decrease in the durations of syllables within the sentence with increasing age.]Figure 7.2 near here[

To facilitate comparison of the developmental trajectories for the various measures we made, we plotted normalized growth curves for amplitude, velocity, and duration measures. In these plots, adult values for each measure were arbitrarily assigned a value of 100 percent, and younger subjects' means were plotted as a percentage of the adult value. In Figure 7.2 (adapted from Walsh & A. Smith, 2002) the relative growth curves are plotted for duration, velocity, and displacement of lower-lip (plus jaw) movements for groups of 30 participants aged 12 to young adult. These measures were taken from two syllables (“Bob” and “pup”) produced within a sentence context. The measures were averaged across the opening and closing movements for each of the two syllables. From this plot, it is clear that adolescents have higher speech rates compared to young children, because by age 12 years, durational measures were already 90 percent of the adult value. In contrast, at age 12, velocity of articulatory movement was only about 60 percent of the young adults' value, and movement amplitude was approximately 70 percent of the young adults' value. In real terms, for example, 12-year-olds had a mean velocity of approximately 75 mm/s for the movements we measured, while for young adults, the mean velocity was approximately 120 mm/s. Average amplitude of movement increased approximately 2 mm over the period from 12 years to young adult. These results show that at different points in the course of development, varying trade-offs between speech movement amplitude and velocity occur, and we have hypothesized that these are driven by the goal of increasing speech rate (Walsh & Smith, 2002; Smith & Zelaznik, 2004).

A number of authors have discussed changes in speech motor control processes after age 10–12 years as “refinements” of basic patterns that already have been well established (Green et al., 2002; Cheng et al., 2007). Our study, however, showing as much as 30–40 percent increases in velocity and amplitude of articulatory movements between the ages of 12 and 21 years, suggests that rather dramatic changes are occurring during this late developmental period. Furthermore, the use of the term “refinement” suggests that basic patterns of behavior are the same, and that the developmental curve is a slowly changing trajectory always moving toward the adult state. In contrast to this view, our results suggest that movement amplitude for speech follows a U-shaped developmental trajectory. Speech movement amplitude is relatively large in very young children, decreases in adolescence, and then increases again toward the young adult values. As noted above, one possible factor driving this pattern of amplitude change may be that achieving adult speech rate is a high priority of the speech motor control system, but adolescents apparently cannot produce a higher rate by simply increasing the velocity of articulatory movement as the 21–22-year-olds do. Sixteen-year-olds are still producing significantly lower velocity movements compared to young adults, thus in order to achieve a higher speech rate, they appear to be reducing articulatory displacements

compared to the displacements they produced as younger children. Presumably teenagers age 12–16 years are capable of producing velocities of oral movements in the adult range in nonspeech tasks (but this should be tested empirically), and therefore there is no biomechanical or neuromuscular reason for the reduced velocities of speech in these age groups. This suggests that the lower velocities of speech movements are a result of immature cortical networks involved in language formulation, pre-speech planning and/or execution. Obviously the work to date has employed limited speech samples, and future studies will need to replicate these findings in additional utterances and across additional articulators. It should be noted, however, that these recent studies of large numbers of participants have shown rather convincing developmental trends, which seemed likely to require a change in our thinking about speech motor development during late childhood and adolescence.

Our investigation of basic lip and jaw speech movement parameters and that of Cheng et al. (2007) of relative tongue and jaw motion in adolescence also reveal another interesting result: no sex differences have been found. We had predicted, based on anatomical growth curves showing that adolescent girls reach maturity in orofacial structural growth before boys (Farkas, 1994), that girls would show adultlike movement parameters and variability on these articulatory kinematic measures before boys. This was not the case. Cheng et al. (2007) and we (Walsh & Smith, 2002) found no differences between the adolescent girls and boys, nor were there any differences between the young adult men and women. These findings speak to the speculation of B. Smith and McLean-Muse (1986) that the development of adult speech output is delayed by physical growth and by the continued development of the neural systems involved in the formulation and planning of speech. The lack of differences in articulatory kinematic parameters and variability between adolescent boys and girls again suggests that the prolonged developmental course to mature adult speech production systems is primarily driven by the prolonged development of the neural networks involved in cognitive and linguistic processing in the brain (Walsh & Smith, 2002; Smith & Zelaznik, 2004), rather than by peripheral growth factors.

Also relevant to this point is that the only time clear sex differences have been documented for articulatory kinematics is in 4- and 5-year-old children (Smith & Zelaznik, 2004). We found that boys lagged girls in the consistency of their inter-articulator coordination in the production of short sentences. At this age there is no sexual dimorphism in craniofacial growth patterns (Vorperian et al., 2005) which again points to a role for central rather than to peripheral factors driving this difference. These findings are, of course, in contrast to those for speech acoustic, laryngeal, and respiratory measures, because many sex-related differences, which are clearly related to anatomical size and growth factors have been documented in these output measures (e.g., Hoit et al. 1990; Huber et al., 1999).

3.2.2 Nonuniform maturational profiles across articulatory structures? Another basic question about the development of articulatory movement control for speech is whether control of the various structures involved in speech follows a uniform developmental course. In an earlier section (2) of this chapter above, the pronounced differences in anatomical, biomechanical, and neural innervation of the various articulators were noted. Given the remarkable differences in these characteristics for the

jaw, tongue, lips, and velum, it seems reasonable to hypothesize that the development of the control of each of the structures might be nonuniform. In other words, control of one articulator might be more adultlike earlier than control of another. From the frame/content theory (MacNeilage & Davis, 1990, 2000), the prediction would be made that the mandible would show more mature movement patterns earlier than other structures such as the lips and tongue.

Green et al. (2002) addressed the question of sequential development of articulatory control by recording upper-lip, lower-lip, and jaw motion in 1- and 2-year-olds, 6-year-olds, and adults. All groups of speakers produced simple two-syllable utterances such as “mama” and “baba.” Green et al. employed an innovative within- and between-group movement pattern analysis which involved time and amplitude normalization of the displacement trajectories for each articulator. The normalized trajectories were then averaged to produce templates, which were compared by computing cross-correlations between pairs of templates on a within-subject basis, as well as within age groups, and finally across the three age groups. These analyses and measures of the variability of movement trajectories within groups clearly demonstrated that in the infants and children, control of the jaw was much more adultlike compared to control of the lips. Thus these results support the frame/content proposal that jaw open–close cycles provide a basis for the subsequent development of the precise control of all the articulators needed to produce the full repertoire of sounds in the language (MacNeilage & Davis, 1990, 2000).

There has also been some evidence from studies of preschool and school-age children that jaw movements for speech are less variable compared to upper lip and lower lip movements (Sharkey & Folkins, 1985; B. Smith, 1995). We (Walsh & Smith, 2002) examined the issue of nonuniform maturation of articulatory control in adolescence. Using a measure of the composite spatial and temporal variability of sets of normalized movement trajectories of upper lip, lower lip, and jaw for a short sentence, we found that movement variability was lower for young adults compared to all of the younger age groups, and that jaw trajectory variability was lower than that of upper lip or lower lip. However, we did not find evidence of a nonuniform rate of maturation across the three articulators during adolescence. The growth curves toward adult performance were parallel for the three structures during the period from 12–22 years, but it should be noted the end points for the three articulators were not equal. Composite spatiotemporal variability was lowest for the jaw and highest for the upper lip.

When considering the issue of nonuniform maturational profiles for specific articulators and the possibility that the jaw plays a key role early in pre-speech vocalizations, it is essential to keep in mind that the lips have higher degrees of freedom of movement compared to the jaw. Jaw movements for speech are primarily in the vertical dimension and do not occupy a large percentage of the potential working space of the mandible (Ostry et al., 1997). Lip (and tongue) movements and shape goals and the underlying muscle contractions that produce them are extremely complex and multidimensional for speech (Honda et al., 1995; Honda, 1996; Gerard et al., 2003). This may explain why jaw-motion trajectories, from infancy on, display less variability in patterning compared to lip-motion trajectories. In other words, the lower trajectory variability for the jaw may reflect its inherently fewer degrees of freedom and the lower

complexity (compared to, for example, the shape requirements of the tongue and lips) of the demands placed upon it for speech.

Another relevant point is that in the face area of the primary motor cortex, which presumably plays a major role in generating the motor commands to control articulatory muscle activity during speech, there is a mosaic of repeated representations of muscles of the lips, jaw, and tongue (Huang et al., 1988). Huang and colleagues reported that on a single electrode penetration, microstimulation typically activates muscles of each of these structures. Given this kind of interleaved representation, which is clearly ideal for the coordinated activities required of the articulators in speech, the idea that the maturation of control of individual articulators follows very distinctive courses seems unlikely to be correct. Perhaps an alternative hypothesis would be that in infants, preexisting neural circuits, such as those involved in sucking and chewing, generate cyclic open–close jaw movements that provide a stable foundation for pre-speech vocalizations. As infants begin to babble, the form of their vocalizations changes to become more speechlike (Kent et al., 1991). It seems reasonable to hypothesize that at this point, cortical networks, possibly associated with syllable-sized units, are being formed. These cortical networks ultimately will be the predominant source of neural control for the speech musculature. This hypothesis is consistent with the data of Moore and Green and their colleagues showing the jaw to be dominant in early vocalizations of 1- and 2-year-olds (Green et al. 2000, 2002). As toddlers begin to produce more speechlike vocal output in babbling and single words, the coordinative patterns of the muscles involved in speech are quite distinctive from those used in sucking or chewing (Moore & Ruark, 1996; Ruark & Moore, 1997). This finding is consistent with the idea that a different sources of control, e.g., cortically originating networks, are beginning to be established.

]hc[3.2.3 Understanding the sources of variability in articulatory movements and coordination

]hd[*Higher variability in younger speakers: an epiphenomenon of their slower speech rates?* From the earliest studies in which direct measurements of children’s articulatory movements were made by Bruce Smith and his colleagues (Smith & Gartenberg, 1984; Smith & McLean-Muse, 1986 and in earlier acoustic studies of children’s and adults’ speech, the issue of how to interpret differences in variability between child and adult speakers has been debated. One suggestion, repeatedly mentioned, is that the higher variability observed in many measures of children’s speech is simply an epiphenomenon (or statistical artifact) arising from children’s slower speech rates (B. Smith et al., 1983; Crystal & House, 1988); thus reflecting a general principle that slower speakers tend to be more variable speakers. This parsimonious explanation for differences in variability between immature and mature speakers should be rejected on the basis of results from many recent studies, which have shown clear dissociations between speech rate and variability measures (B. Smith, 1992; Maner, Smith, and Grayson, 2000; Smith & Zelaznik, 2004).

One example of such a dissociation is plotted in Figure 7.3. The data used to generate these plots are from our large-scale study of children, adolescents, and young adults aged 4–22 years (Smith & Zelaznik, 2004). If differences in speech rate fully accounted for differences in speech variability measures, plots of speech rate as a function of age should parallel plots of variability measures. In the example in Figure 7.3,

a speech rate measure, the mean duration (and SEM) of two short sentences (“Mommy bakes pot pies” and “Buy Bobby a puppy”) for 30 speakers in each age group is plotted (triangles). Also plotted for each age group is a consistency of coordination measure, the lip aperture variability index (circles, mean and SEM for each group computed across the two sentences). This index reflects the consistency in the pattern of upper-lip, lower-lip and jaw coordination for 10 productions of each sentence. The two sentences were produced in a repetition task.]Figure 7.3 near here[

From the plot in Figure 7.3, it can be seen that from age 4 years to young adulthood, the average duration of the two sentences decreases from approximately 1.45 seconds to 0.9 seconds. If speech rate in syllables per second is computed from these measures, this dramatic reduction in sentence duration translates into an increase in rate from 3.8 syllables/second in 4-year-olds to 6.1 syllables/second in young adults. Interestingly, there is a plateau in the speech rate function, with no increase in rate (no decrease in average sentence duration) occurring from age 7–12 years. This plateau in speech rate is very surprising, given the dramatic changes in a variety of cognitive abilities, including motor abilities, that occur over this developmental period. Returning to the graph of Figure 7.3, it is clear that oral motor coordination for speech, as reflected by the lip aperture variability index, becomes much more adultlike in the period from 7–12 years. This is a compelling example of a dissociation between variability and speech rate. There are periods of time when the two plots are parallel, for example in the 4- to 5-year-old data, there are parallel increases in speech rate and decreases in variability. However, the nonparallel segments of the growth curves clearly demonstrate that changes in variability cannot be explained as an epiphenomenon or statistical artifact of overall speech rate. As a caveat, we note that these data are derived from a repetition task for two short sentences, and that as such, they may not reflect naturally produced, spontaneous speech. This, however, is a necessary limitation of any study in which physiological or acoustic parameters are measured for identical utterances produced by different speakers. In addition, we note that this variability measure is based on the average of coordination indices computed for the entire movement sequences for 10 repetitions of each of two sentences, which would seem to be an improvement over earlier studies, in which kinematic measures typically were made for single movements, and duration or rate measures were often reported for single words, and in some cases single speech segments. In fact, we have made extensive use of the method of time- and amplitude-normalizing sets of single articulator or inter-articulator trajectories produced for a single utterance over multiple repetitions (method described in Smith, et al., 1995 and 2000). An index of the composite spatial and temporal variability computed for these sets of trajectories has proved to be a useful indicator of within-subject and between-group differences in speech motor performance.

In the above example, the question was whether differences in speech movement variability between groups of speakers of varying ages could be accounted for by differences between groups in average speech rates. One can also ask whether within a given age group, the slower speakers tend to be more variable in output. To address this question, correlations between the average duration and the average lip aperture variability index for the two sentences were computed for each of the six age groups whose data were plotted in Figure 7.3. Scatter plots of lip aperture variability and duration are shown for two age groups, the 12-year-olds and 4-year-olds, in Figure 7.4.

As these plots suggest, there was not a significant correlation within groups between mean sentence duration and mean lip aperture variability. Correlations between speech rate (sentence duration) ranged from a low of 0.02 for the 4-year-olds to the highest value of -0.23 for the 14-year-old group. The correlation between the two measures was not significant for any of the age groups.]Figure 7.4 near here[

]hd[*Decreasing movement variability with age: an index of neuromotor maturation?*

Having, hopefully, helped to put to rest the assertion that developmental changes in measures of speech variability simply reflect changes in speech rate, I return to the main issue at hand, which is: many investigators, including the present author, have interpreted the greater variability often observed in children's data to be a sign of the operation of immature motor control systems. Thus, the general phenomenon of decreasing variability observed with age, described in many studies in the sections above, commonly has been interpreted as a sign of the maturation of the speech motor control systems. Stathopoulos (1995) strongly objected to this general interpretation of decreasing variability with increasing age; she presented acoustic, aerodynamic, and respiratory kinematic data from 72 participants ranging in age from 4 years to adults. She reported a very large number of physiological and acoustic measures and found that significant age differences were present for only a subset of the measures. Furthermore, within that subset, statistical analysis revealed that the 4-year-olds primarily accounted for the age effect. Stathopoulos argued that, given the generally accepted view that variability is an index of neuromotor maturation, she would have to conclude that 6-year-olds possess adultlike speech production systems. She therefore rejected the idea that declining variability is always or even usually a hallmark of maturation toward the adult state and instead suggested that when studying variability as an index of maturation, different subcomponents of the system may show very different maturational profiles. It should be noted, however, that the experimental data on which Stathopoulos based her argument were derived solely from measurements made on repeated trains of a single syllable ("pa, pa, pa"). Therefore one might argue that she purposely chose a "speech" production task that would be least likely to reveal age-related differences.

In any case, Stathopoulos made a useful theoretical argument, and as pointed out above, significant differences in developmental trajectories have been reported for the different subsystems involved in speech and for different measures within a single subsystem. When studying variability in speech output as an index of neuromotor maturation, observed between or within group differences in variability must be placed within the appropriate context. Regardless of these points, declining variability and increasing accuracy classically have been viewed as hallmarks of maturing motor systems and of successful motor learning in the limb motor control literature (Schmidt, 1988). The influential work on the application of dynamical systems theory to motor development by Esther Thelen and her colleagues (Thelen & Smith, 1994) has also emphasized the necessity of contextualizing interpretations of higher or lower levels of variability. For example, higher variability often has been viewed as an undesirable feature of motor control systems, but as Thelen and Smith pointed out, over the course of development, variability may provide a flexible substrate from which new patterns of behavior may emerge. Furthermore, variability is not a unidimensional construct, and as we will discuss in more detail below, many sources of variability contribute to the

observed output variations. Recent models and experimental approaches to motor development in the limb literature have emphasized the need to uncover the relative importance of multiple contributing sources to movement output variability over the course of development (Davids et al., 2006).

This is the point of view that we have taken in interpreting our kinematic studies of the development of articulatory control and coordination (Walsh & Smith, 2002; Smith & Zelaznik, 2004). It would not be desirable for children to produce speech movements with the almost machinelike consistency of adults. Children need flexibly organized motor control systems, so that they can acquire new patterns, e.g., new words and/or new languages. In addition, while we have argued that peripheral biomechanics are not the only factors driving the prolonged maturation of speech motor control processes in adolescence, certainly children's speech motor control systems must make adaptations as craniofacial growth occurs (Vorperian et al., 2005).

To interpret the higher variability we have observed in children and adolescents, we (Smith & Zelaznik, 2004) have also relied upon Bernstein's definition of the development of motor coordination as "the process of mastering redundant degrees of freedom of the moving organ, in other words its conversion to a controllable system" (1967, p. 127). He proposed that the degrees of freedom for movement are reduced through the soft assembly of muscle synergies, also referred to as coordinative and/or functional synergies. Functional synergies (the term we have used) are fundamental units of the control of movement, and they consist of collectives of muscles or motorneurons that in turn control muscle contraction (Bernstein, 1967; Gelfand et al., 1971). In speech, given the complexity of the movements to be produced and the necessity of recruiting specific subpopulations of the motorneurons within a motorneuron pool (Honda et al., 1995), the idea of motorneurons (or motor units – a motor unit is a single motorneuron plus the muscle fibers that it innervates) rather than muscles as the basic elements comprising functional synergies is appealing. The repeated coactivation of collectives of motor units results in the formation of synergies, which are organized to achieve functional goals. For example in babbling, motor units of upper-lip, lower-lip, and jaw muscles would be repeatedly coactivated, for example, for the syllable /ba/. With repeated activation, the synergistic group of motor units would be linked to the goal of producing the acoustic output for /ba/. As children mature, these functional synergies become more stable, and there is less variability in the pattern of recruitment of motor units to achieve the behavioral goal.

In the developmental limb motor control literature, many investigators (e.g., Crossman & Szafran, 1956; Schmidt et al., 1979; Van Galen et al., 1993) have suggested that one source of variability in the recruitment of motorneurons is a global factor, "neuromotor noise." Neuromotor noise is postulated to arise from a variety of sources, including a background of unpatterned synaptic inputs to motorneuron pools and from the motor commands generated to achieve movement goals. Both sources of neuromotor noise, the background, unpatterned synaptic inputs and the variability of motor commands generated by the CNS, are hypothesized to be greater in young children. With maturation, neuromotor noise is hypothesized to decrease, which contributes to the increased consistency of motor output seen in adults (Smits-Engelsman & Van Galen 1997; Yan et al., 2000).

The nature and sources of variability in motor output have been extensively discussed in the limb motor control literature (Davids et al., 2006). With regard to motor development, another important perspective is that sources of movement output variability operate over different time scales (Newell et al., 2001). Neuromotor noise is hypothesized to operate over a long developmental time scale, such that the level of variability contributed by neuromotor noise would be relatively constant on a day-to-day or even week-to-week basis. In other words, 7-year-olds on average will show higher movement variability than 12-year-olds. Other sources of variability operate over very short time scales, for example, within a single experimental session (Newell et al., 2001, 2006; Deutsch & Newell, 2004). Furthermore, during development the operation of the distinct sources of variability may change. For example, Deutsch and Newell (2004) demonstrated that children can exhibit short-term improvements in motor performance, becoming more accurate and faster within a single experimental session. Age-related differences in short-term changes in movement output variability are hypothesized to reflect differences in the way children and adults use a variety of feedback loops and potential differences in the way the systems' degrees of freedom are controlled to achieve movement goals (Newell et al., 2006). Finally, these investigators have also used spectral analysis to explore the possibility that the structure of movement variability arises from both stochastic and deterministic processes (Deutsch & Newell, 2003).

These issues are just beginning to be addressed within the developmental speech motor control literature. To our knowledge, our laboratory was the first to explore experimentally the possibility that short-term motor learning effects would be observed in a speech production task in children and adults. We (Walsh et al., 2006) assessed the potential role of short-term plasticity by examining performance on a novel nonword learning task. Learning effects were measured by computing the consistency in coordination over repeated productions of a higher-level (lip aperture) and a lower-level (lower-lip–jaw) functional synergy. This experimental approach was derived from our earlier study (Smith & Zelaznik, 2004), in which we hypothesized that lip aperture is a higher-order synergy compared to the lower-lip–jaw synergy, because lip aperture control has important acoustic effects, while the relative lower-lip–jaw motions do not. This hypothesis was supported: for all age groups studied, the higher-order synergy showed less variability across repeated sentence productions compared to the lower-order synergy. This was true, despite the fact that the lip aperture synergy involves the relative motions of the upper lip, lower lip, and jaw, while obviously, the lower-lip–jaw synergy involves only two articulators. (To understand the idea of higher- and lower-level functional synergies, consider the analogy of clapping your hands 10 times. For each clap cycle, we plot the trajectory over time of the inter-hand distance, which is analogous to lip aperture, and we plot the trajectory of relative motion of the right wrist and elbow, analogous to lower lip–jaw. We would expect that the inter-hand difference trajectories would be much more consistent from cycle to cycle than the within-arm wrist–elbow difference trajectory.)

In the novel nonword learning task, participants heard novel nonwords in random order and were instructed to repeat the word after hearing it. There were five novel nonwords and they ranged from one (“mab”) to four syllables (“mabshaytidoib”). With increasing length, phonological complexity of the nonwords also increased. The analysis was designed to determine whether the early repetitions of the novel nonwords were

more variable in inter-articulator coordination compared to the later repetitions. For each of 10 repetitions of each word, the lip aperture and the lower-lip–jaw difference signals were computed. The sets of early (first five) and late (last five) trajectories were compared on variability and duration. All participants (twenty young adults and twenty 9–10-year-olds) correctly produced all of the novel nonwords.

Our results confirmed that speakers of different ages have different speech motor learning characteristics. The young adults showed no changes in lip aperture or lower-lip–jaw coordinative patterns over the course of experiment. Variability for both upper- and lower-level synergies and nonword duration did not change over early and late productions for young adults. As predicted, the higher-order synergy showed less variability across all nonwords in both groups. Unlike the adults, the 9- and 10-year-olds showed a pronounced practice effect within the experimental session. Coordination variability for the lip aperture signal was significantly lower for the children’s last five productions. This effect was dramatic and was most pronounced for the longer and more complex nonwords. A parallel result was observed with regard to duration of the nonword productions for the children: the duration of the last five trials was significantly shorter than the duration of the first five. These results demonstrate that young children learning novel words show rapid and dramatic decreases in movement variability and increases in the speed of the sequential movements necessary for articulating the novel nonwords. In this case, children were able to simultaneously improve in consistency of motor execution, while speeding up the execution process. Interestingly, with regard to our hypothesized higher- and lower-order synergies, the motor learning effect was observed only for the higher-order synergy, lip aperture. Lower-lip–jaw coordination, the lower synergy, did not become more consistent over the early to late trials. This result provides additional evidence that lip aperture is a higher-order synergy, and that lip–jaw coordination is adjusted to more consistently achieve a higher order-control variable, that is, the distance between the lips.

The results of our experiment support a role of neuromotor noise in speech production, which operates over a relatively long time scale. The 9- and 10-year-olds were more variable than the young adults on all measures, and their level of performance on the improved later trials did not reach adult values. This suggests that there are sources of variability that, even with practice, prevent younger speakers from attaining adultlike performance levels. The question could be raised whether if given enough practice trials, the children would reach adult levels of consistency and speed. We suggested that this is unlikely, because even when children and adults repeat familiar well-practiced utterances, such as “Mommy bakes pot pies,” children are more variable and slower speakers. Our results also support the idea that there are sources of movement output variability that operate on shorter time scales compared to neuromotor noise. The improvement the children showed in the consistency of coordination of the upper lip, lower lip, and jaw and in the rate of nonword production occurred over the 30-minute experimental session. The five nonwords were randomized, so this was not simply a result of an improvement over repeated, sequential productions of the words. We would suggest that this improvement reflected systematic changes in cortically originating motor commands to the motoneuron pools. With just five practice trials, children were already becoming more consistent in generating the motor commands necessary to produce this novel sequence. These observations are consistent with the model proposed by Newell and his

colleagues, suggesting that there are sources of movement variability that can be observed to change over short time scales (Newell et al., 2001).

Another interesting issue that arises from the study of short-term motor learning in speech is whether adults would show short-term motor learning effects if they produced nonword stimuli that were more difficult. We are addressing this issue in a follow-up study (Sasisekaran et al., In press), and the results indicate that similar short-term motor learning effects are present in young adults when the novel nonwords are longer and phonologically more complex. It seems likely that the stimuli in our first study were easy, such that adults were at ceiling in the early trials, and therefore they showed no improvement from early to late trials. Another interesting question concerning these short-term changes in speech production performance within a single experimental session is whether they represent speech motor learning. In other words, have changes in synaptic connections occurred, such that on retesting the next day, participants would retain the improved performance observed on the later trials of the day 1 testing. In our second experiment, participants returned for second-day testing, and it is clear that speech motor learning does occur. Participants', both 9–10-year-olds and young adults, early trials on the second day show greater consistency compared to their early trials on day 1.

In summary, the recent literature on speech and limb motor development reveal that movement trajectory or inter-effector coordinative variability typically decreases as humans mature. Variability is not unidimensional and must be interpreted within the context appropriate for the task under study and the ages of the subjects. The time courses over which reductions in variability occur, short- and longer-term, can reveal many significant aspects of the underlying maturational processes. Recent studies demonstrating the extremely prolonged developmental course to adult levels of speech motor control and coordination are intriguing, and the relationship of this developmental trajectory to the growth curves characteristic of other skills, e.g., language processing abilities, will be significant areas for future investigation.

3.3 Theoretical issues and models of speech motor development

There is general agreement among those who have written about speech motor development that the process involves the formation of neural mappings among motor, somatosensory, and auditory systems (Kent et al., 1991; Callan et al., 2000; Smith & Goffman, 2004; Guenther, 2006; Smith, 2006). The earliest speechlike vocalization of infants is babbling, in which the canonical syllable appears, followed by repetitive canonical babble and variegated canonical babble (Oller, 1980; Stark, 1980; Kent & Bauer, 1985). Kent et al. (1991) proposed a model of early vocal development in which they applied Edelman's theory of neural group selection (Edelman, 1987, 1989) to postulate how these mappings might be generated. They suggested that the production of even a simple sound, such as a syllable, would activate a variety of sensory "receptor sheets," including static and dynamic intraoral mechanoreceptors, pressure and flow receptors, and auditory pathways. For each sensory modality, a sensory map would be formed, and with repetition of the syllable, the various sensory maps would be correlated with one another and with the motor map that produced the behavior. As we noted earlier, "neurons that fire together, wire together" – thus neural connections would develop to form these functionally linked maps arising from the infant's vocal behavior. Kent et al. suggested that, in addition, sounds made by others, such as parents, are also

represented in the auditory receptor sheets and associated map. “Reentrant” or repetitive signaling of this type would ultimately lead to the establishment of phonetic categories, which would be defined, not by the specific sensory information generated by the category of behavior, but by the correlations among the various maps. This kind of model, the authors noted, avoids the problem of postulating invariant motor or sensory representations of speech sounds. This is an important feature of any model attempting to account for developing or adult speech motor control, because the ubiquity of variability is a cardinal feature of speech production (e.g., MacNeilage, 1970).

Written in 1991, the model of early vocal development proposed by Kent and his colleagues presaged later, more formal neural network models of speech. Guenther (1995) proposed the DIVA (D = directions in orosensory space, I = into, V = velocities of, A = articulators) model for speech sound acquisition. Like the Kent et al. model, the DIVA model posits that babbling is an action–perception cycle, and that with repetition, cyclic babbling behaviors tune the speech production system by establishing mappings among reference frames (orosensory, acoustic, and motor). Like the speech production theory of Perkell and his colleagues, which focuses on adult speech motor control (Perkell et al., 1995, 2000), the DIVA model posits a major role for auditory targets, and the phoneme is the basic unit of production. After the babbling phase, the DIVA model can produce phoneme strings entered as input by the user (Guenther, 1995).

In our discussion of linguistic units and models of speech motor development (Smith & Goffman, 2004; Smith, 2006), we proposed a preliminary model of speech motor development which also included the idea that mappings between various neural systems must occur during speech acquisition. In addition to orosensory, acoustic, and motor linkages, however, we proposed that bidirectional linkages from motor to linguistic representations must be formed as toddlers begin to produce first, words, then longer utterances. In general then, there appears to be agreement that speech motor development entails the establishment of a variety of connections among the various neural centers involved in language formulation, speech motor control, and sensory representations. Beyond this basic premise, the speech motor development literature is extremely diverse in the theories, models, and/or frameworks used to generate experimental questions and to discuss the resulting data. Aside from the DIVA model, there are no formal models that attempt to elucidate the course of speech motor development. Therefore, in the sections that follow, I consider critical issues likely to be relevant to future theoretical approaches to speech motor development.

3.3.1 Units of production: the language–motor interface There is one period during human development when the basic unit of speech production seems clear. When the infant begins to babble, the unit of production is clearly the syllable (in my view, but note that the DIVA model of Guenther originally assumed phonemes as the input unit during the babbling stage, though later descriptions of the DIVA model indicate the input is a “speech sound,” which can be a phoneme, a syllable, or a word (Guenther, 2006)). One can return to the chapter by Kent and his colleagues (1991) for an insightful discussion of the role of the syllable in infant vocal development. They note that all units of speech production, including syllables, “present interpretive difficulties across and within levels of observation. A major factor in these difficulties is the attempt to impose segmentation on what is often a continuous motor pattern. But of all the candidates for

behavioral analysis of vocal development, the syllable appears to be the most practical and the most commonly used” (Kent et. al., 1991, p. 136). They consider the syllable to be the fundamental unit of early infant vocalization, and that the generation of sequences of syllables gives rise to the rhythmic structure of early infant vocalizations. Within this context, they defined the syllable as “a grouping of motor adjustments, highly variable in composition from one syllable to another, that is associated with the auditory perception of the fundamental prosodic unit” (p. 137). In the babbling stage then, the unit that serves as a basis for the mappings among the oral sensory, auditory, and motor systems is proposed to be the syllable.

We have hypothesized (Smith & Goffman, 2004; Smith 2006) that the nature of mappings between linguistic, auditory, and motor networks changes over the course of development. As suggested above, the syllable is the most likely unit of babbling. As the toddler enters the single word and multiword period of development, we proposed that multiple units emerge as the basis for neural mappings. In the toddler, syllables, words, and word combinations would serve as bases for mappings. In 4- and 5-year-olds, we proposed that phonemes, syllables, words, and phrases would serve as units of interface among the systems. In adults, we hypothesized multilayered mappings between linguistic units and the motor system. In other words, there is no privileged unit of production in the adult system, and as the child matures, he or she acquires these multilayered mappings.

The data to support this proposal comes from experiments from our laboratories and others to suggest that motor output is intimately shaped by the linguistic goals of the speaker. We have examined the relationship between motor output and linguistic units for many different sizes of units, including the phoneme, syllable, word, phrase, and sentence levels (reviewed in Smith & Goffman, 2004; Smith, 2006). Goffman and her colleagues have also demonstrated clear effects of prosodic goals on the details of speech movement output (Goffman, 1999; Goffman et al., 2006, 2007). One compelling example, which supports the idea of the parallel operation of many units of production, comes from our study of coarticulation in 5-year-old children and adults (Goffman et al., submitted). Participants produced three pairs of sentences (10–15 repetitions of each) that varied only in an utterance internal vowel (e.g., “Mom has the *goose/geese* in the box”). We measured the timing and amplitude of the lip rounding gesture for /u/ relative to the duration of the lip movement sequence for the entire utterance. For both children and adults, the lip rounding gesture had broad influences on the lip movement sequence for the entire sentence, with the rounding gesture continuing for 50–60 percent of the sentence duration. Adults showed less variable rounding gestures, but the influence on the entire utterance was similar across age groups.

Returning to Figure 7.1, we note that in order to produce the sentence, “Mom put the goose in the box,” the brain has to generate motor commands to activate the appropriate muscles with exquisite control of the timing of their activation. What this experiment reveals is that the neural commands to the lip muscles involved in the rounding gesture are modified across a large portion of the sentence in relation to the identity of a single vowel in the middle of the sentence. Adults and 5-year-olds make a similar modification in terms of the temporal organization of the gesture. Thus these findings suggest that by 5 years of age, children are already using multiunit speech production planning strategies. In order to produce this long-lasting change in the motor

commands for the sentence specifically attached to a single segment, the speaker would have to have at least a phrase-level motor plan. This result, in combination with an earlier study (Goffman & Smith, 1999) showing that children as young as 4 years produce phonetically specific oral movement patterns for consonants that vary only by a single feature (e.g., “ban”/“pan”), supports the claim that by 4–5 years, children are using multiple planning units in speech production.

Our multiunit view may seem at odds with models of speech production that propose a privileged or basic unit of production planning, often the phoneme (e.g., Perkell et al., 2000), or the syllable, for example, the syllabary of Levelt and Wheeldon (1994). On the other hand, the suggestion that some units may be more prominent, “more fundamental” than others does seem reasonable. In my view the syllable would be a good candidate as the “most basic” unit, because of its connection to the open–close oral movement cycle and its appearance as the first speech like vocalization of infants. In any case, from the point of view we have taken (Smith & Goffman, 2004; Smith, 2006), as the child matures, stored commands can be of varying lengths, from syllable, to word, to phrase, to sentence length. I am certain that many Americans have extremely stable, stored motor commands for the phrases, such as “Hi, how are you,” and “Have a nice day.”

In summary, future theoretical work on speech motor development must address the gap between language production models that ignore the motor system and speech motor control models that ignore the language system. This is a difficult gap to bridge, but by studying the unfolding relationship between motor output and the linguistic and metalinguistic goals of the speaker as children mature, future theorists will have better chance to understand how linguistic constructs are transformed into muscle contraction and movement.

3.3.2 Factors driving the protracted developmental course to mature speech motor control A comprehensive account of speech motor development will have to consider the long developmental trajectory for attaining adultlike speech motor control processes. In addition to the protracted developmental course for speech motor control, some periods in development are marked by very rapid changes toward the adult end product, while in other intervals, for example, the period from 7–12 years, plateaus in some aspects of performance are observed. It seems likely that in various developmental periods, the factors that drive either rapid or relatively slow speech motor development vary.

Compared to girls, 4- and 5--year-old boys are less mature in the consistency of inter-articulator coordination (Smith & Zelaznik, 2004). This sex difference disappears by age 7, and in terms of consistency of coordination and speech rate, we observed no sex differences in any of the other age groups we studied. The fact that preschool boys lag girls in articulatory coordinative development is not surprising, given that girls are often shown to be better in verbal tasks, but the reasons for this difference in development are unknown. In the burgeoning neuroimaging literature, in which large groups of children are being imaged in cross-sectional and longitudinal studies, many sex differences in brain development have been documented. These include different developmental trajectories for global measures, such as white and gray matter volumes, and differences in specific regional measures (Lenroot & Geidd, 2006). In their study of 200 normal

children, Wilke et al. (2007) reported that girls have a proportionally higher gray matter volume in a very distinct area in the left inferior frontal gyrus, a difference not observed for the right homologous area. This finding is consistent with a number of anatomical and functional imaging studies pointing to neurophysiological bases for sex differences in verbal tasks (Harasty et al., 1997; Plante et al., 2006).

The idea that speech motor control processes continue to mature post puberty would have been surprising some years ago. Now it is widely recognized that adolescence is a time of very significant development behaviorally and cognitively, and there is clear evidence that brain development continues well into the twenties (see review by Blakemore & Choudhury, 2006). For speech motor control, it is important to note that the frontal lobe continues to show increased myelination throughout adolescence, which would contribute to faster conduction speeds allowing more rapid inter-regional communication among neural populations (Giedd et al., 1996, 1999). Furthermore, there is an increase in white matter in the left arcuate fasciculus during adolescence, and the corpus callosum undergoes regionally specific changes until the mid-twenties (& and Choudhury, 2006). Given these results, it is not surprising that 16-year-olds are not yet adultlike in speech motor control processes. We suggested that there are trade-offs during adolescence, such that higher rates of speech are achieved at the expense of more variable coordinative patterns. Also, we noted that given that girls and boys do not differ in articulatory motor control during the adolescent years, the protracted course of articulatory motor development apparently is not related to craniofacial growth. Rather, we hypothesize that the continued maturation of the brain is a primary factor delaying maturation of speech motor control processes to adult levels.

Another interesting issue that future models of developing speech motor control must address is individual differences. Much of the focus of this chapter has been on between-group effects, and the developmental growth curves under discussion reflect changes in group means and variability with maturation. As Figure 7.3 shows, however, there are dramatic differences between individuals within an age group as is evident for the thirty 4-year-olds and thirty 12-year-olds whose data are plotted. Some of the 12-year-olds have coordinative consistency (as measured by the lip aperture variability index) equal to adult levels (in the 10–15 range). Some 12-year-olds, however, have coordinative consistency indices equal to that of some of the 4-year-olds (19–25 range). The 4-year-olds have a remarkable dispersion of speech rate. What accounts for these individual differences? Future studies in which measures of speech motor control, language abilities, and general cognitive abilities are obtained in addition to neuroimaging data for the same subjects will be necessary to explore the potential factors contributing to these differences between individuals in speech motor performance.

3.3.3 The role of feedback and the nature of stored motor commands There is general agreement that auditory and somatosensory feedback play a critical role in the development of speech motor control processes (e.g., Kent et al. 1991; Guenther, 1995), and it is well known that normal speech production patterns cannot be established in the absence of auditory information. Furthermore, there is also general agreement that with maturation, speech motor control becomes primarily under feedforward control, that is, driven by stored neural commands for speech movement sequences. The nature of what is stored and how these stored motor commands relate to linguistic units is, as already noted

above, a matter of debate. Despite the general agreement about the importance of sensory information in developing speech motor control, almost nothing is known about the details of how and when somatosensory and/or auditory information is used to shape ongoing motor output, to build internal models of movement goals, and to tune feedforward commands.

In general, speech production systems of children are slower, and it has been noted that this is consistent with a feedback-based control system (e.g., Riely & Smith, 2003). As children mature, they become faster speakers and their movement output patterns become much more consistent from trial to trial. Presumably, during maturation children are establishing stored motor commands for speech production and they are relying less and less on feedback. In order to understand how this process of shifting from feedback to feedforward control unfolds in development, experiments are needed to manipulate feedback and examine the effects on motor output. Adults can compensate automatically online to mechanical perturbation of the articulators as well as to alterations and auditory feedback (reviewed in Smith, 1992). While a few preliminary studies of children's responses to bite block perturbations have been completed using acoustic analyses, the results of the studies are mixed (Baum & Katz, 1988; Edwards, 1992). It would be useful in future studies to examine the effects of altered somatosensory and auditory feedback on the variability of movement output in children at different ages. In addition, studies of novel word learning could incorporate altered feedback conditions and address the question of the role of sensory information in establishing new patterns of output.

3.3.4 Neuroplasticity and sensitive periods for speech motor learning A primary source of evidence for the existence of sensitive periods for speech motor learning comes from the well-known fact that the ability of humans to learn new languages and to achieve near-native accents in them decreases as we mature into adulthood. In general the loss of capacity to acquire new languages with aging has been attributed to a sensitive or critical period for language acquisition, such that with maturation there is a loss of plasticity in the neural systems involved in language learning (see references cited by Flege et al., 1999). While this explanation seems intuitively appealing, the issue of age-related changes in second language (L2) performance is a complicated one. The sensitive period hypotheses for L2 performance changes have not been specific with regard to what particular abilities are lost (Flege et al., 1999). For example, the inability to achieve a near-native accent in L2 could be due to a loss of plasticity in speech motor output circuitry, a decrement in the ability to auditorily discriminate L2 sounds, a loss of ability to create new perceptual representations of sounds, and/or a decrement in the ability to translate stored auditory representations into speech motor commands (Flege et al., 1999). Flege and colleagues have completed many experiments designed to test the sensitive (or critical) period hypothesis, and with regard to accent, the data do not support a strictly maturational explanation. They therefore prefer an alternative explanation for the age-related decline in L2 pronunciation accuracy, which is that the greater the stability of the first language (L1) phonetic system, the more interference L1 has on L2 learning. As children mature into adolescence and young adulthood, the L1 phonetic system becomes extremely stable, and new patterns of phonetic output are more difficult

to achieve. They also note that the difficulties in acquisition of L2 morphosyntax may be affected by a different set of factors compared to those that determine accent.

Perhaps, if one considers the sensitive period hypothesis within the framework proposed by Knudsen (2004), some of the issues suggested above become clearer, and one could propose the combined operation of both sensitive periods and L1 interference in the age-related decline in L2 performance. Knudsen notes that while we tend to think of sensitive periods in terms of behavior, they are actually properties of neural circuits. In his enlightening article, Knudsen provides a variety of examples of sensitive periods in development, including those of human language, birdsong, visual representation in monkeys, filial imprinting in ducks and chickens, and auditory processing of spatial information in owls. He defines the term sensitive period as one that “applies whenever the effects of experience on the brain are unusually strong during a limited period in development.” In some of the animal models mentioned above, changes in the neural circuitry that arise during sensitive periods, in other words the changes that underpin learning, have been mapped out. These involve axonal elaboration and synapse formation in addition to axon and synapse elimination. The metaphor Knudsen uses to explain stable neural circuits is relevant for the present discussion of speech motor learning. He invokes a stability landscape in which experience shapes troughs or wells of stable behaviors over development (note the similarity to the stability landscapes of Thelen & Smith, 1994). Once a highly stable neural circuit has been formed, there is a loss of plasticity in that circuit. “After a sensitive period has ended, many independent mechanisms that support plasticity continue to operate. The amount of plasticity that persists in a mature circuit varies widely, depending on the circuit’s function. The plasticity that remains enables mature circuits to modify their patterns of connectivity within the enduring constraints established in response a result of experience during a sensitive period” (Knudsen, 2004, p. 1417). Adults have passed the sensitive period for speech motor learning, but they retain some degree of plasticity. Applying Knudsen’s framework, learning new behaviors, such as a second language, requires more attention and effort after the sensitive period has passed, and the new behavior may be atypical (e.g., retention of an L1 accent) due to influences of previously established neural circuitry.

Also relevant to the observation that accent and morphosyntax may show different age-related performance trajectories in L2 learning (Flege et al., 1999) is Knudsen’s observation that complex behaviors such as language result from the interactions of multiple hierarchies of neural circuits. Therefore, he suggests it will be difficult to identify critical or sensitive periods based on behavioral measures. As discussed above, widely distributed neural circuits contribute to language production, including cognitive, linguistic, motor, and sensory circuits. The different circuits are likely to undergo different developmental trajectories and thus display distinctive sensitive periods. He notes that while the neural circuitry involved in semantic analysis remains highly plastic throughout life, the L2 data strongly suggest that the neural hierarchies involved in phonetic processing lose a great deal of plasticity with maturation to adulthood. As another example, Weber-Fox and Neville (1996) concluded from studies of event-related brain potentials recorded in language processing tasks that there is a sensitive period for acquiring the syntax of a language. These ideas are important to bring to bear on interpreting data in speech motor control experiments. For example, in a recent

study we hypothesized that speech coordination variability would be higher for L2 compared to L1 in bilingual Bengali–English speakers. At first, we were surprised to find that movement variability assessed in L1 (Bengali) and L2 (English) was equal and independent of age of immersion in L2 (Chakraborty et al., in press). Despite the fact that many of the speakers had a pronounced accent in L2, their movement variability in L2 was low and typical of adult levels of performance in L1 for native speakers. This suggests that the strongly accented L2 production is also highly stable, and that the neural circuitry underlying it has lost plasticity. Furthermore, there are strong interference effects on L2 of L1.

The idea of sensitive periods for speech motor learning is also supported by the experience of young cochlear implant recipients in learning to produce speech. The younger the recipient, the more likely he or she is to produce speech that is highly intelligible, and after age 4–5 years, high degrees of intelligibility typically are not attained, even after many years of implant use (Peng et al., 2004). Ertmer et al. (2007) assessed vocal development in a prospective longitudinal study of seven children who received cochlear implants between 10 and 36 months of age. These infants and toddlers, for the most part, had passed the age at which babbling begins when they received their implant; however most of them proceeded from babbling through the normal stages of vocal development. Interestingly, though, relative to the sensitive period hypothesis, the older implant recipients in this study (30 and 36 months) achieved all the milestones of complete vocal development in the shortest time frame. Apparently, these older toddlers were still young enough to take maximum advantage of the new input, and they did so in a very rapid manner given their more mature overall cognitive developmental levels. Taken together, the results of these two studies suggest that there is a sensitive period which extends through 3 to 4 years of age when optimal gains in speech production abilities can be made in response to auditory inputs. As our technical ability to record movement and muscle activity during early vocal behavior improves, our understanding of the operation of sensitive periods for speech motor development should expand.

Other theoretical issues and conclusion There are many other issues that will be relevant for future modelers of speech motor development. Many of these have been discussed at some length in earlier sections of this chapter, for example, the need to understand the sources of variability in speech movement output and their differing time scales of operation, and the issue of the relationship between the neural systems that generate speech movements and those that generate other, earlier appearing motor behaviors using the same output pathways.

As a final note in this discussion of future theories of speech motor development, I would like to point out that one of the most astonishing conclusions one reaches after completing a review of this literature is that there is a real paucity of studies of oral motor development for speech. There are very few laboratories doing work in this area, and this is surprising given the importance of normal speech development in human experience. In contrast, there are many more investigators studying the development of a variety of limb movements, from gait, to finger tapping, to precision and power grip. The recent literature on power grip, in fact, would serve as a good model of what the future might hold for the study of the development of speech motor processes. My summary of the research on power grip is based on the review provided in Halder et al. (2007).

Early behavioral studies of the development of power grip performance under visual feedback revealed that younger participants were slower in reaction time to produce a target force, slower in rise times to the target, and more variable in achieving the target. The developmental course of the increasing abilities of young children and adolescents to produce power grip was mapped out in many studies of children from 3 years through adolescence. A series of functional imaging studies completed on adults in the period from the late 1990s to the early 2000s demonstrated the extensive neural network involved in producing power grip under visual control. It involves the contralateral primary sensory motor cortex, the ipsilateral cerebellum, the superior parietal cortex, the ventrolateral thalamus, occipital, and premotor regions. In addition to mapping the network involved in visually guided power grip, imaging studies also confirmed a linear relationship between activity in motor regions and the level of the target force. Electroencephalographic studies were completed to examine movement related potentials, which were also found to be sensitive to force parameters.

These studies provided the experimental foundation for the 2007 developmental study of Halder and colleagues, a large Swiss team. In this study power grip performance was studied in 17 participants in each of three age groups (9–11 years, 15–17 years, and young adults) in both functional magnetic resonance imaging and electroencephalographic (EEG) recording sessions. Thus this team had detailed motor output measures (e.g., reaction time, target force achieved, rising slope), excellent spatial resolution of the activated neural networks from the fMRI data, and excellent temporal resolution of the neural activation patterns preceding and during performance of the power grip task from the EEG data. Their developmental study replicated the results of earlier studies in adults showing an extended neural network involved in producing a power grip under visual feedback. The spatial distribution of the network was consistent over all the age groups studied. The expected activation patterns in relation to increasing target force levels were also observed in all the age groups studied. They also replicated earlier developmental findings with regard to slower reaction times and shallower slopes in the force trajectories.

These authors were able to conclude that the spatial distribution of the power grip network matures early in development. Interestingly, however, a network that is robustly deactivated when performing the power grip task in adults showed little or no deactivation in the younger groups. The younger groups also showed substantially higher amplitude task-related premovement potentials, and the ERPs in the feedback interval were also much larger in children and adolescents. These results suggest that children and adolescents show less focused neural activity in relation to performance of the visually guided power grip task. Thus, as humans mature from adolescence to young adulthood, the neural circuits involved in power grip continue to undergo changes until the neural activity is much more task specific. From the details of this study, which are not reviewed here, we know the specific brain regions showing greater activation and lesser deactivation in the younger participants, and we know the time course of increased activation in the younger participants in relation to performance of the task.

It seems clear that much more is known about the neural control of power grip generation over development than is known about the development of neural control of orofacial movements for speech. We have begun the stage of making detailed behavioral observations of speech motor output over many developmental periods, and imaging

studies in adults are beginning to map the neural networks involved in prespeech planning and production (Bohland & Guenther, 2006). Obviously, there are technical difficulties involved in imaging during performance of a motor task that takes place in the head, which makes it more difficult to study speech movements with imaging and electroencephalographic approaches. However, signal processing methods which reduce noise and artifact contamination of data are improving. In any case, the work by Halder and colleagues may be seen as a map of what the future holds for the study of speech motor development. In addition to the nature of the experiment, which allowed detailed assessment of the motor output at the periphery along with excellent spatial and temporal resolution of the accompanying central nervous system activity, an important aspect of this study is the research team itself. Advances in understanding the neural control of speech motor development will depend upon assembling similar research teams who can make multileveled observations of both peripheral speech motor output and the neuronal activity generating that output in young children, adolescents, and adults.

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]hx[Note

This investigation, as well as those of Riely and Smith, 2003, and Smith and Zelaznik, 2004, was part of a large study of the development of speech motor control in typically developing children and young adults in which 240 participants were tested on the same protocols.

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Chapter 7 Figures

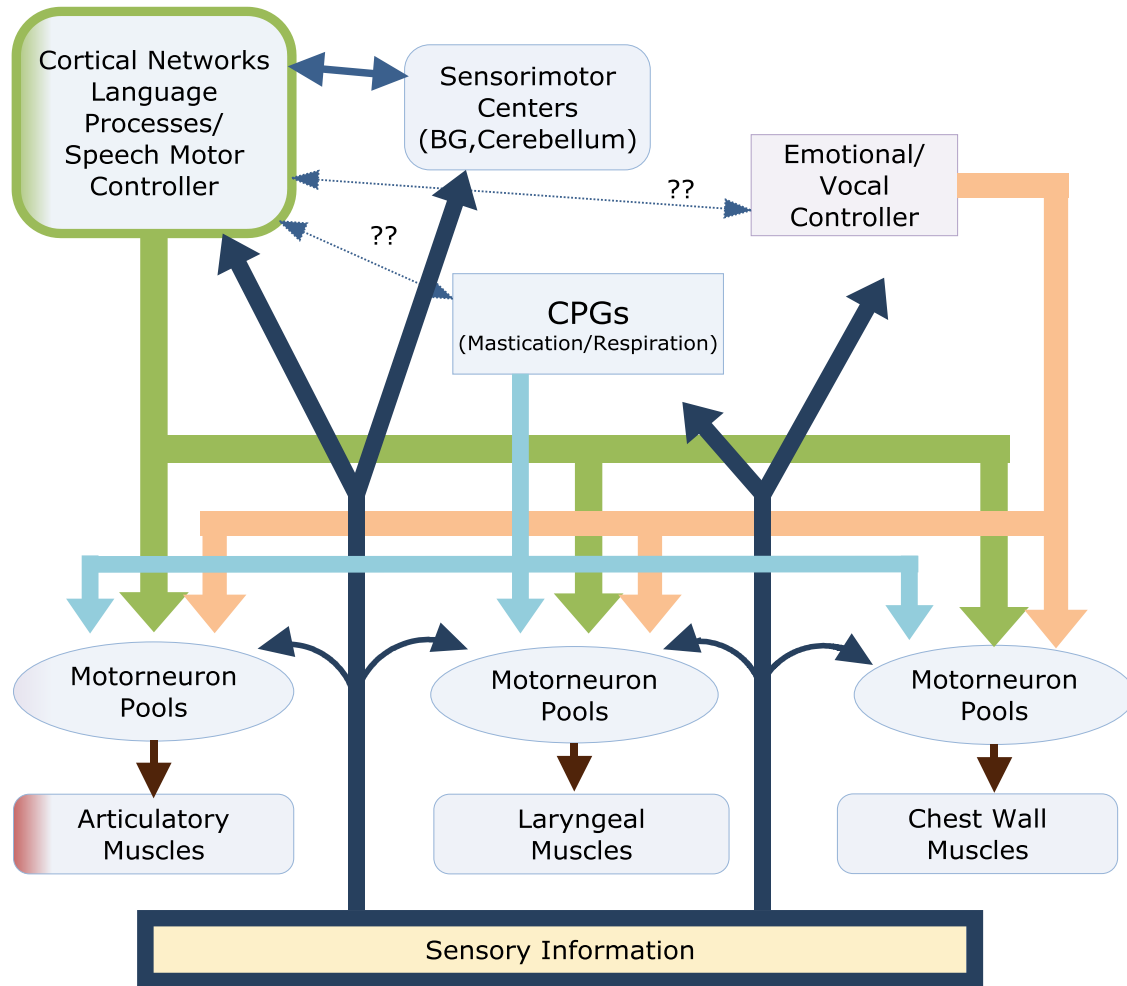


Figure 7.1 A schematic diagram of the many control pathways operating on the motorneuron pools that we use in speaking.

Relative Growth Curves: Duration, Velocity, and Displacement of Articulatory Movements

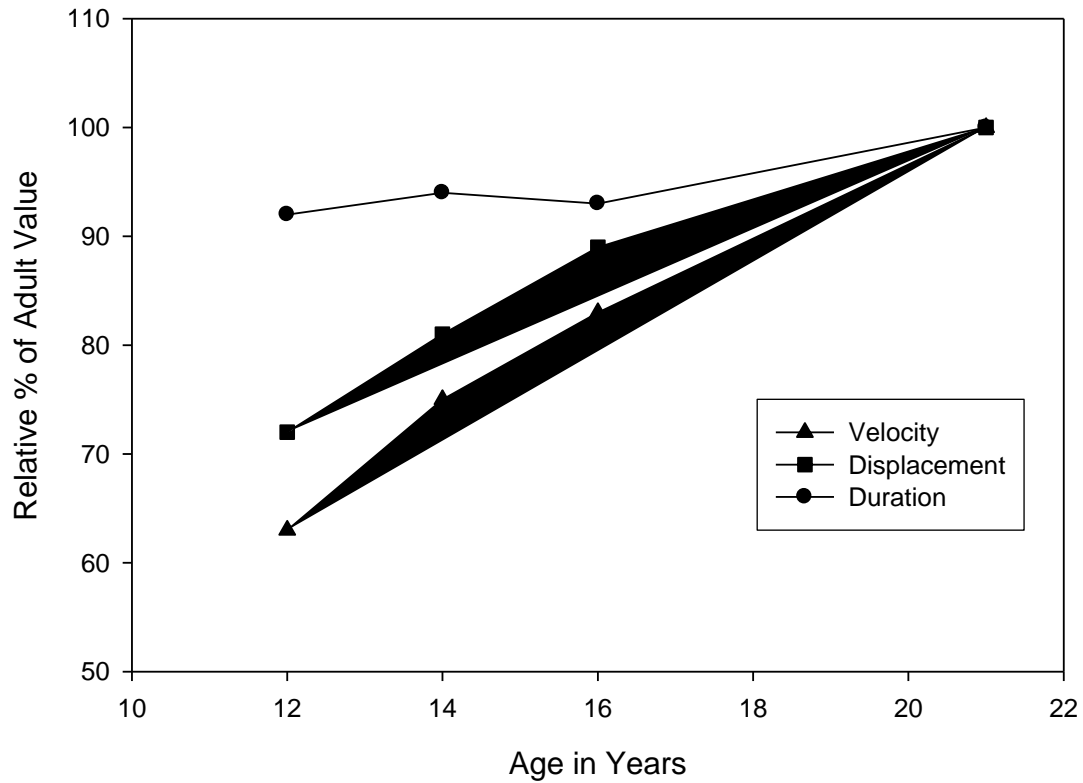


Figure 7.2 The adult values for each measure are arbitrarily set to 100 percent so that we can compare the growth curves of three different variables, duration (average duration computed from two syllables), displacement, and velocity (both averaged across four lower-lip movements). Speech rate, as reflected in the syllable duration measure, is almost adultlike by age 12 years, but the speed and extent of oral movements for speech become adultlike much later.

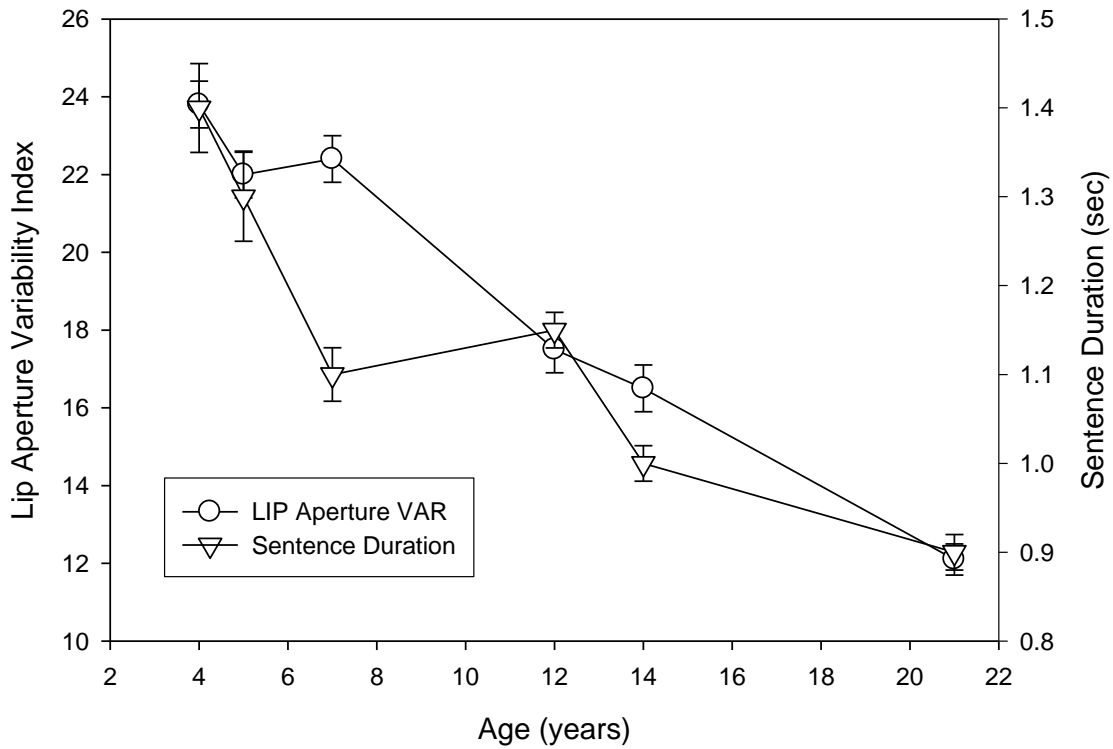


Figure 7.3 The lip aperture variability index (a composite measure of spatial and temporal variability computed for 10 repetitions of a sentence) averaged across two sentences (“Mommy bakes pot pies” and “Buy Bobby a puppy”) and the average duration of the two sentences are plotted as a function of age. As children mature, their variability on repeated productions of the sentences and the duration of the sentences drop dramatically (speech rate increases). The two growth curves show very different slopes in various developmental periods; thus demonstrating that changes in speech movement variability with maturation are not simply an epiphenomenon of increasing speech rates.

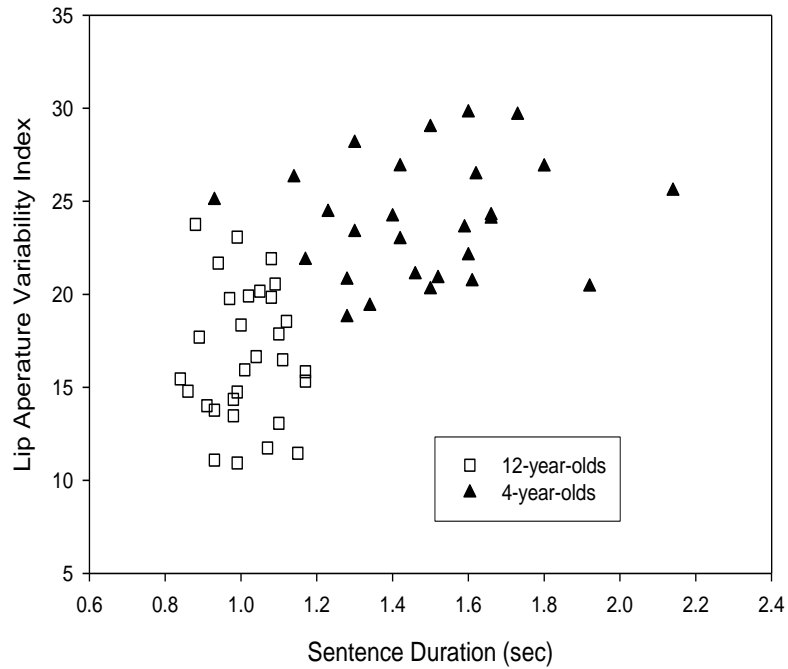


Figure 7.4 Scatter plots of a speech coordination variability index, lip aperture variability, computed for 10 repetitions of a sentence (averaged across two short sentences) plotted as a function of sentence duration (again averaged across the two sentences) for thirty 4-year-olds and thirty 12-year-olds. It is apparent that there is no correlation between these two measures. Thus within an age group, more variable speakers do not tend to be the slower speakers of the group. Note the large range in sentence duration, from about 1.0–2.2 seconds in the 4-year-olds and the much smaller range in sentence duration in the 12-year-olds, about 0.8–1.2 seconds.