OROMOTOR KINEMATICS OF SPEECH IN CHILDREN AND THE EFFECT OF AN EXTERNAL RHYTHMIC AUDITORY STIMULUS

BY

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Abstract

The purpose of this study was to determine the effect of an external auditory rhythmic stimulus on the kinematics of the oromotor musculature during speech production in children and adults. To this effect, the research questions were:

1) Do children entrain labiomandibular movements to an external auditory stimulus?
2) Does the ability to entrain labiomandibular movements to an external auditory stimulus change with age?
3) Does an external auditory stimulus change the coordination and stability of the upper lip, lower lip, and jaw when producing speech sounds?

The oromotor kinematics of two groups of children, age eight to ten (*n* = 6) and eleven to fourteen (*n* = 6), were compared to the oromotor kinematics of adults (*n* = 12) while producing bilabial syllables with and without an external auditory stimulus. The kinematic correlates of speech production were recorded using video-based 4-dimensional motion capture technology and included measures of upper lip, lower lip and jaw displacement and their respective derivatives. The Spatiotemporal Index (a single number indication of motor stability and pattern formation) and Synchronization Error (a numerical indication of phase deviations) were calculated for each participant within each condition.

There were no statistically significant differences between age groups for the Spatiotemporal Index or for Synchronization Error. Results indicated that there were statistically significant differences in the Spatiotemporal Index for condition; with

Post-hoc tests indicating that the difference was between the first condition (no rhythm) and the second condition (self-paced rhythm). Results indicated that both child groups were able to synchronize to an external auditory stimulus. Furthermore, the older child group was able to establish oromotor synchrony with near-adult abilities.

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Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Speech production is a complex skill involving coordination of respiratory, laryngeal, pharyngeal, intraoral, and labiomandibular muscle systems. Furthermore, motor speech production requires mastery of a series of complex temporally precise movements (Tremblay, Houle, & Ostry, 2008). Oromotor kinematics studies have indicated that stability of this system does not mature until late adolescence (Sadagopan & Smith, 2008) or early adulthood (Walsh & Smith, 2002). This indicates that a prolonged period of practice is necessary to master speech production; a process that may be further protracted by developmental speech disability.

Speech production involves the integration of auditory, somatosensory, and motor information in order to generate the intended speech goal (Guenther, 2006; Larson, Altman, Liu, & Hain, 2008). Although feedback and feedforward speech systems have been explored in relation to external manipulations of auditory information (i.e., phase shift or pitch shifting), there is little evidence regarding the effect of an external rhythmic cueing device on the motor patterns involved in producing speech.

Music therapy services have been employed to target speech goals in persons with developmental disabilities for many years, using melody, rhythm, and structure to promote speech production. A few studies have shown that external auditory rhythmic cueing can be successful for improving the sequencing or prompting of speech production in adults with dysarthria, Parkinson's Disease, and Huntington's

Disease (e.g., Pilon, McIntosh, & Thaut, 1998; Thaut, 2005; Thaut, G. McIntosh, K. McIntosh, & Hoemberg, 2001). Rhythmic and musical cueing have also been utilized with children to promote speech communication.

The extant literature supports music and rhythm to improve communication in children with developmental disabilities (e.g., Braithwaite & Sigafoos, 1998; Hurt-Thaut & Johnson, 2003; Kumin, 2003; Rainey Perry, 2003); however, there is little quantitative research supporting the efficacy of music therapy interventions that are based on motor synchronization for speech production. Furthermore, the effect of an external cueing device on the typical child's speech motor system has not yet been established and there is some indication that external rhythmic cueing may not be effective in children due to perceptual motor learning differences (e.g., Hurt-Thaut & Johnson, 2003; Sloboda, 1985). Although there are no known child oromotor synchronization studies in the extant literature, some researchers have examined the ability of children to synchronize limb motor movements to an external auditory stimulus.

The ability to synchronize limb motor movement with an external auditory stimulus has been reported to become stable around age seven (Smoll, 1974a, 1974b, 1975; Thomas & Moon, 1976; Volman & Geuze, 2000). Research has indicated that children synchronize limb movements better to a faster stimulus than a slower stimulus (Kumai & Sugai, 1997; Mastrokalou & Hatziharistos, 2007; Rao, Mayer, & Harrington, 2001) and that synchronization of the off-beat can be more stable in children (Volman & Geuze, 2000). Although these studies suggest that children can entrain limb motor movements, the ability to synchronize speech production to an external auditory stimulus has not yet been studied in children.

The purpose of the present study is to examine the effect of an external auditory stimulus on the coordination of the oral musculature. To this effect the following research questions will be addressed:

1) Do children entrain labiomandibular movements to an external auditory stimulus?
2) Does the ability to entrain labiomandibular movements to an external auditory stimulus change with age?
3) Does an external auditory stimulus change the coordination and stability of the upper lip, lower lip, and jaw when producing speech sounds?

Chapter 2

Review of Literature

Music is often used in some capacity to help engage and motivate children with disabilities to use speech communication. The parent or speech language pathologist may use musical instruments or rhythmic tapping on a drum in order to promote oromotor skills and speech communication (Kumin, 2003). A child with a speech disability may also receive services from a certified music therapist; a professional who is trained to utilize music in individualized treatment to address non-musical goals, inclusive of speech communication (AMTA, 2003, *Professional Competencies*). Music therapists have long utilized music stimuli to facilitate speech communication. Edwards (2008) documented the frequency of articles published in the *Journal of Music Therapy* (JMT) that address communication goals and found that music therapists have regularly published on the topic of speech communication, with 26.5% of all articles in the JMT between 1964 and 2007 focused on communication.

The use of music for speech goals continues in current music therapy practice, with numerous music and speech therapy texts supporting the use of music and rhythm for speech communication goals (e.g., Anderson & Peters, 2001; Clair, Pasali, & LaGasse, 2008; Hurt-Thaut & Johnson, 2003; Kumin, 2003; Morris, 2002; Neve, Dodds, & Guy, 2005; Wong, 2004). Music therapy encompasses many strategies, however one prevalent method for addressing speech production is the use of rhythmic cueing (e.g., Pilon, McIntosh, & Thaut, 1998; Thaut, 2005; Thaut, G.

McIntosh, K. McIntosh, & Hoemberg, 2001). Rhythmic cues are used to provide a predictable auditory template for sequencing motor movements, and when implemented with children, may be utilized within a motivating therapeutic exercise that specifically targets speech communication.

Rhythmic cueing has been shown to be effective in improving speech intelligibility in persons with dysarthria due to traumatic brain injury (Pilon, McIntosh, & Thaut, 1998) and Parkinson's disease (Thaut, G. McIntosh, K. McIntosh, & Hoemberg, 2001). Although positive results are promising with adult populations, there is little research to support the use of rhythmic cueing for speech production in children. Furthermore, the effectiveness of rhythmic cueing with children has not been adequately explored and some of the extant literature has suggested that auditory entrainment is not effective with children before adolescence due to delays in perceptual motor and cognitive processing (Hurt-Thaut & Johnson, 2003; Sloboda, 1985). Despite the lack of evidence supporting the use of musical and rhythmic cues for speech communication goals in children, there appears to be a consensus that music is an effective tool for speech communication (e.g., Anderson & Peters, 2001; Clair, Pasali, & LaGasse, 2008; Hurt-Thaut & Johnson, 2003; Kumin, 2003; Morris, 2002; Neve, Dodds, & Guy, 2005; Wong, 2004). However, there is a lack of empirical evidence supporting current practices in music therapy for speech communication goals.

Building empirical evidence to determine the efficacy of using music for speech production in children requires an understanding of speech production, auditory speech feedback, speech development, and the principles of rhythmic entrainment. These areas are also necessary for informed practice in music therapy. Therefore, it is the purpose of this chapter to provide an overview of current literature as it relates to the science of speech, rhythm, and oromotor processes of children. This information will be used to support a theoretical foundation for using rhythmic cues for entrainment of speech production in children.

Neurological Basis of Speech Production

Speech requires the organization of planned sounds that are produced by the oral musculature at precise times (Kent, 2000). Fluency of speech is therefore dependent on the ability of the neural system to plan and coordinate sequences of complex movements. Studies regarding cortical involvement during speech production have become more prevalent; however, when compared to other motor systems, there is relatively little known about the cortical and subcortical systems involved in speech production (Bohland & Guenther, 2006; Riecker et al., 2005). Most of the existing research has proposed functional speech systems based on the affected brain regions of persons with disordered speech production (Riecker et al., 2005). Although this research provides information about the effect of cortical insult or degeneration, there are fewer studies attempting to define the neural processes in overt speech production. The lack of research concerning the cerebral organization of speech control may be due to the complex nature of speech production.

Neuroimaging studies have provided evidence that multiple cortical areas underlie speech motor control. Blood oxygen level-dependent (BOLD) activity during syllable sequences has demonstrated recruitment of a large bilateral network of subcortical and cortical regions involved in speech production (Ackermann, 2008; Bohland & Guenther, 2006; Estep, Barlow, Auer, Kieweg, Lee, & Savage, 2008). Regions included portions of the medial and lateral frontal lobe, parietal lobe, temporal lobe, thalamus, basal ganglia, and the cerebellum. Functional MRI (fMRI) of syllable repetitions synchronized to an external stimulus demonstrated bilateral responses in the mesiofrontal and sensorimotor cortex, putamen/pallidum, thalamus, cerebellum, and left-sided activation of the dorsolateral premotor cortex and anterior insula (Riecker et al., 2005). Many of these areas including the sensorimotor cortex, premotor cortex, supplementary motor area, cerebellum, thalamus, and basal ganglia are also known to contribute to planning and producing voluntary gross motor movements. These cortical areas are therefore suggested to plan, sequence, and execute complex motor movements in order to produce fluent speech production.

Contributions from Cerebral Cortex

The somatotopically mapped sensorimotor cortex has been studied in great detail due to its role in voluntary motor control (Barlow, 1999). The precentral gyrus of the cerebrum constitutes the primary motor cortex (MI), which receives somatosensory inputs and allows for rapid adaptations of the signals sent via the corticospinal and corticobulbar tracts. These areas are represented in Figure 1, where the MI area consists of Brodmann's area 4 and possibly the posterior strip of Brodmann's area (BA) 6 (Barlow, 1999). The postcentral gyrus is the primary "receiving" area for sensory information and is referred to as the sensory cortex (SI).

This area consists of BA 1, 2, and 3 (Figure 1). The inputs from the sensorimotor cortex are directly involved with descending input to the lower motor neuron (LMN) system, known as the “last link” in the process of speech motor production (Duffy, 2005). Although the MI and SI are integral to the process of speech production, several other cortical areas are also involved in these complex and highly time-ordered movements.

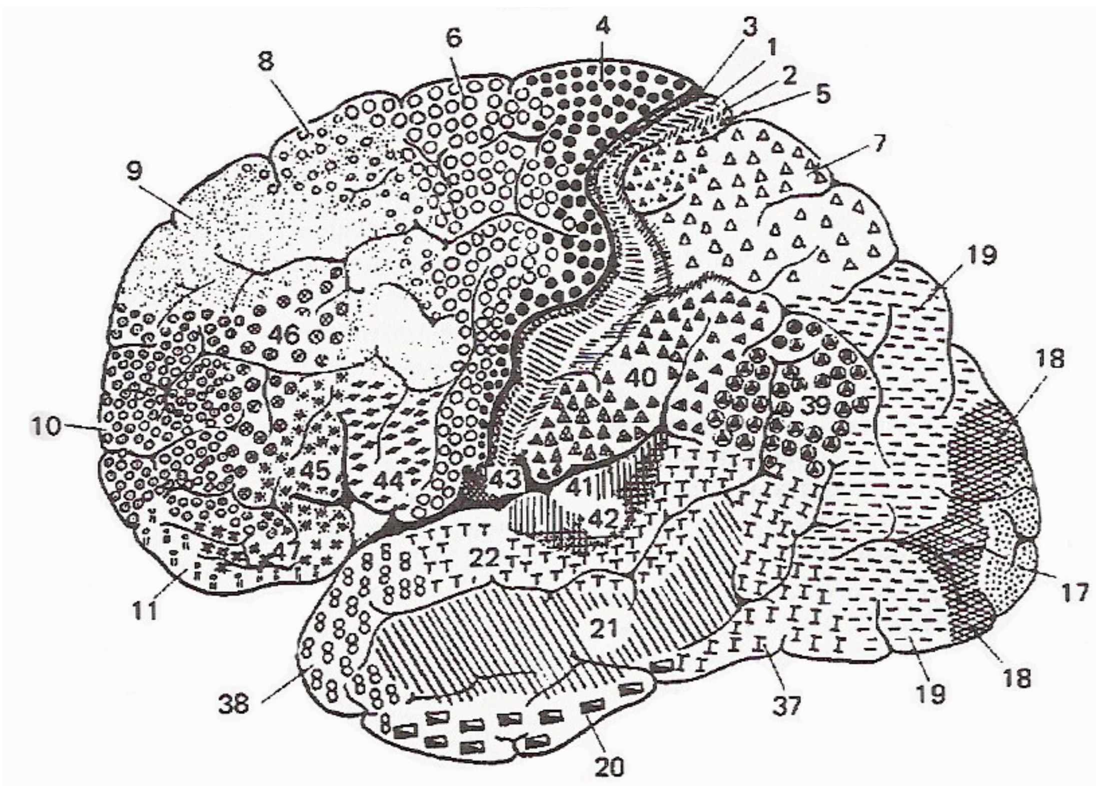


Figure 1. Brodmann’s representation of regions of the cerebral cortex. The primary motor cortex is indicated by numeral 1, the premotor regions are represented by numeral 6, and Broca’s area 44.

Additional cerebral areas directly involved in speech production include the supplementary motor area (SMA; medial BA 6), premotor cortex (PMC; lateral BA 6), Broca's area (BA 44), anterior cingulate cortex, and subcortical areas (Barlow, 1999). The efferent pathway for speech is comprised of fibers originating in the primary lateral precentral motor cortex. The MI receives input from several indirect pathways including inputs from the SMA and PMC. The SMA and PMC are considered "premotor" areas that project to the motor cortex, and are thought to contribute to the programming and organization of the motor cortex output (Penfield & Roberts as cited in Barlow, 1999). The PMC is more responsive to visual stimulation, and although it projects to the motor cortex, is thought to play a lesser role in speech production (Barlow, 1999), whereas the SMA has been suggested to be primarily involved in speech preparation and planning (Riecker et al., 2005).

One of the most recognized speech areas is Broca's area, located in the opercular and triangular portions of the inferior frontal gyrus, directly anterior to the area of the primary motor cortex involved in controlling the musculature of the face, tongue, and vocal folds (Bhatnagar, 2008). The left SMA is thought to program Broca's area, activating the motor cortex for propositional speech (Jonas, 1987). The exact role of Broca's area has been debated in the extant literature with suggestions of involvement in grammatical speech production (Meyer, Friederici, & von Cramon, 2000) and articulatory control (Blank, Scott, Murphy, Warburton, & Wise, 2002), with an unclear understanding of the role of Broca's area in motor speech production (Duncan & Owen, 2000). Furthermore, some studies suggest that Broca's area is only involved when there are linguistic components involved, as opposed to pure motor speech production (Murphy et al., 1997). Although Broca's area is possibly the most recognized cortical region for speech production, there are many additional areas that contribute to direct activation of motor speech.

Areas of the cingulate cortex have been suggested to be integral for central control of movement. Specific areas of the cingulate cortex that have been implicated for movement of the orofacial musculature include the rostral cingulate cortex and the anterior cingulate region (Barlow, 1999). Damage to the right anterior cingulate gyrus has been suggested to produce an inability to initiate speech (Chang, Lee, Lui, & Lai, 2007). Additionally, the anterior cingulate cortex has been shown to be vital in the production of vocalizations in subhuman primates and has been suggested to be involved in early human vocalizations including cry and laughter (Ackermann & Ziegler as cited in Ackermann, 2008). Thus, the cingulate cortex has been suggested to provide premotor input for the production of speech (Dum & Strick, 1993) and activation of the vocal pattern generator (Hage & Jürgens, 2006). Although major contributions to the production of speech come from the above cortical regions, contributions of subcortical regions are also imperative for coordinated motor output.

Contributions from Subcortical Areas

The descending speech motor pathway described above does not operate alone; rather motor speech production also involves co-input from subcortical areas. Subcortical areas identified in the production of speech include the thalamus (Murphy et al., 1997), the basal ganglia (Murdoch, 2001; Riecker et al., 2005), and the cerebellum (Ackermann, 2008; Guenther, 2006). The cerebellum and the basal ganglia are hypothesized to contribute to programming of skilled motor movement and the sequencing of motor events (Ackermann, 2008; Barlow, 1999), and are thought to perform complementary functions of programming (Dreher & Grafman as cited in Van der Merwe, 2009). The cerebellum and basal ganglia do not, however, directly innervate the MI, rather they project to the thalamus, which projects to the MI, PMC, and SMA.

The basal ganglia and the SMA are suggested to form a highly integrated system that is involved in the programming of complex motor movements (Martin, Phillips, Iansek, & Bradshaw, 1994). Outputs from the basal ganglia for speech primarily arise from the internal segment of the golbus pallidus (GPi) and the substantia nigra (Barlow, 1999). Association areas carry information from the SMA to the basal ganglia and information is sent from the basal ganglia to the SMA via the thalamus (Evarts & Wise as cited in Van der Merwe, 2009). Basal ganglia pathways have been shown to project to the venterolateral portion of the thalamus, which then projects to different regions of the cortex. The basal ganglia-thalamo-cortical (BGTC) pathway has been shown to project discrete channels from separate areas of the basal ganglia to the venterolateral portion of the thalamus to the MI, SMA, and PMA (Barlow, 1999). These discrete contributions to the cortex from the basal ganglia may result in different clinical manifestations of disturbance due to the precise location of lesion (Barlow, 1999). Disruption of the basal ganglia has been shown to disrupt initiation, synchronization, automatic production, and timing of speech (Van de

Merwe, 2009). Another subcortical area that contributes to the execution of speech is the cerebellum.

Ackermann (2008) suggested that the cerebellum has two major contributions to speech production; a) the temporal organization of speech motor control or sequencing of speech syllables and b) a prearticulatory verbal code for memory and internal speech. The cerebello-thalamo-cortical (CTC) pathway originates from several areas of the cerebellum including the deep cerebellar nuclei, the interpositus, and fastigial (Barlow, 1999). These areas of the cerebellum project to the PMC, MI, and prefrontal cortex via three areas of the thalamus, including the ventralis posterior lateralis oralis and portions of the venterolateral thalamus (Barlow, 1999). The cerebellum receives input from the periphery, the brainstem, and the cortex. This input allows for the motor comparisons and regulation of motor movements involved in the production of speech (Rose as cited in Van der Merwe, 2009). Speech involves precisely sequenced fine motor movements, and therefore disruption of the CTC pathway can result in ataxic speech (Ackermann, 2008; Bohland & Guenther, 2006; Riva, 1998).

The execution of motor speech involves input from the cortical and subcortical regions, which generate a motor program/plan that will be sent via the efferent corticobulbar pathway to the LMN. Inputs from the subcortical regions project primarily to the premotor areas via the thalamus; however, there is some evidence that subcortical efferents also project directly to the motor nuclei of the brainstem (Van der Merwe, 2009). This suggests that although the subcortical pathways primarily influence the cortical motor areas, they may have some direct influence on the LMNs.

Corticobulbar Tract

Muscle fibers are activated via the descending impulse from the MI to the motor neurons nuclei that originate in the brainstem. Axons of the descending speech pathway predominantly travel via the corticobulbar tract. These tracts begin in the cortex and as they descend, they converge from a fan-like formation of the corona radiata into a compact band known as the internal capsule, which consists of all fibers that ascend and descend to and from the cortex. The region of the internal capsule that has been mapped for corticobulbar fibers is the posterior limb close to the genu (Duffy, 2005). The tracts then descend to the level of the brainstem where some of the fibers in the corticobulbar tract will decussate (others will continue on the ipsilateral side) and innervate the cranial nerves. Damage to the descending tract produces different motor deficits dependent on the precise location of the insult. For instance, damage of fibers in the hemisphere may result in an isolated limb/facial paralysis, whereas damage in the internal capsule may result in widespread motor deficits (Duffy, 2005).

Descending inputs from suprabulbar structures form connections with LMNs in the brainstem, with the latter component constituting the “final common pathway” for motor execution. There are six cranial nerves that have significant LMN functions that regulate speech production. These bilaterally paired LMN pathways include the trigeminal (V), facial (VII), glossopharyngeal (IX), vagus (X), accessory (XI), and hypoglossal (XII) nerves (Duffy, 2005). Most of the cranial nerves that affect speech receive bilateral innervations from the cortex, with inputs to motoneurons mapped to the lower two-thirds of the face predominantly contralateral (Duffy, 2005). The motor divisions of the respective cranial nerves transmit efferent signals to subsets of muscle fibers and constitute the functional entity known as the motor unit which vary in size and are essential for finely graded force and smooth contractions for speech and other orofacial behaviors. Damage to any component of the motor unit results in flaccid paralysis (Webb & Adler, 2008).

Motor Speech Pathways

Ackermann (2008) proposed two cerebral networks of human sound production. The first network is exhibited in subhuman primates and infants in the production of laugh and cry vocalizations. These vocalizations are generated from the anterior cingulate gyrus and adjacent mesiofrontal areas via the periaqueductal gray and adjacent tegmentum to central pattern generators of the brainstem. Production of more complex speech encompasses a more extensive network including the premotor cortex, supplementary motor area, primary motor cortex, basal ganglia, cerebellum, and anterior insula. This network encompasses areas of the frontal lobes and cortico-subcortical loops in order to coordinate the nearly 100 muscles of fluent speech. Damage to the cerebellum has been suggested to severely compromise complex speech in this pathway due to its role in temporal organization of speech and sequencing the prearticulatory verbal code (Ackermann, 2008).

Overt speech control has been proposed to involve two circuits including the execution and preparation circuit (Riecker et al., 2005). Repetitions of syllable trains to an external stimulus revealed an execution circuit consisting of the sensorimotor cortex, basal ganglia, thalamus, and inferior cerebellum. The preparation circuit consisted of the SMA, left premotor area, anterior insular cortex, and superior parts of the cerebellum. The superior cerebellum was also observed in silent repetitions, suggesting that the superior cerebellum plays an integral role in preparation/initiation of overt speech. Increased activation was observed in the cerebellum with repetitions above 3 Hz, suggesting that cerebellar contributions of speech timing may be restricted to speaking above this rate. Damage to these networks or the cerebellum may result in altered speech production and sequencing abilities.

Auditory Feedback and Speech Production

As a fine motor system, speech is not only preformed with speed and accuracy, but quickly adapts in response to somatosensory and auditory feedback systems (Guenther, 2006). Although models have been created for the incorporation of feedback mechanisms into speech output, the exact processes involved in feedback and feedforward mechanisms are not fully understood. However, according to Van der Merwe (2009), “it is generally accepted that sensorimotor interaction is integral to movement control and that the brain uses feedforward and feedback information in a plastic and generative manner depending on the task demands or context of motor performance” (p. 5).

There are two models of motor speech control that developed out of observations that movements were controlled by peripheral reafferent information; however, following deafferentation, movements could still be performed (Van der Merwe, 2009). This led to two "schools" of speech motor control, one in which feedback is unessential (open-loop) and one where motor movements are constantly effected by feedback (closed loop). The closed loop consists of the effecter units, the feedback loop, and the comparator. The effecter unit is comprised of the oral/speech musculature, the feedback loop carries the information to the effecter units, and the comparator compares the speech output with the intended target. Whereas the open loop postulates that speech does not rely on feedback to have proper execution. The theory is based on a pre-wired nervous system program, in which the needed movements are selected from and carried out in a preordained fashion (Hall, Jordan, & Robin, 1993). Although the exact process is not understood, current research has indicated that the role of sensory feedback may be dependent on the experience of the speech motor system (Guenther, 2006).

It has been proposed that different modes of centrally generated and sensory feedback programs may exist, with motor learning primarily dependent on feedback and learned patterns dependent on centrally-generated patterns that are not reliant on sensory feedback. In a learned pattern the sensory feedback would be continually present but would only be necessary when the predictive model is challenged (Finocchio & Luschei as cited in Van der Merwe, 2009; Guenther, 2006; Jones & Munhall, 2003). One method of studying the impact of sensory feedback is to challenge a predictive model through externally evoked manipulations of sensory information. For the purposes of this paper, auditory feedback will be the focus; however, it is important to note that there are numerous studies concerning tactile feedback (e.g., Andreatta, Barlow, Biswas, & Finan, 1996; Estep & Barlow, 2007; Guenther, 2006**;** Johansson, Tulsson, Olsson, & Abbs, 1988; McClean, 1991).

Several studies have documented the role of auditory feedback on the production of speech through demonstrations of speech adaptation deficiencies in pre-lingual deaf persons or degradation of speech in post-lingual deaf speakers (Matthies et al., 2008; Ménard et al., 2007). In hearing populations, the masking of auditory feedback has been shown to decrease the ability to maintain pitch control in singers (Murbe, Pabst, Hofmann, & Sundberg, 2002). Adaptations of auditory pitch feedback have demonstrated that pitch-shifting results in compensatory strategies in pitch output to compensate for perturbations (Chen, Liu, Xu, & Larson, 2007; Donath, Natke, & Kalveram, 2002; Hain et al., 2000; Jones & Munhall, 2003; Larson et al., 2008; Liu & Larson, 2007; Shiller, Sato, Gracco, & Baum, 2009**;** Xu, Larson, Bauer, & Hain, 2004). These studies have lead to a model of sensory feedback that incorporates motor and auditory feedback into feedforward mechanism of speech production (Guenther, 2006).

According to Guenther (2006), speech production involves a feedforward control system that works in conjunction with a feedback system. This system is proposed to develop over time, with auditory feedback initially utilized to store an auditory target for the sound and to control production of the sounds in early repetitions. This occurs through updating or adjusting the feedforward command for the sound based on the auditory feedback. As the system matures, the feedforward system becomes more accurate in producing the target sound and the need for the feedback information becomes less vital and the auditory feedback control system is invoked less often, in part due to fine-tuned somatosensory feedback information. This model, called the Directions into Velocities of Articulator (DIVA) model also proposes that there are certain cortical areas that detect perturbations in the intended target sound and thereby attempt to correct via auditory or sensorimotor feedback information (Guenther, 2006).

According to the DIVA model (Guenther, 2006), projections from the speech sound map cells (left frontal operculum) to the auditory cortical areas contain the auditory target for the sound. When the speaker hears her/himself speak, the sound produced is compared with the auditory target. If the production is outside the accepted target region, the auditory error cells send corrective motor commands to the motor cortex. Studies comparing perturbed speech and unperturbed speech have indicated that these auditory error cells are located in the posterior superior temporal gyrus and planum temporale (Buchsbaum, Hickok, & Humphries, 2001; Guenther, 2006; Hickok, Buchsbaum, Humphries, & Muftuler, 2003). If the sound is within the target region then no auditory error will be detected and the auditory feedback system will not be activated. The auditory error cells can be invoked with imposed perturbations of the auditory information, which has been shown to generate corrective commands within 70 – 150 ms after the onset of the external perturbation (Tourville, Reilly, & Guenther, 2008).

Although speech production and auditory feedback studies are increasing, there is still relatively little research on the production of speech in children. Speech production has been shown to continue developing through early adulthood (Walsh & Smith, 2002). In order to understand the implication of external cueing for speech production in children with and without disabilities, the development of typical motor speech must first be considered.

Development of Speech Production

Speech production is a complex skill involving coordination of respiratory, laryngeal, pharyngeal, intraoral, and labiomandibular muscle systems. Furthermore, speech production requires mastery of a series of complex temporally precise movements (Tremblay, Houle, & Ostry, 2008). Speech production is an integral component of speech communication, as correct production of a phonetic repertoire helps to ensure intelligibility and communicate meaning. Although it is clear that speech communication involves more than just the motor processes of speech, the focus of this literature review will be on speech production, as opposed to development of language in speech communication.

In early development, anatomical constraints restrict sound production (Lester & Boukydis as cited in Lamb, Bornstein, & Teti, 2002; McLeod, 2007), limiting the infant to a range of sounds that are commonly produced in infants across many cultures (Locke, 1983). Maturation of the performance anatomy, coupled with experience, allows the child to increase sound repertoire, and by eight months of age, cultural differences in sound production can be perceived (Boysson-Bardies, Sagart, & Durand, 1984). Production of speech-like sounds begins as early as five to six months with babbling, progressing from seemingly random production of syllable-like sounds to repetition of one syllable by about eight months of age (Hulit & Howard, 2006). The production of canonical babbling, or the repetition of clear syllables, has been suggested to be an exhibition of the oromotor and timing characteristics required for production of consonants and vowels (Oller, 2000). Beginning around 10 months of age, children will produce more varied, or variegated babbling (Hulit & Howard, 2006). The exact relation of babbling to beginning speech production is debated (Hulit & Howard, 2006); however, from a neuroanatomical standpoint, there are suggestions that as the oral musculature and cortical connections develop, the ability to form and produce speech increases.

Changes in the first to second years of life are substantial. Development of the facial skeleton, along with the surrounding musculature, undergoes a massive amount of growth in early childhood (McLeod, 2007). Growth in the facial mask provides more space for manipulation of the tongue, and more possibilities for speech sounds including vowels. The peak of myelination also occurs in the first year of life, allowing for faster nerve impulse transmission (McLeod, 2007). During the first few years of life the brain establishes a large amount of neuronal connections between the different cortical areas, allowing for memory, attention, and learning. According to Colombo and Cheatham (2006), the integration of memory and attention systems occurs from 6 to 15 months of age due to maturation of the frontal circuitry. This integration allows for the development of endogenous attention, a function essential for learning. This coincides with the timeline of developmental progression from babbling to speech production. These factors, along with environmental exposure, provide the child with a basis for meaningful speech production. The motor production of speech also has a developmental timeline.

According to McLeod (2007), there is a large amount of variability in early speech learning both between children and within a child's own speech. For this reason, speech development milestones are often presented with a range of age acquisition. An example of the range of acquisition of typical speech developmental milestones is presented in Table 1. Within each child there is also reposted variability of speech production in an early age, most likely due to the process of motor learning. Young children 12 months – 24 months showed 17% – 59% interword variability (Vogel Sosa & Stoel-Gammon, 2006). From 21 months – 33 months, analysis of consonant-vowel-consonant words showed 60% at 21 months, declining to 19% at 33 months. As may be expected, as the brain and musculature develop there is less variability in production.

Acquisition of speech production does not end in the early years; in fact, speech production does not become adult-like until around eight years of age, when children typically have reached phonemic mastery (Sander, 1972). Acoustical studies have suggested, however, that speech motor control continues to develop until about 16 years of age (Smith & Goffman, 1998). This is perhaps due to the time involved in speech production system maturation, which ranges from six years (larynx) to 18 years (mandible) to reach adult size (McLeod, 2007). Further evidence of the protracted development of speech motor control has been shown through kinematic analysis of the oral musculature.

Table 1

Typical speech milestones adapted from the National Institute on Deafness and Other Communication Disorders (2000) and from Lust (2006)

Birth-1.5 months	• Child unable to control tongue, lip, and jaw muscles • Larynx not developed; high larynx • Displays primitive oromotor reflexes • Reflexive and vegetative sounds (i.e., crying, burping, grunts)
1.5-3 months	• Maturation of larynx and vocal tract • Does not yet suppress reflexive activity • Vocalizes pleasure and displeasure sounds • Makes noises when talked to • Demonstrates vocal play • Begins babbling
4 months	• Vocal play • Continues babbling
5 months	• Expansion, exploration of sounds • Playful use of sounds such as squealing and yelling • Attempts to imitate sounds • Elaborate productions of sounds possible
6-10 months	• Canonical babbling and reduplicated babbling • More adult-like timing develops • Babbling takes on characteristics of native language

10-12 months	• Variegated babbling, variation of consonant and vowel sounds • Greater variety of stress and intonation patterns • Babbling takes on even more characteristics of native language • Possible sound-meaning correspondence • Onset of first words
12-17 months	• Produces two to three words • Tries to imitate words
18-23 months	• Correctly produces bilabial consonants • Uses a wider variety of speech sounds • Says eight to ten words • Asks for common foods by name • Starting to combine words
2-3 years	• Says 40 words at 24 months • Uses two to three-word phrases • More accurate in speech production • May still drop ending consonants
3-4 years	• Uses most speech phonemes • May inaccurately produce more difficult phonemes • Produces consonants at beginning, middle and end of words • Produces sentences
4-5 years	• Vocabulary of 200 – 300 words • Speech is intelligible to most listeners • May produce errors in multisyllablic words
5+	• Vocabulary continues to grow • Can produce most speech phonemes • Speaks in full sentences

Green, Moore, Higashikawa, and Steeve (2000) studied the development of lip and jaw coordination in 1-year-old, 2-year-olds, 6-year-olds, and adults. Coordination underwent drastic changes in the first several years of life. One-year-olds demonstrated the greatest amount of jaw displacement and variability in motor pattern within the same speech task. Two-year-olds showed greater lip displacement (compared to one-year-olds) whereas jaw displacement decreased. This was suggested to be a result of increased jaw contribution to lip closure in the 1-year-old participants. The six-year-olds demonstrated more stability, similar to that seen in adults, however with more variability than observed in the adult population. The researchers suggested that in early speech prevalence of jaw movement, poor lip and jaw coupling, poor lip control, and poor movement independence may limit sound-producing capabilities. Other studies have indicated that the development of speech motor output continues into adolescence.

Walsh and Smith (2002) studied the oromotor variability of adolescents 12, 14, and 16 years of age while producing a short phrase. Results indicated that adolescents had higher movement variability than adults in their jaw, lower lip, and upper lip movement. Although there was less variability in the jaw than in the upper or lower lips, there were parallel decreases in variability across all three effectors with an increase in age. These results indicate that the coordination and stability of speech production continues to develop through adolescence. Development of speech motor control for simple versus more complex speech has also been studied across different age groups (Maner, Smith, & Grayson, 2000; Sadagopan & Smith, 2008).

Compared with adults, children have demonstrated higher variability in motor speech movements when asked to produce complex sentences (Maner, Smith, & Grayson, 2000; Sadagopan & Smith, 2008). Sadagopan and Smith (2008) studied speech variability in sentences with lower and higher cognitive demand in participants age five, seven, nine, twelve, fourteen, sixteen, and over twenty. Results showed that there was an increase in speech variability for higher demand sentences as late as sixteen years. This indicated that increasing cognitive/linguistic demands decrease movement stability in children and adolescents. These results could suggest that children with delayed cognition may require more cognitive demand for speech tasks, which may increase speech movement variability.

Treatment Methods for Motor Speech Deficits

The speech-language pathologist (also called a speech therapist) may provide oromotor treatment in order to improve oromotor strength. Exercises in oromotor treatment address all the different aspects of the oral musculature utilized in making speech sounds including the lips, tongue, jaw, and cheeks (Kumin, 2003). Specific exercises, foods, and props (such as musical instruments) are incorporated into each child's oromotor program (Kumin, 2003). Oromotor therapy may also incorporate oral massage and Beckman Facilitation Techniques (Beckman, 1997), which consist of 25 manipulations to the oral and facial tissue (as cited in Kumin, Von Hagel, & Bahr, 2001). Although oromotor therapy is common, some research has suggested that oromotor skills may not transfer to speech production skills (Bunton & Weismer, 1994; Clark, 2003; Forrest, 2002; Weismer, 2006), possibly due to differing cortical engagement (Moore & Ruark, 1996; Moore, Smith, & Ringel, 1988; Ruark & Moore, 1997). Therefore, practice of oromotor skills within speech production tasks, called articulation therapy, is often incorporated into therapy for children with speech disorders.

In traditional articulation therapy, specific sounds that a child has not mastered are practiced repetitively in the initial, middle, and ending position of words (Kumin, 2003). In this method, the children are first taught to identify the sound in words and then, through phonetic placement, will produce the sound (Kumin, 2003). According to Kumin (2003) this process is completed for each sound error that the child exhibits and, therefore, can be a slow and tedious form of therapy. Another approach involves categorization of production errors according to placement, manner, or voicing errors, which are then treated accordingly. This approach is based on generalization theory, that sounds learned will be generalized into other sounds that require that place, manner, or voice (Kumin, 2003). Additional forms of articulation therapy involve considering the phonological process patterns used by the child and sounds used in coarticulation patterns to promote success (Kumin, 2003). In addition to treatment techniques focused on articulation, techniques for improving speech rate may also improve intelligibility.

Rate cues are often provided to children with who have either a very fast or slow speech rate, for instance children with Down syndrome or speech apraxia (Kumin, 2003). Reduction in speech rate has been shown to reduce variability in speech in individuals who have dysarthria (McHenry, 2003) and Parkinson's (Helm, 1979), however, there is little research on the effect of rate cues on speech production in children. Speech pacing techniques for children include pacing boards, drum playing, singing a target phrase, auditory demonstration of rate, and play (Kumin, 2003). The pacing board is perhaps the most widely utilized pacing tool and combines a visual and tactile cue that can be used as a reminder of the number of words or can be used to pace syllables (Kumin, 2003). Another possibility for cuing the pace of speech is an external cue that utilizes properties of entrainment to engage a functional rate for speech production.

Facilitating Speech Production with External Stimuli

Rhythmic Entrainment

The neurological process that occurs in auditory rhythmic motor entrainment is not entirely understood. Research studies have shown that motor synchrony to an external auditory stimulus is quickly achieved and maintained, even with perturbations in the period of the stimulus that are below the level of conscious awareness (Thaut, Miller, & Schauer, 1998). When perturbations occur, the sensorimotor system responds with a temporary over-correcting for one to two cycles of movement, followed by re-synchronization (Thaut, Miller, & Schauer, 1998). Furthermore, evidence from these studies has shown that the synchronized motor movement precedes the actual stimulus. Thaut (2005) suggested that auditory rhythm provides a predictable template to which the motor system anticipates the occurrence of the stimuli, resulting in motor synchronization that precedes the stimuli, followed by correction of motor movement. Although studies have shown that motor synchronization is not only possible, but also precise, the exact neurobiological process involved in motor synchronization is not fully understood.

There are several theories about how rhythmic motor entrainment occurs in the brain. Stephan et al. (2002) utilized positron-emission tomography (PET) during an isochronous right-handed finger-tapping task to determine cortical areas involved in entrainment and found that there were no specific "entrainment" areas in the brain. Rather, widespread representation was evident with activation of the left primary sensorimotor areas, bilateral sensory association areas, right ventro-lateral prefrontal cortex, and bilateral opercular premotor areas. Subcortical areas including the contralateral insula, putamen, and thalamus were also activated, as were the right cerebellar anterior hemisphere and the right cerebellar vermis. Stephan et al. (2002) reported that only cerebellar and prefrontal areas differed from scans without auditory rhythm. These findings suggest that rhythmic entrainment does not occur in any specific cortical region; rather that temporal auditory information is somehow projected into the motor system.

Rhythmic entrainment is suggested to occur through direct projection to the motor system, beginning with the encoding of temporal information in the auditory system (Thaut, 2005). The pathway from the auditory cortex to the motor system has been debated, with suggestions that information transfers directly to motor areas (direct resonance) or that the auditory cortex contributes to entrainment via common thalamic projections shared with cortical motor areas (Thaut, 2005). Another theory involves the interaction with structures such as the basal ganglia or cerebellum in synchronization tasks (Thaut, 2005). Involvement of the basal ganglia and cerebellum has been debated due to the ability of persons who have basal ganglia or cerebellar disorders to synchronize motor movement to an auditory stimulus (e.g., Pilon, McIntosh, & Thaut, 1998; Thaut et al., 2001; Yorkston & Beukelman, 1981). These studies demonstrate that motor synchronization occurs despite damage to motor circuitry of the basal ganglia or cerebellum, which may suggest that motor entrainment could be beneficial as a treatment for children with motor regulation difficulties due to cerebellar hypoplasia. However, there are far fewer studies in the extant literature concerning the ability of children with and without disabilities to synchronize motor movement to an external auditory stimulus.

Although there is limited research on the ability for children to synchronize motor movements to an external auditory stimulus, there is a growing body of tactile motor synchronization research with premature infants. Oromotor entrainment to a mechanically evoked tactile rhythmic stimulus (called the NTrainer) has been successful in evoking perioral motor activity during non-nutritive suck (NNS) in premature infants (Barlow & Estep, 2006; Barlow, Finan, Chu, & Lee, 2008; Poore, Zimmerman, Barlow, Wang, & Gu, 2008). Suck is an ororhythmic motor behavior that is controlled by a central pattern generator (Barlow & Estep, 2006; Poore et al., 2008). The suck central pattern generator has been shown to phase-lock to peripheral tactile rhythmic inputs, consequently organizing NNS of term infants (Finan & Barlow, 1998) and infants who have endured orosensory deprivation (Barlow et al. 2006; Barlow et al., 2008). Rhythmic entrainment of NNS has been demonstrated not only to improve NNS sucking abilities, but also oral feeding abilities in preterm infants (Poore et al., 2008; Barlow et al., 2008). External stimulation has also been effective in entraining the respiratory central pattern generator in preterm infants (Barlow & Estep, 2006).

Entrainment of the respiratory central pattern generator in preterm infants has been shown with vestibular input. Infants rocked between 30 and 60 cycles per minute demonstrated strong respiratory entrainment (Sammon & Darnell, 1994). Infants who were greater than 35 weeks post-menstrual (PMA) age exhibited greater respiratory coherence. Respiratory entrainment has also been demonstrated utilizing an auditory/tactile stimulus. An external stimulation provided by a "breathing" teddy bear was shown to increase respiratory regularity in infants between 35 and 45 weeks PMA (Ingersoll & Thoman, 1994). These studies demonstrate that external entrainment of the respiratory CPG can be effective for changing CPG behavior. Motor synchronization abilities vary as children develop their perceptual motor abilities.

Studies on the ability for children to synchronize their motor movement to an external stimulus have shown that abilities increase with chronological development (Smoll, 1974a,b, 1975; Thomas & Moon, 1976; Volman & Geuze, 2000). Volman and Geuze (2000) found that seven-year-old children could perform at 77% accuracy in a synchronization task involving finger tapping to an external auditory stimulus. Eleven-year-olds performed at 98% accuracy for the same task. Although the seven-year-olds went "out of phase" more during the trials, they were still able to correct and maintain the task, suggesting that they were entrained to the stimulus, however, they required more corrections.

In a study by Mastrokalou and Hatziharistos (2007), children between the ages of six and nine performed a foot-tapping synchronization task at their preferred tempo, at a fast tempo (140 beats per minute [bpm]), and slow tempo (75 bpm). The results showed no difference in ability to synchronize motor behavior in the self-paced and faster paced tempo. However, children varied by age in the slow-tapping condition, where the older children performed better than the younger children. Poor synchronization at a slow tempo has been suggested to be due to the need for cognitive processing when the interval between the auditory stimuli becomes too large (Madison as cited in Mastrokalou & Hatziharistos, 2007). The finding that children better synchronize motor movement to a faster tempo has been supported in the extant literature (e.g., Kumai & Sugai, 1997; Rao, Mayer, & Harrington, 2001). This finding has also been demonstrated in motor synchronization to rhythmic visual cues.

Kumai and Sugai (1997) compared responses to different tempos and stimulus medium (auditory and visual) across three age groups including ages 3-4.5 (younger), 4.5-5.5 (middle), and 5.5-6 (older). Both auditory and visual stimuli were presented at a fast (100 bpm) and slow (50 bpm) tempo. Similar to Mastrokalou and Hatziharistos (2007), there were no differences in synchronization of finger tapping across ages at the faster tempo, however, children performed better as they matured for the slower tempo. Children from all age groups performed better in the auditory condition, compared to the visual condition, for both the fast and slow tempos. These studies suggest that an auditory stimulus, set to a faster tempo, may be better mediated by the motor system for auditory entrainment in children. However, there are few studies investigating the active synchronization abilities of children with disabilities in the extant literature.

Stedron (2004) studied the ability for adolescents with Down syndrome (DS) to synchronize motor movement to an external auditory stimulus at 109 beats per minute. The task involved synchronizing to the auditory tone for 12 beats (synchrony phase) and then continuing at the same pace for 30 additional repetitions without the auditory stimulus (continuation phase). Analyses were completed on the continuation phase only, and therefore no data on the ability to actively synchronize motor movements were presented. However, during the continuation phase the participants with DS were less accurate in reproducing the target interval than their typical peers. Furthermore, the children with DS showed greater variability in their timed motor movements.

Peter and Stoel-Gammon (2005) completed a similar study with children with apraxia of speech, ages four and nine. Children were asked to tap in synchrony with an auditory tone at 104, 132, and 160 beats per minute. Following 20 beats in-synchrony, the tone ceased and the children tapped for 30 additional beats without the tone. Again, data were only presented in the continuation phase. Children with apraxia showed higher variability and a greater amount of error in their motor movements. Tempo results were different within this study, with the younger child with apraxia performing less accurately on the fast-paced tempo than the slow paced tempo. However, it should be noted that the slow-paced tempo in this study was faster than the fast tempo in the Stedron (2004) study. Consistent with the extant literature was the ability to maintain motor synchrony to the stimulus with increased age. It should be noted, however that this study was comprised of only four participants, two with apraxia and two without apraxia. The small number of subjects could have produced an anomaly in the data. Although these studies provide some basic information, the ability for children with or without disabilities to synchronize oromotor movements to an external stimulus has not been researched in the extant literature.

Music Therapy Techniques for Speech Production

There are two Neurologic Music Therapy techniques that specifically address speech productions through external cues, (a) Rhythmic Speech Cueing and (b) Melodic Intonation Therapy. Rhythmic Speech Cueing (RSC) is a technique that uses an external auditory rhythm to control the rate of speech production (Thaut, 2005). This technique has been shown to be effective in rehabilitation of speech in persons with fluency disorder, dysarthria, ataxia, and apraxia (e.g., Pilon, McIntosh, & Thaut, 1998; Thaut et al., 2001; Yorkston & Beukelman, 1981). Rhythmic Speech Cueing relies on rhythmic motor entrainment to facilitate rate control of speech (Thaut, 2005). Although synchronization of speech production has been less researched than other motor behaviors, the principles of entrainment of the oral musculature are thought to be similar to entrainment of the limbs (Thaut, 2005).

Rhythmic Speech Cueing has not yet been studied with child populations; however, Melodic Intonation Therapy (MIT) has been studied with children who have apraxia of speech and Down syndrome. Melodic Intonation Therapy was originally a method developed to rehabilitate speech processes in patients who have suffered left hemisphere ablation following a cerebrovascular accident (Sparks & Holland, 1976). Since its implementation, several researchers have attempted to utilize the technique with children with apraxia; however, there are mixed reports of success with the technique (Krauss & Galloway, 1982; Helfrich-Miller, 1984; 1994; LaGasse, 2004). LaGasse (2004) found that following a five-week implementation period, children improved in their fluency, sentence length, and intelligibility utilizing a modified MIT technique. Rhythmic timing was more impacted than prosodic elements, suggesting that the rhythmic cues provided temporal information for organizing speech in children with apraxia. A comparison of rhythmic cues to melodic and rhythmic cues in MIT has also been completed within the extant literature.

Carroll (1996) compared rhythmic intoning of phrases with the MIT technique for improving utterance length in children with Down syndrome. Eight participants between the ages of three and six were assigned to the MIT or intoned-speech groups. Both groups improved in their ability to produce modeled utterances, with children in the MIT group showing greater improvements than the intoned-speech group. Carroll relates some of the observed gains to the use of motor tapping of syllables on a drum, but also reported that the children had inconsistent improvements despite rhythmic tapping. Furthermore, the author reports issues with compliance due to distractions in the different settings. One possible explanation for inconstant gains is the lack of an external timing cue in the MIT technique. Without a consistent external rhythmic cue, phrases may have been presented at differing tempos or may not have been predictable enough for the children to anticipate and respond appropriately. Although this study provides some evidence that rhythmic/melodic cueing may be beneficial for children with DS, further research is needed to better explore the effect of rhythmic cueing on speech.

Speech improvements based on external auditory cues would entail entrainment of speech production to a consistent external auditory stimulus. With the current scope of research, there is not enough evidence to conclude that children have the perceptual motor ability to synchronize oromotor movements to an external auditory cue. It would be misguided to suggest that the application of music in therapy with children who have speech production deficits only involves a rhythmic auditory stimulus; however, there is a need to investigate the use of rhythmic cues in order to better understand the effect of auditory entrainment of the labiomandibular system during speech production. Once the role of auditory entrainment is better understood, other elements such as melodic and structural cues can be investigated in addition to rhythmic stimuli.

In conclusion, there is no known research specific to the use of auditory entrainment principles for speech production in children. However, the presented evidence suggests that (a) children and early adolescents have the ability to entrain limb movements to an external auditory stimulus, (b) maturation of the motor system coincides with the ability to synchronize volitional movements to an external auditory cue, and (c) that the ability to entrain to an external auditory stimulus has been useful in the treatment of speech disorders in adults.

The purpose of this study was to examine the coordination of labiomandibular movements during speech production in children and adults to determine the effects of a rhythmic auditory stimulus on labiomandibular motor synchronization. The presented auditory stimulus may synchronize oromotor movement in children, increasing stability and timing of syllable repetitions. To this effect the following null hypotheses were tested: (a) there will be no difference in the ability for children and adults to synchronize labiomandibular movements to an external auditory stimulus, (b) there will be no difference in the ability to synchronize labiomandibular movement across age groups, and (c) there will be no difference in oromotor kinematics with and without an external rhythmic stimulus in children.

Chapter 3

Method

Participants

Twenty-seven participants were recruited for this study, of whom twenty-four successfully completed the research protocol. These participants included six children ages eight to eleven, six children ages twelve to fourteen, and twelve adults ages eighteen to thirty two. Characteristics of participants are represented in Table 2. Three participants were excluded from the study, one due to a learning disability, one due to a calculation error in the mean preferred tempo, and one due to obstruction of the necessary headplate markers. All participants were native English speakers. Participants were not chosen based on gender or ethnicity.

Table 2

Characteristics of Participants

Group	n	Mean Age	SD	Female	Male
Young Group	6	9.17	.753	3	3
Older Group	6	12.17	1.39	2	4
Adults	12	23.17	5.02	12	0

Inclusion criteria for all participants consisted of: (a) negative report of disability or speech delay, (b) the ability to participate and follow simple directions, and (c) hearing within normal ranges, as determined by an audiological assessment. Participants were recruited through flyers and word-of-mouth in Northern Colorado.

In order to determine eligibility for inclusion, a parent interview was conducted prior to the experimental session regarding the participant's speech and hearing abilities (Appendix A). Participants who met the inclusion criteria were then seen for a single experimental session, which lasted approximately 30 minutes. The experimental session was held at the Center for Biomedical Research in Music Motor Kinematics Lab in Fort Collins, Colorado. Before the study began, the participants were informed of the study's purpose and tasks. Participants were asked to give their verbal assent and their legal guardian was asked to review and sign a consent form. The proposal for this study and the consent form were approved by the Human Subject Committee, University of Kansas, Lawrence and the Institutional Review Board, Colorado State University, Fort Collins.

Materials

The audiological screening tool that was administered was a test of loudness utilizing the frequency that was played by the Boss® Dr. Beat (DB-88) metronome (250 Hz). The auditory entrainment stimulus during the experimental session was set at 60 dB from speakers located five feet in front of the participant. In order to ensure that the participants could hear the entrainment stimulus, an initial hearing test was competed. The metronome frequency was played and the participants were asked to indicate when they could hear the tone.

Motion Capture System

A Peak Motus (Peak Performance Technologies/Vicon Technologies version 9.0) digital four-dimensional motion capture system was used to record kinematics of the jaw, lower lip, and upper lip at 60 samples per second. The system consists of three Panasonic digital cameras (WV-CL350) and computerized software that constructs the view from each camera into a four-dimensional position of the reflective markers. The cameras were strategically placed around the experimental area and were directed at an angle that ensured video capture of the movement of the reflective markers placed on the participant's face. The special resolution of the markers was demonstrated as 16 ms in time and 0.1 mm in displacement by the Peak Motus analysis system.

Reflective Markers

Three hemispherical reflective markers that were 3mm in diameter (B&L Engineering) were used to track movement of the facial musculature. Markers were placed at midline on the vermilion border of the upper lip (UL) and lower lip (LL) and slightly inferior to the mental protuberance of the mandible (J). A rigid reference marker array (head marker) was placed on the participant's forehead. All markers were adhered with hypoallergenic double-sided tape. To ensure standardized placement, the head marker was centered at the nasion and placed 5 cm above the superior border of the orbits. Marker placement is illustrated in Figure 2.

Coordinate System

A consistent anatomical referent was created using a pre-defined calibration plate coordinate system. The calibration plate was 14" x 14" x 14" and included 30 points that were spaced in 5cm increments. The rigid head marker was the second pre-defined coordinate system and consisted of three markers. The calibration plate provided coordinates for calibrating the cameras and creating a three-dimensional space around the participant's head. As shown in Figure 2, the head marker has three points; upper left side (ULH), lower right side (LRH), and lower left side (LLH). A coordinate system was created with these markers as follows:

- Y (vertical) axis: line formed by ULH and LLH
- X (horizontal) axis: line formed by LRH and LLH
- Z (orthogonal) axis: orthogonal to the X and Y axis

The head plate coordinate system was utilized to track the position of the head during the speech trials.

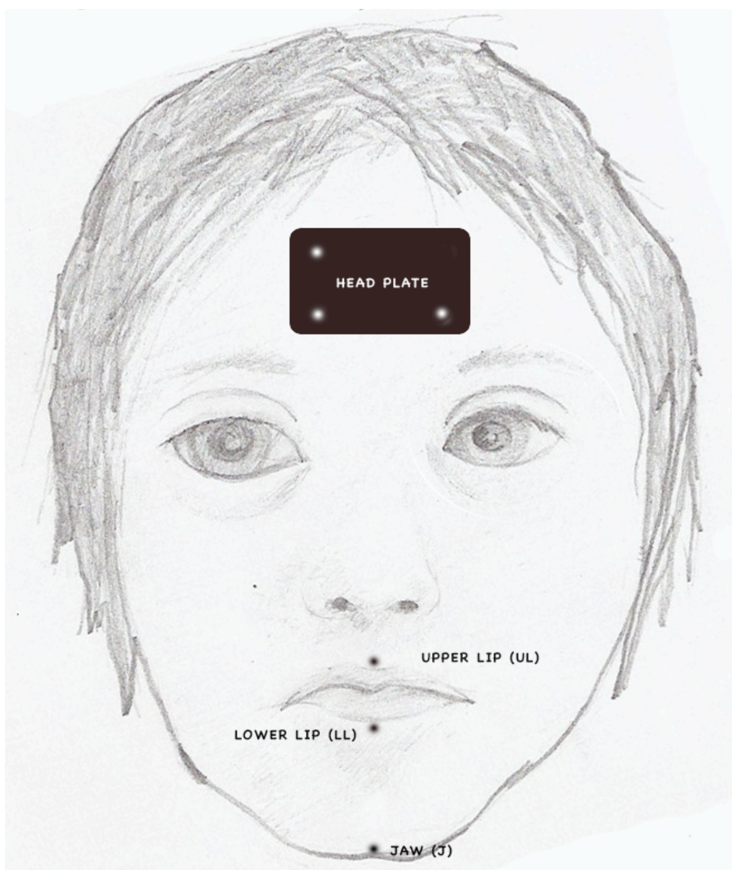


Figure 2. Placement of 3mm reflective markers on participant's face.

Auditory Entrainment Stimulus

The auditory entrainment stimulus was generated by a metronome (Boss® Dr. Beat DB 90 Talking Metronome) at the participant's self-generated (preferred) tempo and at 10% faster than the preferred tempo (which were referred to as the "fast" tempo). The stimulus was delivered though speakers (Bose® Companion 2 Series II Multimedia Speakers) at 60 dB, five feet in front of the participants. The auditory signal consisted of a metronome click that was presented without any accented beats. The auditory signal was captured through the Peak Performance system, which provided a visual marker of when the click occurred.

Procedure

Prior to participant involvement, calibration of the digital cameras was completed. Data collection was preceded by a period of familiarization for the child and legal guardian and placement of the reflective markers. Once all markers were placed, initial recordings were gathered to ensure all equipment was in working order.

For each condition, the participants produced eight sequential repetitions of the bilabial syllable "pa" in seven trials. The participants were provided breaks between every condition (seven syllable trains). This syllable was chosen because bilabials often occur early in speech (Green et al., 2000). Furthermore, this specific syllable has been used in speech kinematic studies in typically developing children across many ages (e.g., Green et al., 2000), which may be compared to data collected in the present study. The syllable was practiced for one set of seven repetitions before data recording began in order to ensure that the participant understood that they were to repeat the syllable. Participates were then instructed to repeat the syllable “pa” at a comfortable and steady pace, starting and stopping with the “stop” and “go” sign held by the researcher. Visual props were used to maintain a forward face position during all trials. In addition, participants received a five-minute break following each condition at which point they had access to water and musical instruments.

The participants were then asked to produce the syllable trains while exposed to an external auditory stimulus set at their preferred tempo and at 10% faster than their preferred tempo (“fast” tempo). A faster stimulus was chosen due to evidence in the extant literature that has indicated that children demonstrate better motor synchronize to a faster stimulus (Kumai & Sugai, 1997; Mastrokalou & Hatziharistos, 2007; Rao, Mayer, & Harrington, 2001). The participant’s preferred tempo was determined during the first condition (no rhythm). Preferred tempo was the average tempo observed in the no rhythm syllable trains (seven trains). Once their cadence was determined the participants were instructed that they would be listening to a metronome click and that they were to speak the syllable “on the beat”. The participants then listened to the metronome click three times before beginning.

Experimental Design

This study utilized a repeated measures design with the between factor of group (younger group, older group, adult), within-subject factor of entrainment condition (none, self-paced, fast), and dependent measures including the UL STI, LL STI, and J STI. The experimental design is outlined in Table 3.

Table 3

Depiction of experimental design, a repeated measure Analysis of Variance, where factor A is condition (entrainment vs. no entrainment) and Y is the STI score resulting from seven syllable trains

		Factor (Entrainment Condition)			
Group	Participant	No rhythm (a_1)	Preferred Tempo (a_2)	Fast (a_3)	Population Mean
A	p1	$STI_{1,1}$	$STI_{1,2}$	$STI_{1,3}$	μ_{p1}
(Child	p2	$STI_{2,1}$	$STI_{2,2}$	$STI_{2,3}$	μ_{p2}
8-10	p3	$STI_{3,1}$	$STI_{3,2}$	$STI_{3,3}$	μ_{p3}
years)	p4	$STI_{4,1}$	$STI_{4,2}$	$STI_{4,3}$	μ_{p4}
	p5	$STI_{5,1}$	$STI_{5,2}$	$STI_{5,3}$	μ_{p5}
	p6	$STI_{6,1}$	$STI_{6,2}$	$STI_{6,3}$	μ_{p6}
B	p1	$STI_{1,1}$	$STI_{1,2}$	$STI_{1,3}$	μ_{p1}
(Child	p2	$STI_{2,1}$	$STI_{2,2}$	$STI_{2,3}$	μ_{p2}
11-14	p3	$STI_{3,1}$	$STI_{3,2}$	$STI_{3,3}$	μ_{p3}
years)	p4	$STI_{4,1}$	$STI_{4,2}$	$STI_{4,3}$	μ_{p4}
	p5	$STI_{5,1}$	$STI_{5,2}$	$STI_{5,3}$	μ_{p5}
	p6	$STI_{6,1}$	$STI_{6,2}$	$STI_{6,3}$	μ_{p6}
C	p1	$STI_{1,1}$	$STI_{1,2}$	$STI_{1,3}$	μ_{p1}
(Adult)	p2	$STI_{2,1}$	$STI_{2,2}$	$STI_{2,3}$	μ_{p2}
	p3	$STI_{3,1}$	$STI_{3,2}$	$STI_{3,3}$	μ_{p3}
	p4	$STI_{4,1}$	$STI_{4,2}$	$STI_{4,3}$	μ_{p4}
	p5	$STI_{5,1}$	$STI_{5,2}$	$STI_{5,3}$	μ_{p5}
	p6	$STI_{6,1}$	$STI_{6,2}$	$STI_{6,3}$	μ_{p6}
	Condition Mean	μ_{a1}	μ_{a2}	μ_{a3}	μ_T

Data Analysis

Kinematic data were analyzed for the first through seventh syllable production in each trial. An analog trigger (manually pressed button) marked the beginning of each condition with a thick line appearing in the upper left boarder of the screen. This line created a precise marker on the three camera views that was used for temporal alignment and purposes of cropping and digitizing. The placement of the UL, LL (LL+J), and J markers were then traced in each frame (60 frames per second) from each camera view for each trial. Once the markers for each camera view were traced, the three views were triangulated into the three-dimensional model**.** This process was repeated for each condition with each participant (Figure 3a and b).

Following triangulation of the signals, the vertical positions (monoplanar) of the UL, LL, and J were extracted from the video recordings utilizing a computer-based movement-tracking system (Peak Motus, v. 9). The data were digitally low-pass filtered (f_{lp} = 6 Hz) utilizing the Butterworth filtering method. The data sets that were utilized to compute the STI included peak-to-peak amplitudes (vertical displacement) and segment distances for each syllable production. Segment distances were computed to identify when the UL and LL reflective markers had the least distance between them, signifying lip closure (Figure 4). Lip closure was utilized to mark the beginning and end of each trial of seven syllable repetitions. Peak-to-peak amplitudes were used to show the maximum change in the UL, LL+J, and J from closed lip position to open lip position during each production of the bilabial syllable.

Seven peak-to-peak amplitudes were generated for each syllable train (Figure 5). Data files were imported into MATLAB for further computations.

Figure 3a. Reflective markers placed on adult participant's face. From the bottom the markers are placed on the chin, lower lip, upper lip, and three are on the forehead.

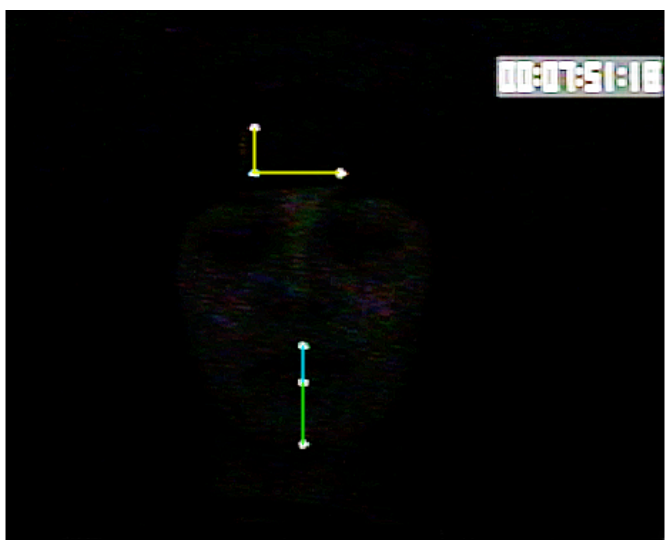


Figure 3b. Digital model superimposed on reflective markers showing segment distances.

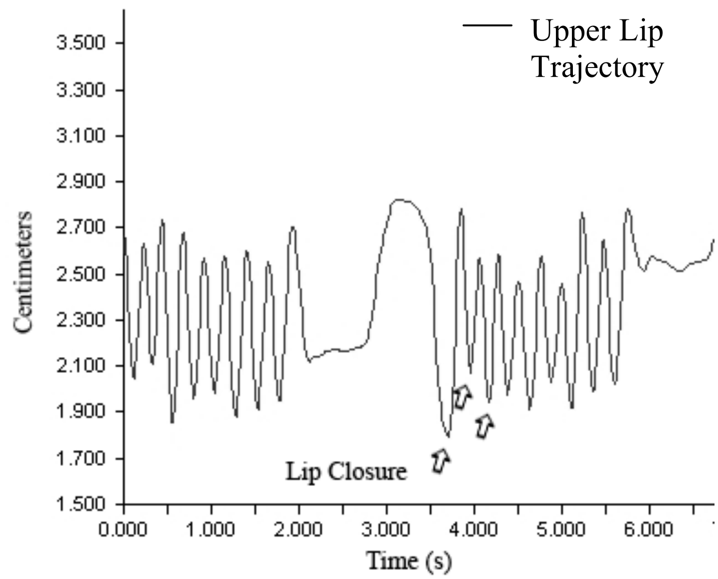


Figure 4. Example of segmental distances graph for syllable trains. Two syllable trains are displayed with arrows marking instances of lip closure in second train.

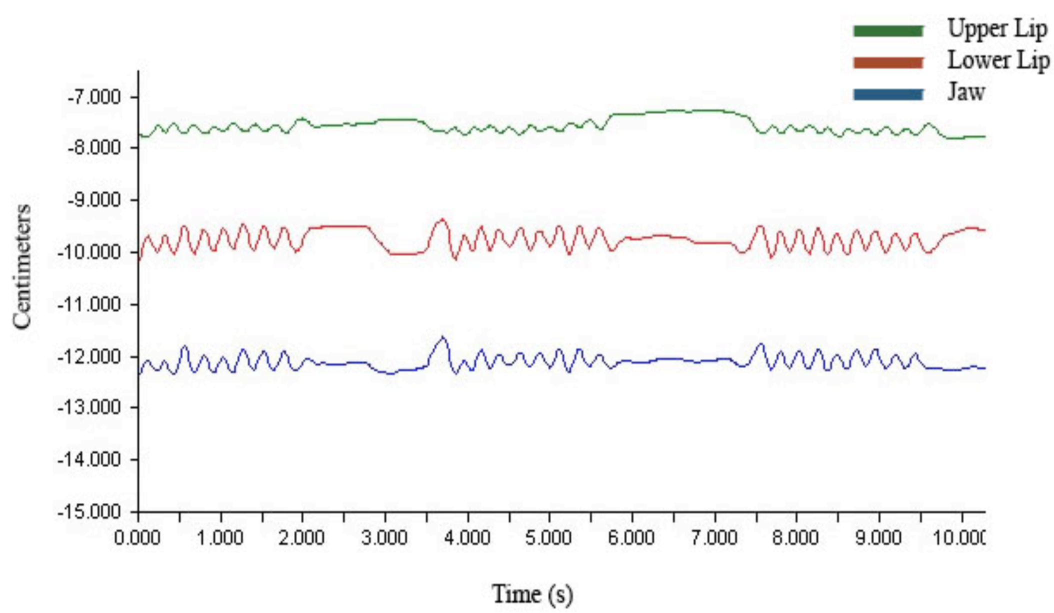


Figure 5. Lip marker trajectories indicating movement in Y axis.

In MATLAB, movement trajectories were computed from the monoplanar vertical displacement of the LL, UL, and J. In order to account for jaw contribution, the movement of LL displacement signals was subtracted from the J displacement signals (LL-J). Each syllable train was segmented beginning with the first lip closure and ending with the last lip closure. Following segmentation, the continuous displacement data were utilized to create the UL, LL, and J movement trajectories for each syllable train. The seven movement trajectories for each condition were then analyzed using the Spatiotemporal Index.

The movement trajectory stability (motor path from maximum open to closed position for each syllable repetition) of the UL, LL, and J with and without the external rhythmic stimulus was analyzed utilizing the Spatiotemporal Index (STI; Wang & Barlow, 2006). The result of the STI is a single-number index of UL, LL, and J pattern variability for each participant in each condition and has been utilized to determine lip movement stability in children (Sadagopan & Smith, 2008; Walsh & Smith, 2002). Once the UL, LL, and J trajectories of the seven syllable trains were computed, the trajectories were normalized based on linear reallocation, which projected the seven trajectories to one time scale (which were larger than the largest non-normalized data length) without altering displacement values of the UL, LL, and J. Therefore the data were taken from a time domain display to a normalized index sample domain for comparison purposes (Figures 6a and 6b). The resultant STI represents the cumulative sum of the standard deviations of the normalized UL, LL, and J syllable productions indexed for 200 samples.

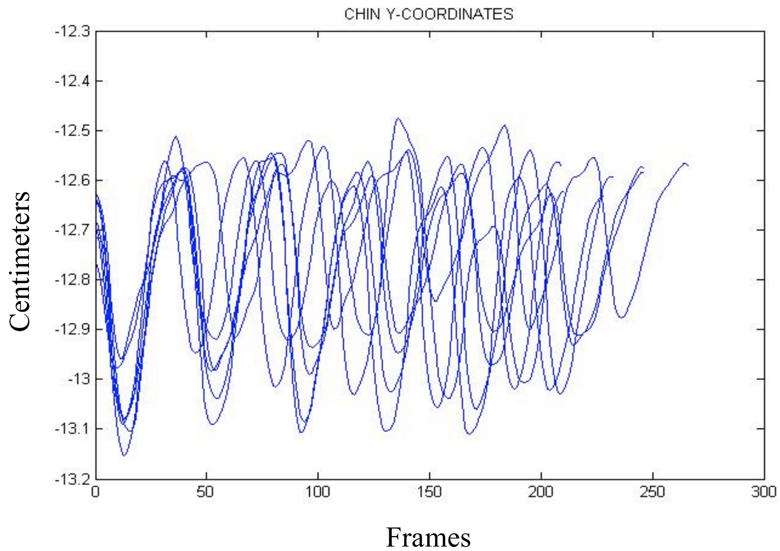


Figure 6a. Non-normalized graph depicting seven jaw trajectories of younger child.

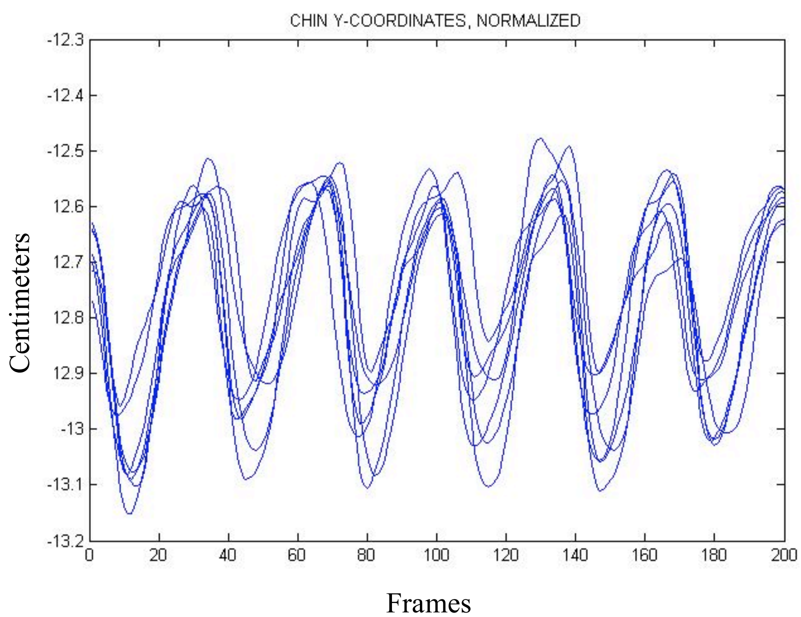


Figure 6b. Normalized graph depicting seven jaw trajectories of younger child.

Measures of entrainment were computed by comparing the auditory stimulus period to the movement trajectory of the UL and LL. The auditory stimulus period data was recorded (at 600 samples per second) and time stamped simultaneously with video samples in Peak Motus. Lip closure was determined for all seven repetitions of /pa/ in each syllable train by computing the distance between the non-normalized UL and LL marker trajectories, with the least distance signifying lip closure. The period of the auditory stimulus was then compared to the instance of lip closure in the entrainment conditions and a synchronization error (SE) was computed. The auditory stimulus is shown in Figure 7. The SE compares the phase of lip closure to the period of the auditory stimulus and determined phase deviation. Computations were completed in a program in MATLAB specifically designed to compute phase deviations in motor responses (Thaut, Miller, & Schauer, 1998).

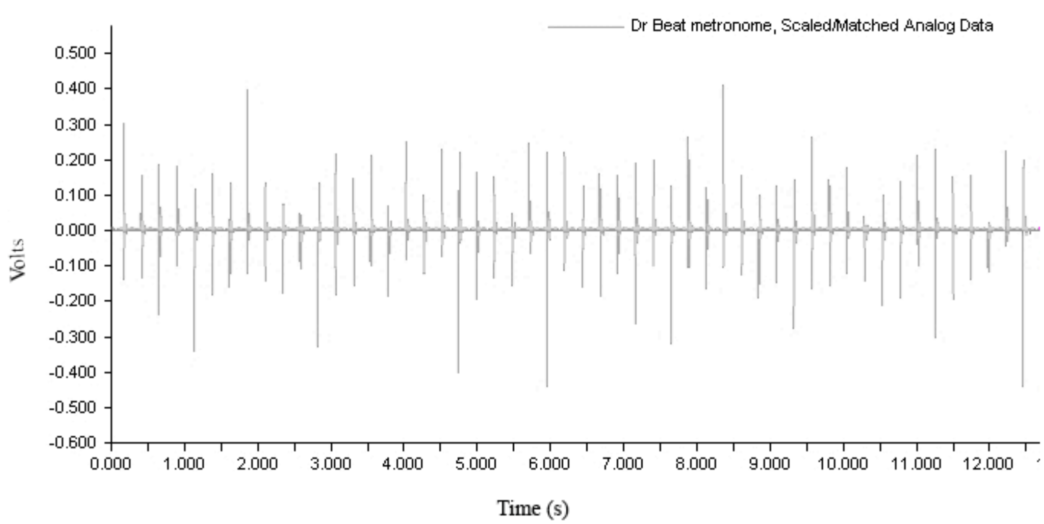


Figure 7. Example of external auditory stimulus analogue data.

In order to further evaluate potential oromotor entrainment response to the auditory stimulus, frequency ratio/phase polar plots were constructed for syllable trains in each condition. The procedures were outlined by Finan (1998) in an experiment that evaluated infant suck entrainment to an external stimulus. The phase plots were completed by creating a frequency ratio for each lip closure cycle concurrent with the stimulus period by dividing the lip closure response period by the external auditory stimulus period (in ms). The resultant number was multiplied by 100 in order to obtain a percentage. The angular phase was defined by the difference between the onset of lip closure response from the onset of the external auditory stimulus. This number was divided by the period of the external auditory stimulus and multiplied by 360 in order to obtain phase angles in degrees. Since MATLAB assumes radians for polar plot inputs, the phase angle value was converted to radians before the polar plots were created.

Chapter 4

Results

A repeated measures Analysis of Variance (ANOVA) was utilized to determine any main or interaction effects. The between factor of group (group), within-subject factors of entrainment condition (none, self-paced, fast) and position (UL, LL, J), and dependent measures including the upper lip (UL) Spatiotemporal Index (STI), lower lip (LL) STI, and jaw (J) STI were utilized in this model. The following effects were tested (a) main effect of condition (no entrainment vs. entrainment condition), (b) main effects for position (upper lip, lower lip, and jaw), (c) main effect of group (young, older, adult), (d) interaction effect between group and condition, (e) interaction effect between condition and position, (f) interaction effect between group and position, (g) interaction effect between position, condition and group.

To determine if motor synchronization occurred, the instance of lip closure was compared to the period of the auditory stimulus. Synchronization was derived from the synchronization error (SE) or phase deviation between lip closure and the stimulus event. Two of the conditions tested motor synchronization, each with seven trials that consisted of eight syllable repetitions. A repeated measures ANOVA was utilized to determine if there was a difference in the dependent measure of the SE for the (a) main effect of condition (self-paced vs. fast condition), (b) main effect of group (young, older, adult), and (c) interaction effect between group and condition.

Preferred Tempo

Each participant's preferred tempo was established in the no rhythm condition. Preferred tempos for all participants ranged from 70 beats per minute (bpm) to 249 bpm. The younger child group mean for preferred tempo was 108.33 bpm (SD = 27.81), the older child group mean was 108.67 bpm (SD = 26.73), and the adult group mean was 110.33 bpm (SD = 47.89). Histograms of preferred tempos are presented in Figures 8a and 8b.

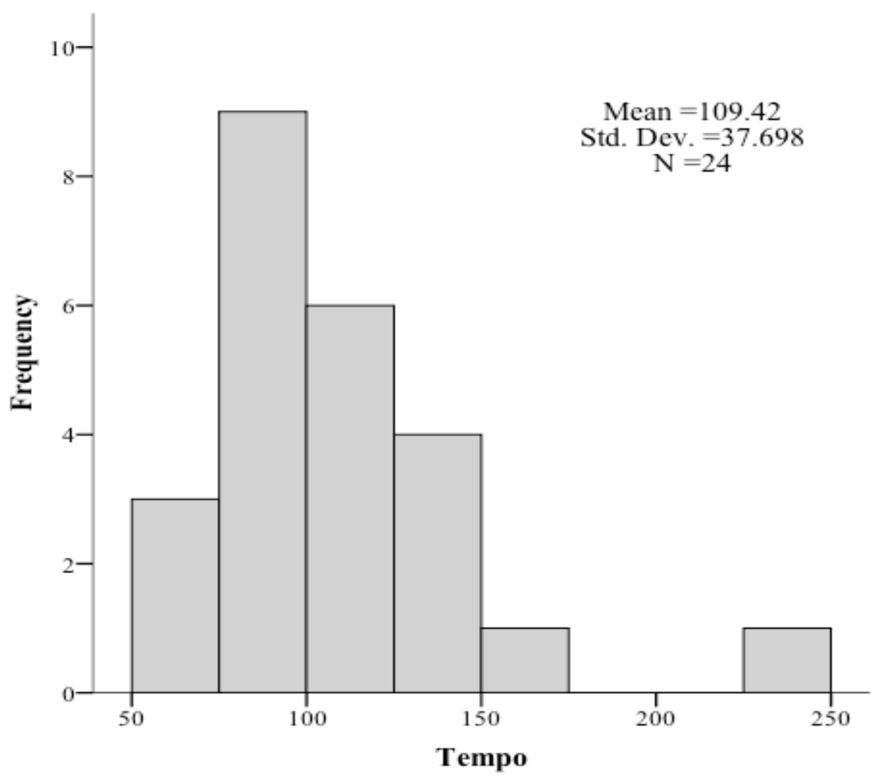


Figure 8a. Histogram of all participant's preferred tempos.

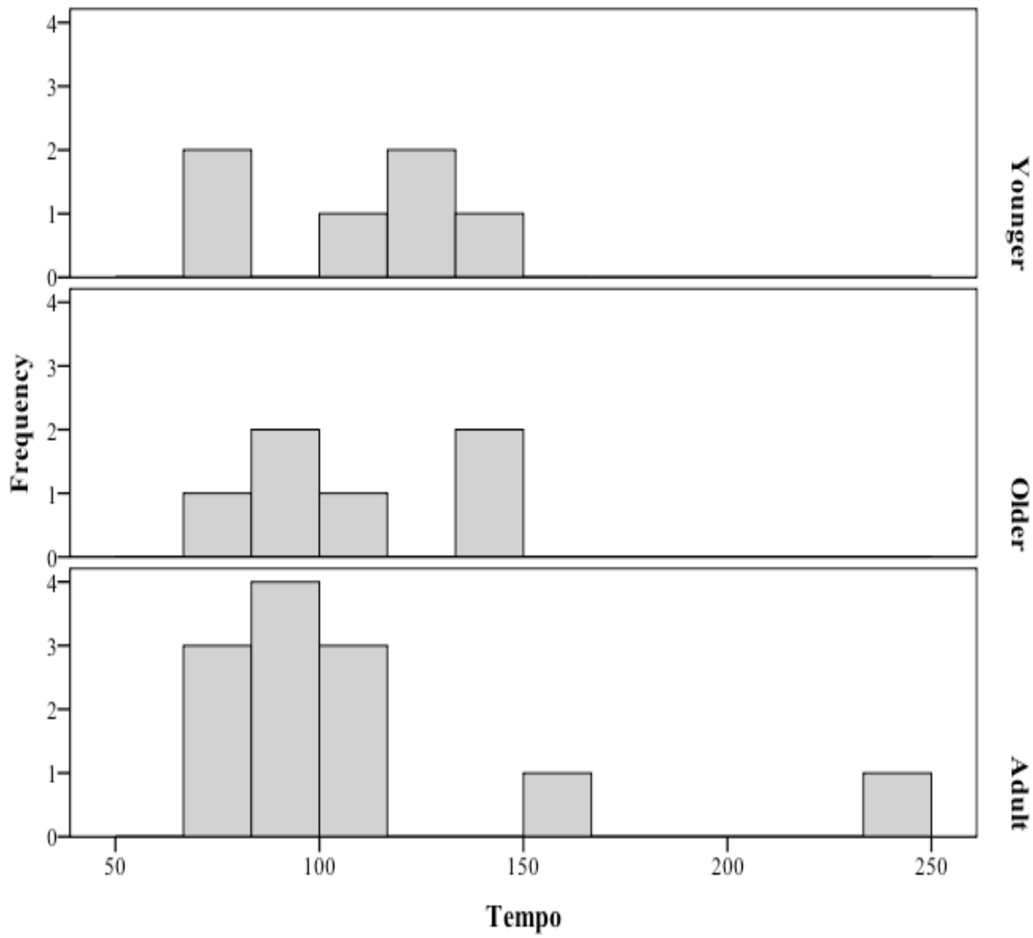


Figure 8b. Histograms of participant's preferred tempos by group.

Spatiotemporal Index Results

Figures 9a-9c display sets of time-normalized movement trajectories for seven productions of /pa/ for a member representative of each group. The STI scores are displayed with each trajectory. The mean scores and standard deviations of the STIs for UL, LL, and J collected for each condition are presented in Tables 4 - 6. Upper lip means are presented in Table 4 and Figure 10, lower lip means are presented in Table 5 and Figure 11, and jaw means are presented in Table 6 and Figure 12. Visual inspection of mean scores revealed that there were small differences in the STI with an increased STI value in the self-paced condition and a decreased value for the fast condition. This indicates that motor movements became less stable with the self-paced entrainment condition.

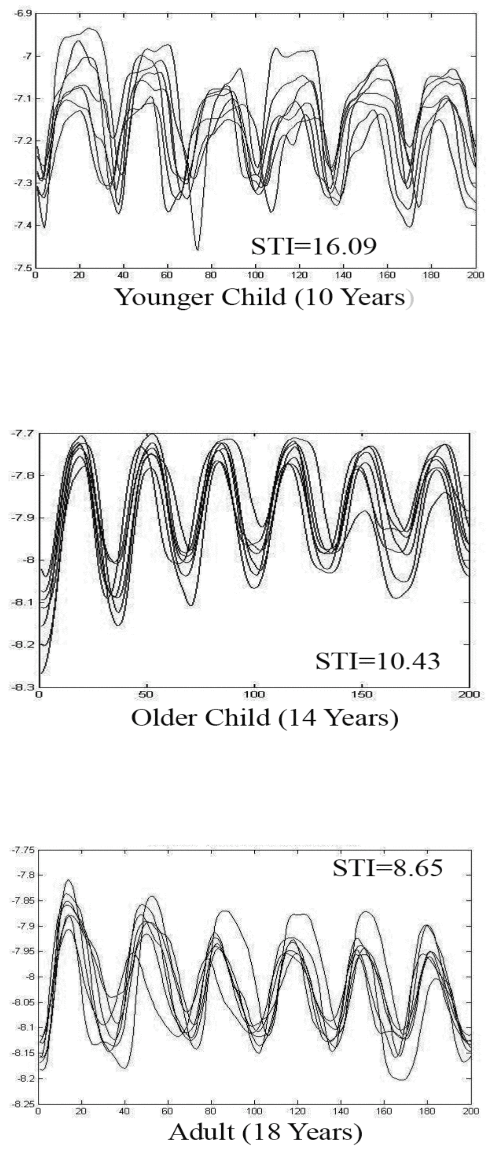


Figure 9a. Motor trajectories of the upper lip for representatives of each group.

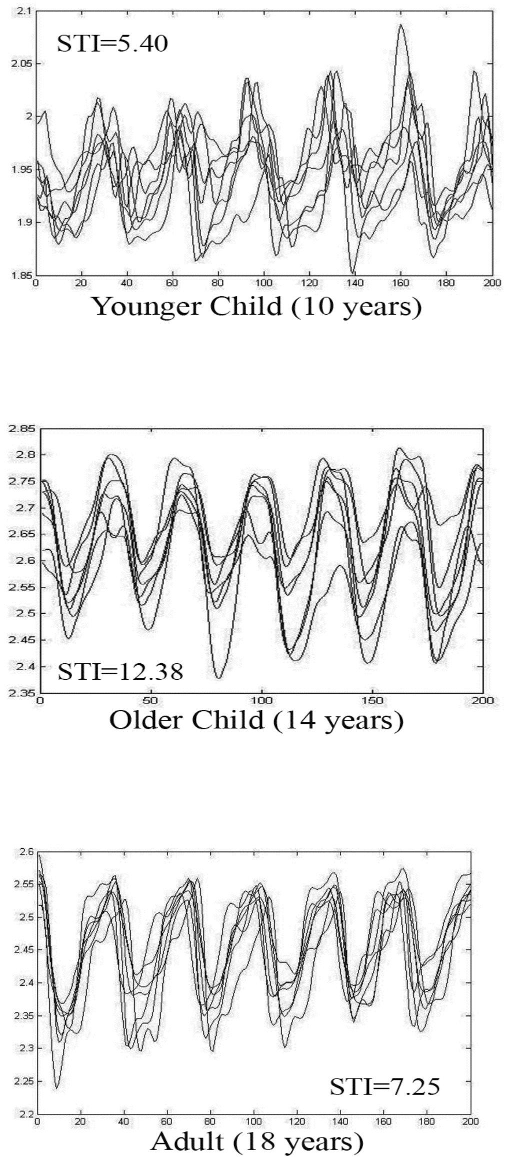


Figure 9b. Motor trajectories of the lower lip for representatives of each group.

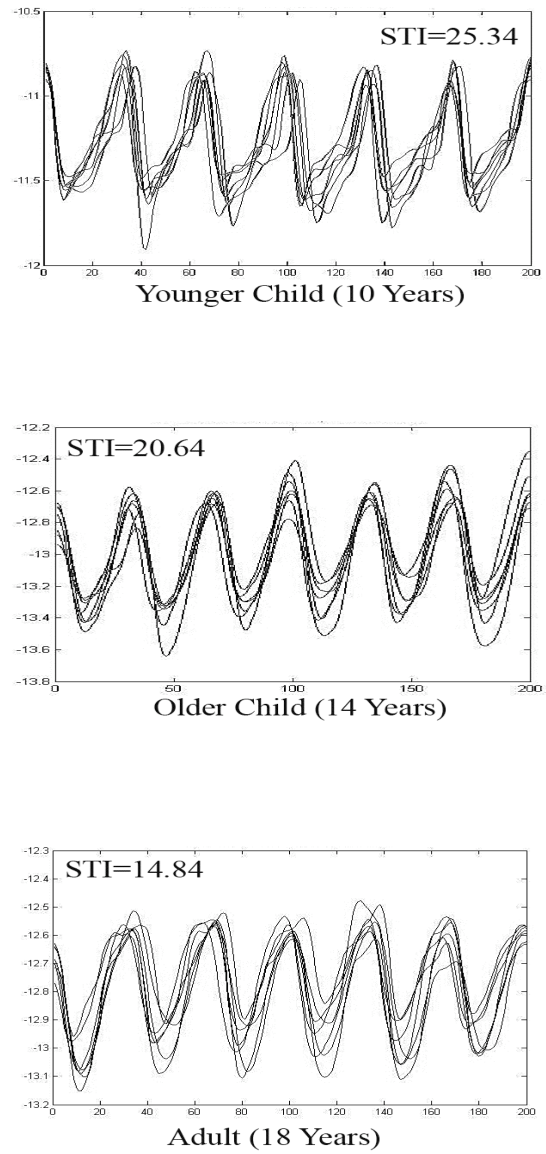


Figure 9c. Motor trajectories of the jaw for representatives of each group.

Table 4

Mean Scores and Standard Deviations of Spatiotemporal Index of Upper Lip

	Younger		Older		Adult	
Condition	M	SD	M	SD	M	SD
No rhythm	12.29	3.62	12.66	5.32	15.09	11.03
Self-paced	14.99	5.05	14.46	6.54	14.33	8.54
Fast	14.23	3.49	12.03	2.43	12.99	9.66

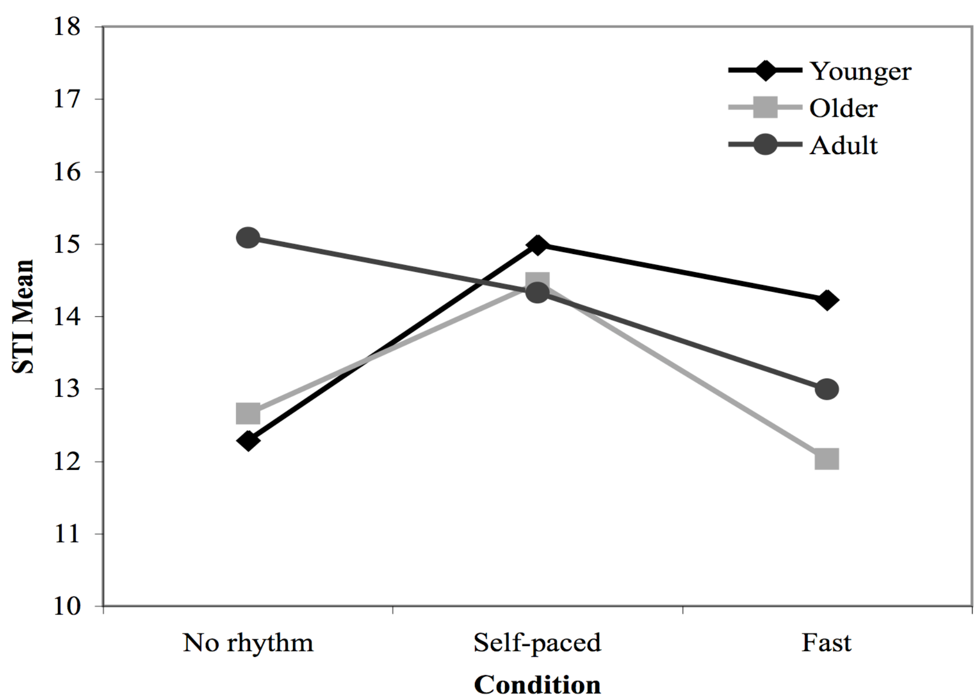


Figure 10. Upper lip Spatiotemporal Index means.

Table 5

Mean Scores and Standard Deviations of Spatiotemporal Index of Lower Lip

	Younger		Older		Adult	
Condition	M	SD	M	SD	M	SD
No rhythm	9.40	3.19	11.00	5.9	10.24	7.84
Self-paced	12.27	6.00	12.97	7.83	10.59	7.75
Fast	11.44	4.59	11.84	7.42	9.73	7.91

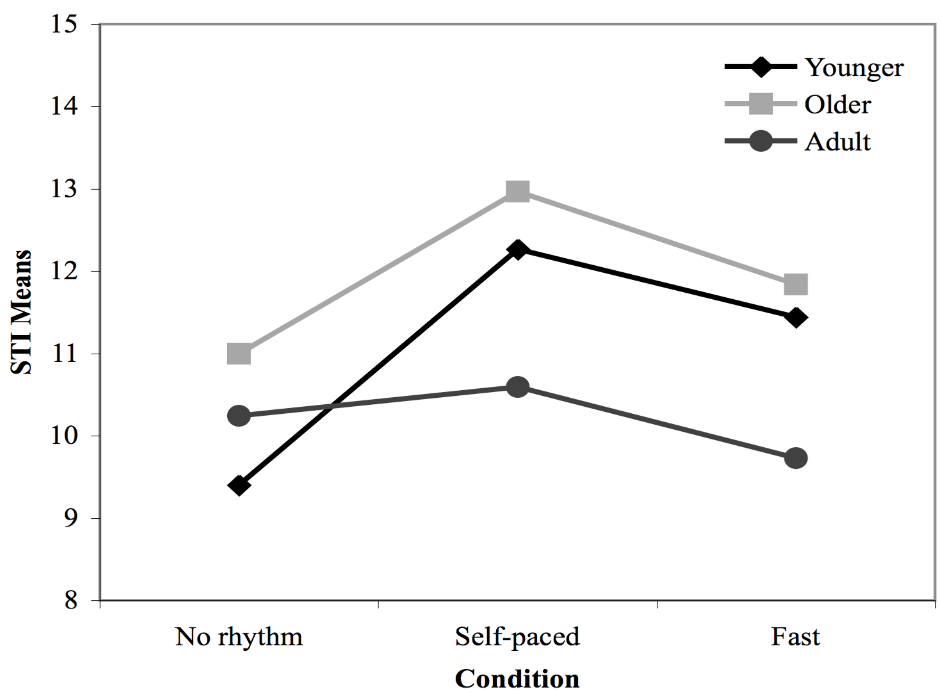


Figure 11. Lower lip Spatiotemporal Index means.

Table 6

Mean Scores and Standard Deviations of Spatiotemporal Index of Jaw

	Younger		Older		Adult	
Condition	M	SD	M	SD	M	SD
No rhythm	25.83	6.50	26.42	12.10	20.51	26.6
Self-paced	30.75	8.81	28.60	22.55	25.17	11.23
Fast	28.45	9.45	25.67	15.60	20.61	9.99

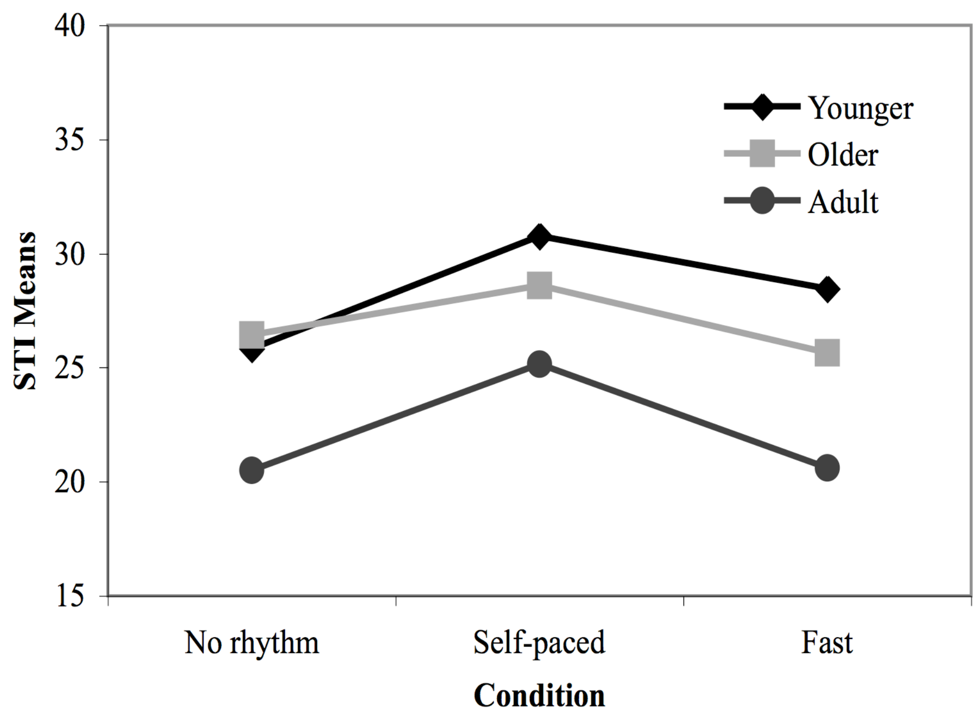


Figure 12. Jaw Spatiotemporal Index means.

The results of a repeated measures ANOVA indicated a violation of sphericity and therefore the Greenhouse-Geisser correction was applied for all reported STI value results. A repeated measures ANOVA for the STI scores indicated that there were significant effects at the .05 level of confidence for the main effects of position $F(2, 42) = 44.102$, $p = .001$, and condition $F(2, 42) = 4.182$, $p = .032$. There were no significant interaction effects observed between condition and group $F(4, 42) = .628$, $p > .05$, between position and condition $F(2, 42) = 1.07$, $p > .05$, or between position, condition and group $F(8, 84) = .379$, $p > .05$, indicating that there were no significant interaction effects between the STI means and the independent variables (Table 7).

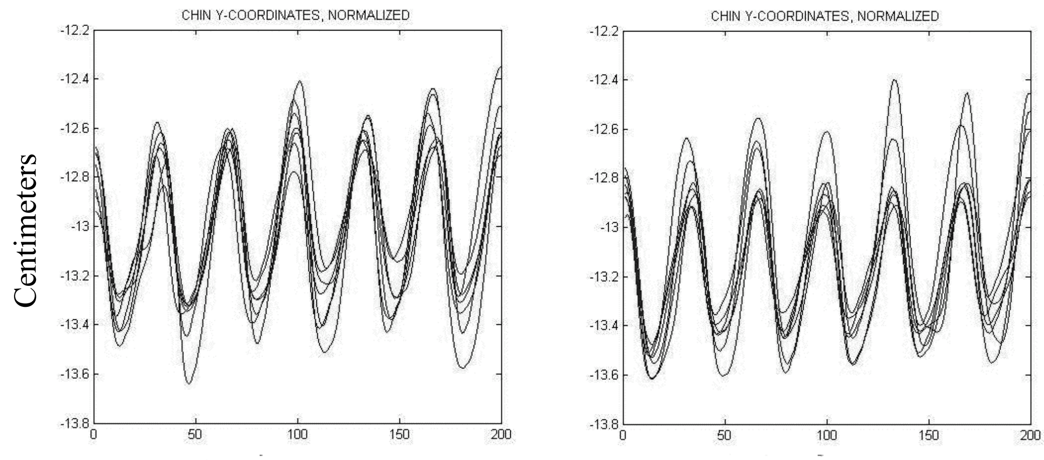
The significant main effects were evaluated with Post-hoc comparisons. Results of dependent *t*-tests for condition indicated that there was a significant difference between condition one (no rhythm) and condition two (self-paced rhythm), $t = -2.35$, $p = .02$. Examples of movement trajectories for the no rhythm condition and the self-paced rhythm condition in the older child age group are displayed in Figures 13a and 13b. Results of *t*-tests for position indicated that there were significant differences between the STI values for the jaw and lower lip, $t = 17.93$, $p = .001$, the jaw and upper lip, $t = 12.52$, $p = .001$, and the lower lip and upper lip $t = -5.42$, $p = .001$.

Table 7

Repeated Measures ANOVA table for Within Subjects Dependent Measures of STI Values, Independent Measure of Condition, and Between Subjects Measure of Group

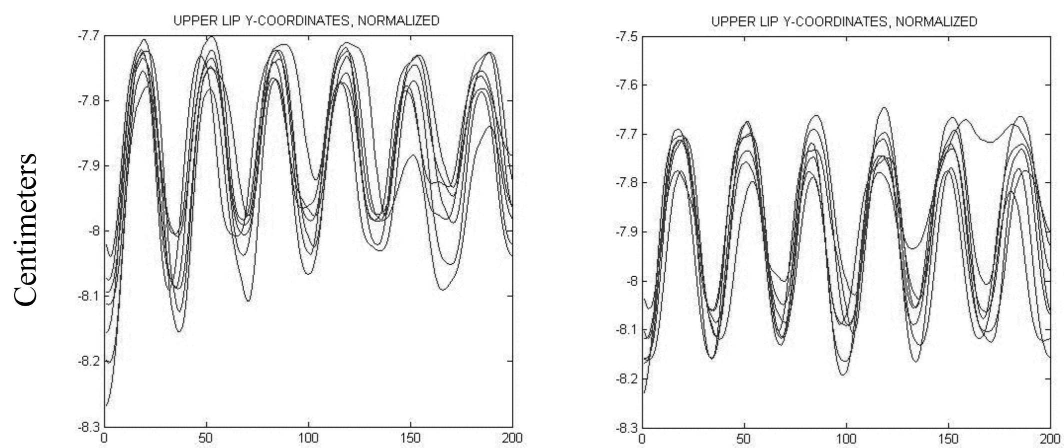
Source	ss	df	MS	F	Sig.
Between Subjects					
Group	231.064	2	115.532	0.246	0.784
Error	9846.42	21	468.87		
Within Subjects					
Position	7996.65	1.166	6860.18	44.102	.000*
Position x Group	388.55	2.331	166.66	1.07	0.367
Error (position)	3807.754	24.48	155.55		
Condition	195.53	1.58	123.86	4.182	0.032*
Condition x Group	58.73	3.157	18.6	0.628	0.61
Error (condition)	981.765	33.153	29.613		
Position x condition	55.05	2.125	25.9	1.23	0.303
Position x Condition x Group	33.926	4.249	7.984	0.379	0.833
Error (position x Condition)	939.02	44.62	21.05		

* $p<.05$



No Rhythm Self-Paced Stimulus

Figure 13a. Example of jaw trajectory with and without external cueing.



No Rhythm Self-Paced Stimulus

Figure 13b. Example of upper lip trajectory with and without external cueing.

Synchronization Error

The mean synchronization error (in milliseconds) and standard deviations are presented in Table 8. Synchronization errors between the onset of the auditory stimulus and the instance of lip closure for the self paced condition showed a mean value of -105.66 ms (SD = 43.5) for the younger child group, a mean value of -62.62 ms (SD = 44.94) for the older child group, and a mean of -77.9 ms (SD = 57.92) for the adult group. Synchronization errors for the fast condition showed a mean value of -101.98 ms (SD = 44.86) for the younger child group, a mean value of -72.26 ms (SD = 39.89) for the older child group, and a mean of -57.11 ms (SD = 105.73) for the adult group. An example of the mean SE for one participant is displayed in Figure 14.

Table 8

Means and Standard Deviations of Synchronization Error in Milliseconds

	Younger		Older		Adult	
Condition	M	SD	M	SD	M	SD
Self-paced	-105.66	43.50	-62.62	44.94	-77.9	57.92
Fast	-101.98	44.86	-72.26	39.89	-57.11	105.73

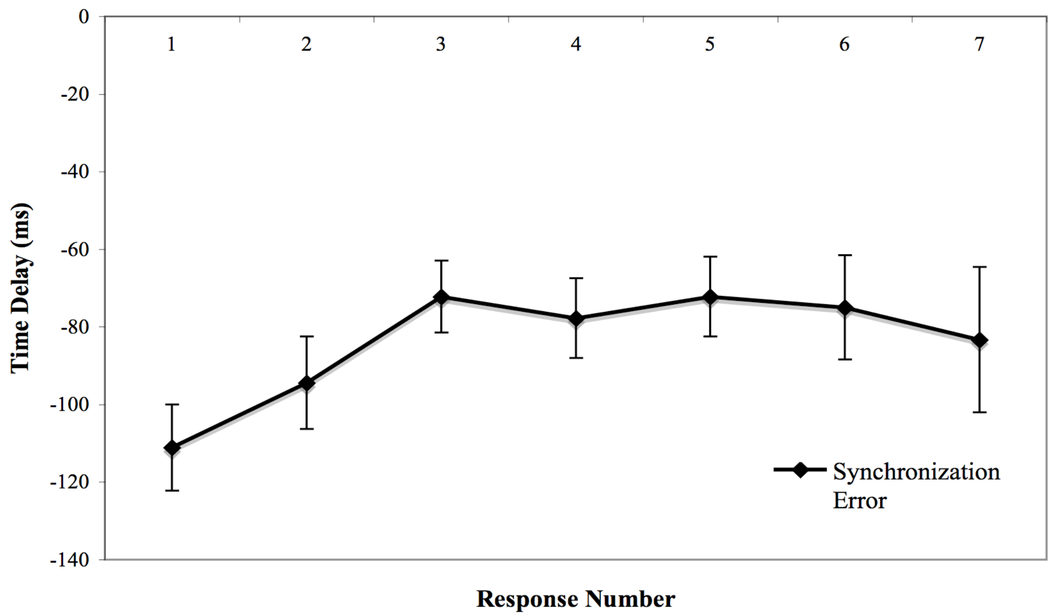


Figure 14. Example of synchronization errors for an adult participant.

A repeated measures ANOVA completed for SE indicated that there were no significant main effects for condition $F(1, 20) = .021$, $p > .05$, no significant main effects for group $F(2, 21) = 1.305$, $p > .05$, and no significant interaction effects between condition and group $F(2, 20) = .139$, $p > .05$. These results suggest that there was no significant difference in the SE of younger children, older children, and adults (Table 9).

The data show that group means both preceded and succeeded the auditory stimulus, which could create an error due to the occurrence of the response (i.e., the mean of -22 and 22 is 0, although the errors are the same size in different directions). In order to account for SEs that were either preceded or succeeded the auditory stimulus, all SE means within trials were transformed into positive integers so that the

SE could be compared regardless of the direction of the error. The adjusted means for the groups are displayed in Table 10.

A repeated measures ANOVA performed on the adjusted SE data indicated that there were no significant main effects for condition $F(1,20) = .084$, $p > .05$, no significant main effects for group $F(2,20) = .806$, $p > .05$, and no significant interaction effects between condition and group $F(2, 20) = .426$, $p > .05$. These results further suggest that there were no significant differences in the synchronization errors of younger children, older children, and adults.

Table 9

Repeated measures ANOVA for Synchronization Error

Source		ss	df	MS	F	Sig.
Between Subjects						
	Group	13357.27	2	6678.641	1.305	0.292
	Error	107494.669	21	5118.8		
Within Subjects						
	Condition	88.64	1	88.64	0.021	0.887
	Condition x Group	1188.48	2	594.24	0.139	0.871
	Error	89951.16	21	4283.39		

Table 10

Means and Standard Deviations of Synchronization Error Re-Calculated as Positive Integers in Milliseconds

	Younger		Older		Adult	
Condition	M	SD	M	SD	M	SD
Self-paced	107.47	40.40	71.35	26.35	97.85	38.53
Fast	101.98	44.86	73.05	39.09	114.16	53.14

Inter-Response-Interval

The inter-stimulus-interval (ISI) and inter-response-interval (IRI) were compared to further determine synchronization. The ISI is the time (in ms) between stimuli. The IRI is the time (in ms) between the occurrences of lip closure. The IRI mean for each trial was calculated and the overall mean was compared with the ISI (which was a steady stimulus). The error was computed according to methods utilized by Kumai & Sugai (1997), where the mean IRI was subtracted from the ISI to determine the mean IRI error, or period error. The mean period errors for participants are displayed in Table 11. A comparison of the IRI error and the SE for the same participant's averaged "fast" trials are displayed in Figure 15a and 15b.

Table 11

Inter-Response-Interval Error Means in Milliseconds for All Groups

	Younger		Older		Adult	
Condition	M	SD	M	SD	M	SD
Self-paced	24.67	8.71	13.14	4.02	15.12	10.83
Fast	10.78	2.99	8.44	2.31	16.61	15.42

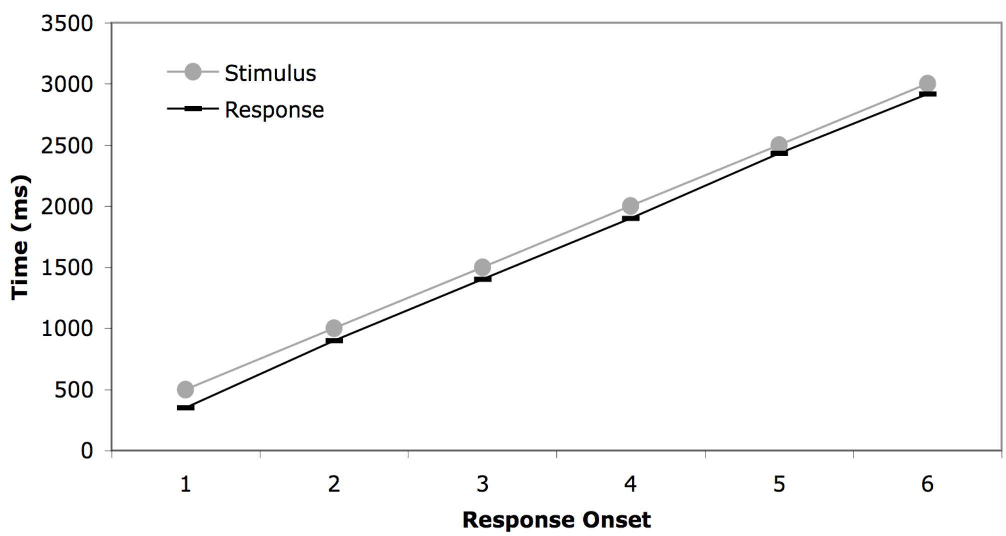


Figure 15a. Illustration of Synchronization Error (stimulus and response onset) for an adult participant.

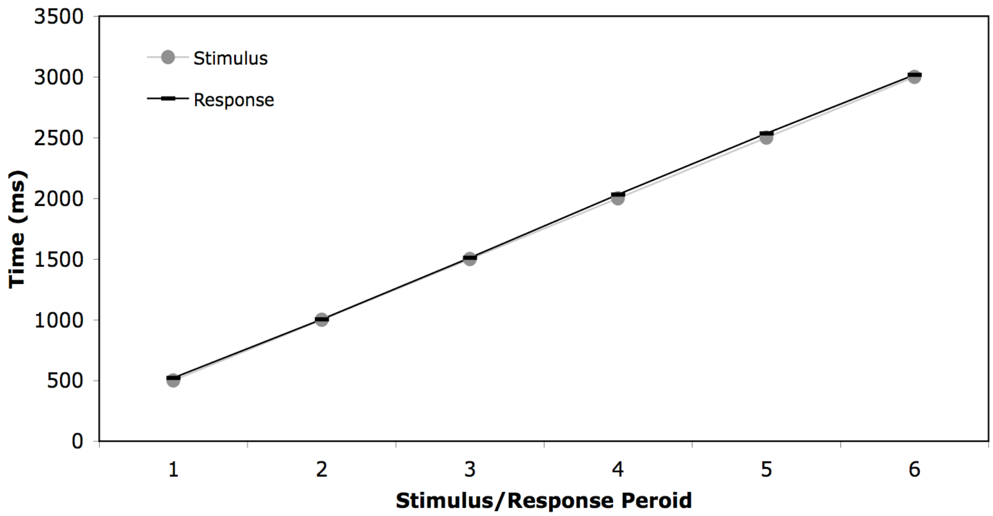


Figure 15b. Illustration of stimulus period and response period for an adult participant.

A repeated measures ANOVA performed on inter-response-interval data indicated that there were no significant main effects for condition $F(1,21) = .661$, $p > .05$, no significant main effects for group $F(2,21) = .941$, $p > .05$, and no significant interaction effects between condition and group $F(2, 21) = .555$, $p > .05$. These results further suggest that there was no significant difference in the synchronization strategies of younger children, older children, and adults.

Further Evidence of Entrainment

According to Finan (1998), "For the polar plots, frequency ratio corresponds to the radius and phase angle represents azimuth (circumference). Harmonic entrainment (1:1 relationship between stimulus cycles and [response cycles]) is evidenced by a grouping of the data points near the 100% frequency ratio radius and a restricted phase angle range" (p. 54). Polar plots demonstrating synchrony (several points close to the 100% frequency) are displayed in Figure 16. Since participants tapped ahead of the stimulus (i.e., the motor response preceded the stimulus by -X ms), the values displayed in the polar plots are negative. A polar plot of a response period that post-ceded the external cue is displayed in Figure 17. An example of a response period that did not appear to maintain synchrony is displayed in Figure 18. An example of a response period that appeared to be syncopated (occurring on the off-beat) is displayed in Figure 19.

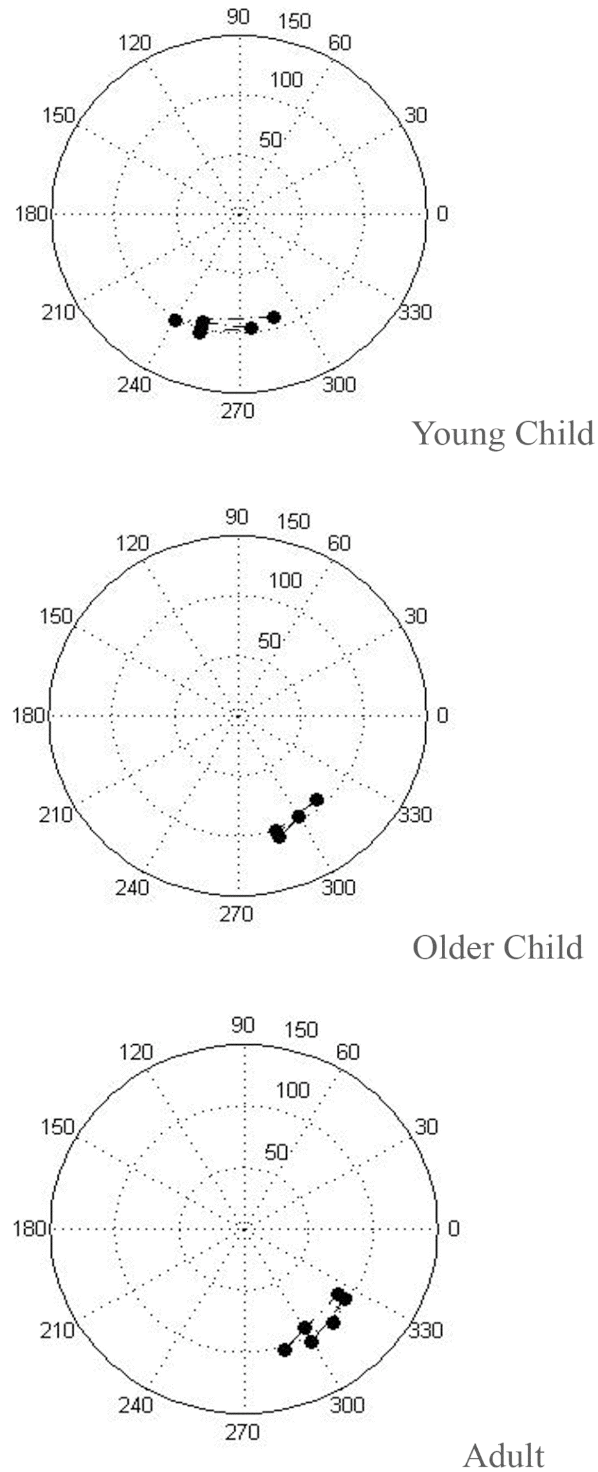


Figure 16. Polar plots representing synchrony (anticipatory response) in all groups.

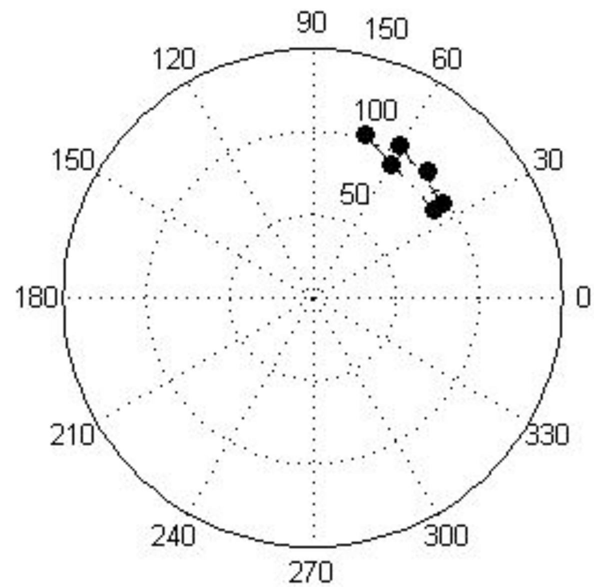


Figure 17. Polar plot depicting post-stimulus synchrony.

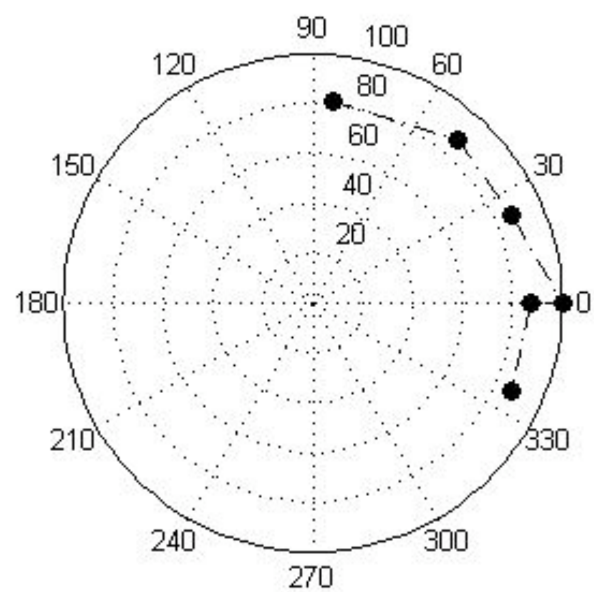


Figure 18. Polar plot suggestive of response "drifting" or non-synchrony.

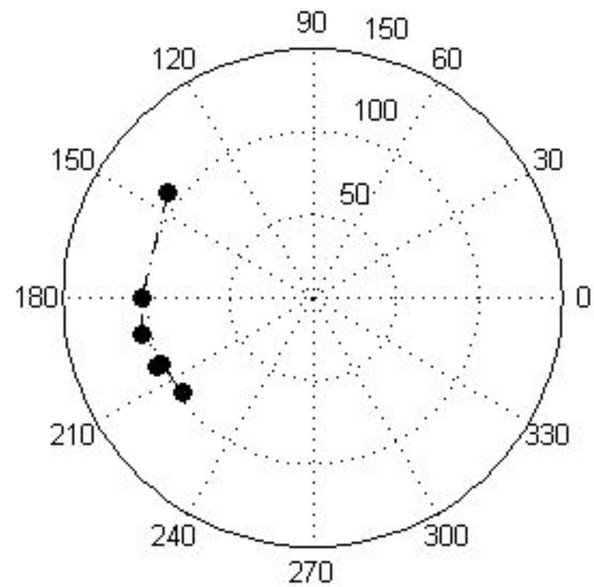


Figure 19. Polar plot depicting “syncopated” response.

Chapter 5

Discussion

The purpose of this study was to investigate the ability of children and adults to entrain labiomandibular movements to an external auditory stimulus and to determine the effects of an external auditory stimulus on their labiomandibular stability. The first two research questions addressed motor entrainment, specifically, if children can entrain labiomandibular movements to an external auditory stimulus and if entrainment abilities change with age within the range studied. The goal of a synchronization task is to produce a response with the same period as the external stimulus (Thaut, Miller, & Schauer, 1998). Since entrainment is not the precise occurrence of the motor response with the external cue, synchronization ability can be considered in terms of both synchronization error and period error.

The synchronization error mean values in this study were different for the child groups, with younger children exhibiting a larger lag (-105.65 ms, adjusted 107.47 ms) and older children exhibiting a lesser lag (-62.62 ms, adjusted 71.35). The adults exhibited synchronization error values that were closer to the younger group of children in both the unadjusted (-77.9 ms) and the adjusted values (97.85 ms). These scores may be skewed due to the musical training of the adults who participated in this study, as many were trained on instruments that primarily play on the off-beat in ensembles (i.e., French horn and bluegrass fiddle). An investigation of the adult raw data indicates that several adults syncopated within trials, producing larger SE scores since the motor response was more delayed from the onset of the stimulus.

Although not statistically significant, the older children in this study demonstrated a mean synchronization error and standard deviation that was less than that demonstrated by adults by about 10 – 20 ms. According to Volman and Geuze (2000), children reach adult levels of motor synchronization abilities by age 11; therefore, the older children in this study were within the age in which adult ranges for motor synchronization error would be expected. The raw scores of the older children did not indicate instances of syncopation, reducing the overall SE score for their group. Therefore, the older children's group mean in this study may be more indicative of adult-like synchronization error. The observation that the adult scores were larger than the child scores may also be an anomaly due to the small group size utilized in this study.

Consistent with limb motor synchronization studies, the actual occurrence of the oromotor response in this study fluctuated within a given syllable train. This variability of successive motor responses has been attributed to internal and external sources of neural "noise" (Thaut, 2005; Thaut et al., 1998). These variations are considered to be continual time adjustments in response to motor output, in order to maintain stable synchronization states (Thaut et al., 1998). Therefore, this fluctuation in oromotor synchronization may indicate that the speech motor process operates similarly to motor synchronization strategies of the limbs. Furthermore, motor responses in this study followed the anticipatory pattern described by Thaut, Miller, and Schauer (1998).

The SEs in the current study preceded the external stimulus, which concurs with adult limb motor synchronization studies (Aschersleben & Prinz, 1995) and finger tapping synchronization studies with children (Volman & Geuze, 2000). Overall, 45 out of 48 condition means preceded the external stimulus in the current study (94.75%). This indicates that the primary method for oromotor synchronization follows the anticipation-correction model described by Thaut (2005).

The motor synchronization errors in this study were larger than reported errors in limb studies. Aschersleben and Prinz (1995) reported a mean synchronization error of -20 – 40 ms in healthy adults performing a tapping task. Volman and Geuze (2000) demonstrated that 11-year-olds performing a tapping task preceded the stimulus by -38 ms, which was reported to be adult-like. The means of oromotor synchronization in the present study indicated a larger SE than in limb motor studies, with the shortest SE mean for a group in the current study at -61 ms. The overall larger SEs could be due to the nature of the task being preformed. Unlike a tapping task, the speech task involves lip closure that is followed by phonation of the syllable. The time difference between when the lips closed and when the syllable was produced would account for some of the "lag", since the "goal" of the speech synchronization task is to match the sound with the external auditory stimulus. In order to account for the onset time, the period error can be examined to determine if the period of the stimulus was matched.

The Inter-Response-Interval Errors in this study were smaller than the SEs, with the largest IRI Error mean of 24.67 ms (SD = 8.71) in the younger group. The IRI Errors demonstrate the period error in the synchronization task. If the participant can match the period of the stimulus, entrainment is implied. Therefore, a participant may have a large SE but a small IRI error, which would indicate motor entrainment to the stimulus period despite a continual motor onset delay. The participants in the present study demonstrated small IRI Errors, providing further evidence that entrainment occurred in all three age groups.

The presented data provide evidence that motor synchronization of labiomandibular movements is possible in children as young as eight years of age. The findings also indicate that by age 11, children reach adult levels of oromotor synchronization ability. Although preliminary, these data suggest that auditory rhythmic entrainment may be useful in therapeutic applications addressing motor speech production. However, further evidence concerning the ability of children with disabilities to synchronize oromotor movements to an external stimulus and the use of an external stimulus for production of speech (as opposed to a single syllable) is necessary.

Motor Stability and Synchronization

The third research question concerned the effect of an external auditory stimulus on the upper lip, lower lip, and jaw stability when producing speech sounds. In the current study the position of the markers was statistically significant. This finding was expected due to the three distinct positions for the reflective markers, yielding three different STI values. When compared to STI values for 12 – 16 year-olds from other motor kinematic studies, there are differences in the STI values for the upper lip and jaw. Walsh and Smith (2002) found more motor variability in the upper lip than with the jaw in 12 – 16 years-olds who produced a short phrase. These findings are contradictory to findings in the current study, where that jaw was the most variable for all groups. This discrepancy may be due to the demand of the motor task with the current study utilizing a repetitive syllable; whereas, the Walsh and Smith study utilized a short phrase.

According to Smith and Zelaznik (2004), children plateau in their speech abilities between seven and twelve years of age. Although seven to twelve-year-olds are close to achieving adult stability in their motor patterns, they will continue to develop through fourteen (Smith & Zelaznik, 2004). Therefore, no significant effect between the STIs of the child age groups was expected in the present study. Interestingly, no significant differences were seen between the younger group and the adult group, which has been shown in previous studies (Walsh & Smith, 2002). This may be due to the small sample size utilized in the present study or the use of a repetitive syllable that is mastered early in development.

The data indicated that the only statistically significant difference in STI values was between the first trial (no rhythm) and the second trial (self-paced rhythm). An investigation of the means reveals that the motor stability decreased with the self-paced entrainment condition (which was counterbalanced with the fast rhythm condition). This increased STI value may suggest that the added demand of the external auditory stimulus increased the motor variability within the slower (self-paced) condition. One explanation for increased variability could be that adding auditory cues to the participant's preferred tempo may have invoked the auditory feedback loop that was not required for the production of the mastered syllable “pa” without the external auditory stimulus. By invoking the auditory feedback loop, the participants may have increased their cortical activity in order to match their phonation with the external stimulus.

Interestingly, this effect was not indicated in the fast entrainment condition (10% faster than self-paced). Several studies have indicated that children have more accurate motor synchronization abilities at tempos slightly faster than their internal pace (Kumai & Sugai, 1997; Mastrokalou & Hatziharistos, 2007; Rao, Mayer, & Harrington, 2001); however, there is no known study on synchronization at different tempos with typical adults (aside from period deviation studies). Reasons for such effects are unknown, but it has been proposed that the faster the stimulus (within a functional range) the less ISI space must be processed, thereby making faster tempos more attainable for motor synchronization tasks (Volman & Geuze, 2002). The STI values at the faster tempo were close to the STI values of the no-rhythm condition, possibly indicating that less cortical/auditory feedback processing was recruited for the faster synchronization task.

These findings suggest that although children and adults have the ability to entrain oromotor movements to an external auditory stimulus, the cognitive demands of such tasks may increase their motor variability. However, an external auditory stimulus at a tempo slightly faster than the self-paced tempo may not impact labiomandibular motor stability. Therefore, external cueing tasks utilized in therapy may consider slightly increasing the tempo (within a functional range) in order to maintain motor stability.

Limitations of the Study and Future Recommendations

This study had several limitations. First, the child groups were very close in age range, with the younger child group from 8 to 10 and the older child group form 11 to 14. Other studies on motor stability have had clear age groups that are several years apart (i.e., 8, 11, 14). Due to the close age of the two child groups, developmental differences that could exist may not have been observed in this study. Furthermore, the two child groups were at an age where their oromotor system was essentially matured, which was supported by no significant differences in STI values across the age groups. Secondly, the adult group had a large age span, between 18 and 35 years of age. This large age span may have been a confounding variable due to the continued maturation of the motor system into early adulthood. Therefore, future research in this area should consider using younger children from distinct age groups and an adult group with a smaller age range.

Another limitation of this study was the use of a convenience sample for the adults. Participants were students or faculty from a music program and were all trained musicians and all female. The program from which the participants were recruited was predominantly female, providing access to more female than male adult participants. Their musical training may have been a confounding variable due to highly refined oromotor abilities of some instrumentalists (i.e., brass players who utilize their embrasure to create segmentation of notes while playing). Several of the children in this study were also musicians, although musical ability wasn't on the initial questionnaire and, therefore, the extent of musical experience is unknown. There are no known studies demonstrating that children with musical training have better motor synchronization skills; however, this may be a confounding factor in the present study. For this reason, future studies should consider the musical experience of child and adult participants.

Another limitation was the number of repetitions that were completed in a short period of time. Once the markers were placed on the face, the total time required for one participant to complete all of the trials was less than 15 minutes. The first condition was the longest and took about two minutes, followed by two one-minute conditions. These were separated by five-minute breaks where the participants would either play with instruments or chat with the research staff. Several of the participants showed signs of fatigue during the last condition, as evidenced by stopping in the middle of a trial or greatly deviating from the period of the stimulus. Although trains that were incomplete or showed clear examples of fatigue were not included in the data, fatigue may have affected the overall motor output on the final condition.

Several participants also reported that their speech production began to sound "robotic" or "weird" when they completed the trials to the external cue. This may have caused additional shifts in the motor pattern due to self-perceived changes of their speech production output. This was specifically observed in two participants who began saying a different syllable mid-trial and required a correction to return to the target syllable. Since repeating a single syllable was reported to feel "unnatural" to some of the participants, they may have changed their motor patterns while repeating the mastered syllable. Future studies in this area may consider utilizing a phrase or sentence to decrease the "unnaturalness" of the entrainment task. Using a phrase would also allow researchers to examine motor strategies for entrainment of different labiomandibular motor patterns.

Lastly, the sample size in the present study was small. Therefore, these groups cannot be a reflection of the general population. A small sample size makes this study more susceptible to a Type II error, which may result in a false negative for one of the hypotheses. Future studies may consider utilizing a larger sample size.

Implications for Music Therapy

The field of music therapy has been moving towards utilizing evidence-based methods of treatment. Part of building the evidence base for the profession is the acquisition of normative data regarding the effect of musical stimuli on basic motor tasks. The current study provides some emerging evidence regarding the effectiveness of rhythmic stimuli for the synchronization of oromotor tasks. With evidence indicating that motor synchronization in children is possible, further research can determine the effectiveness of rhythmic cueing for younger populations and populations with disabilities. Continuing to build this knowledge is necessary in order to better determine which elements of music will be the most effective in the treatment of different disabilities.

Although this study focused on rhythmic entrainment, it is important to note that music therapy treatment involves many other elements of music (i.e., harmony, structure, melody). Furthermore, music therapy treatment with children is often multisensory, involving movement, tactile cues, and visual cues as part of the experience. Providing a multisensory experience that is driven by principles of motor synchronization may increase adherence to treatment plans and aid children in making faster gains toward their goals and objectives. Increasing the understanding of how different musical elements affect function will continue to build support for the use of music in the treatment of speech communication disorders.

Evidence that children can successfully synchronize oromotor movements to speech could also support the use of rhythmic cueing in specific music therapy techniques. Although Melodic Intonation Therapy and Rhythmic Speech Cueing have been shown to be successful with adults, there was no known evidence indicating that oromotor entrainment occurs to a rhythmic auditory stimulus. The current study indicates that the oromotor system can entrain to an external auditory stimulus and that motor synchronization strategies may be similar to those seen in limb motor studies. This evidence supports the continued study of auditory rhythmic cueing for oromotor habilitation and rehabilitation.

Conclusion

This study provides insight to speech synchronization strategies of children and adults to an external auditory stimulus. These results support anecdotal observations that children as young eight years of age have the ability to entrain their speech production to an external auditory stimulus. The results also provide some empirical evidence that music therapy techniques employing rhythmic entrainment, as a means for improving speech production, may be effective with child populations.

Although these results provide initial evidence suggesting that oromotor entrainment occurs with children, this evidence cannot determine if rhythmic cueing would be an effective medium for treatment of children with disabilities. Even though the perceptual motor abilities in many populations are different from the abilities of typically developing children, the verification of entrainment in the typical population provides a rationale for investigating motor synchronization strategies in populations with disabilities. Therefore, this study supports the continued research of auditory motor synchronization in typical and atypical children.

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Appendix A

Screening Questionnaire for Inclusion

Participant's Initials:______________________ Date:_____________

Date of Birth:____________________________ Age: _____________

1. Is English the primary language spoken in the home? Yes No
2. Does your child have visual or hearing impairment? Yes No
3. Does your child currently have any significant medical problems that would limit his/her ability to sit in a chair and imitate words? Yes No
4. Does your child typically follow directions? Yes No
5. Does your child have any special needs? Yes No

Explain:____

6. Is your child sensitive to having stickers or items on his/her face? Yes No