2012

Velopharyngeal function with varying articulatory rate in normal children

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VELOPHARYNGEAL FUNCTION WITH VARYING ARTICULATORY RATE IN NORMAL CHILDREN

by

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A thesis submitted in partial fulfillment of the requirements for the Master of Arts degree in Speech Pathology and Audiology in the Graduate College of The University of Iowa

May 2012

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

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has been approved by the Examining Committee for the thesis requirement for the Master of Arts degree in Speech Pathology and Audiology at the May 2012 graduation.

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ACKNOWLEDGEMENTS

I would like to thank those who have helped me during my journey of completing my thesis. Especially, I would like to thank Dr. Jerald Moon, Dr. Michael Karnell, Dr. Karen Bryant, and Dr. Amanda Owen Van Horne for their assistance. I would also like to thank my friends and family for motivating me from beginning to end.

ABSTRACT

The purpose of this study was to investigate the effect of variation of speaking rate, gender and age on aerodynamic and acoustic measure of the VP function in 19 typically-developing young children aged 4-7 years. Additionally, this study aimed to compare results from children from this study to that of Gauster, Yunusova and Zajac (2010). Aerodynamic measurements such as oral pressure, nasal pressure, nasal flow, and VP area were taken at the /m/ and /p/ segments in the word “hamper” (HAMPER) and the initial /p/ of “puppy” in the utterance “Buy Bobby a puppy” (BBP). Nasalance and nasalance distance was collected for the utterances “Buy Bobby a puppy” and “Mama made lemon jam” (MMJ). Speech tasks were performed in 4 different self-regulated rates including normal, fast, slow, and slowest. Results indicated that only the aerodynamic measures in the /m/ of HAMPER were affected by speaking rate. Rate affected the nasalance measures of BBP and MMJ and nasalance distance. Gender affected the nasalance of BBP, and age affected nasalance distance. Additionally, children varied from the adults in Gauster et al. (2010) in differences in rate, gender and variability. In summary, rate, gender, and age group had various effects on the measures relating to VP function in healthy children, and should therefore be considered when working with children with VP dysfunction.

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INTRODUCTION

In normal adults, the velopharyngeal (VP) mechanism plays a vital role in speech production and resonance. When the velum is raised, it separates the nasal cavity and nasopharynx from the oral and pharyngeal cavity (Seikel, King & Drumright, 1997). According to Bell-Berti (1980), during the production of /m/, /n/, and /ŋ/ in English, the velum is lowered, and airflow passes through the nasal cavity for nasal resonance to be achieved. For all other English sounds, the VP mechanism is closed, directing airflow through the oral cavity rather than through the nasal cavity to utilize oral resonance. An appropriate balance of oral-nasal resonance is important for normal resonance quality during speech.

Impairment of the VP mechanism may involve difficulty moving the velum to achieve full closure. This may lead to the perception of hypernasality or nasal air emission during speech. Possible causes of velopharyngeal dysfunction (VPD) may include anatomical defects, physiologic defects, and mislearning (Kummer, 2007; Dworkin, Marunick & Krouse, 2004). Anatomical defects may include palatal clefts, submucous clefts, short velum, deep pharynx, irregular adenoids, and enlarged tonsils. Anatomical deficits may also present follow surgery or treatments such as adenoidectomy, maxillary advancement, treatment of nasopharyngeal tumors, and cervical spine surgery though the mouth (Kummer, 2007). Possible physiological causes of VPD can include spastic, flaccid, or mixed dysarthrias (Dworkin et al., 2004), poor muscle function due to history of cleft, pharyngeal hypotonia, velar paralysis or paresis due to brainstem or cranial nerve injury, neuromuscular disorder such as Myasthenia Gravis, and apraxia (Kummer, 2007) . In addition, VPD may be a learned behavior or mislearned use of the velum (Dworkin et al., 2004) due to conversion disorder, hearing loss, or abnormal posterior or nasal articulation of certain sounds (Kummer, 2007). In children, the most common occurrences of VPD often occur from cleft palate, submucous cleft, cerebral palsy, closed head injury, head and neck injuries, iatrogenic neck injuries, muscular dystrophy, perinatal hypoxia or anoxia due to birth process complications, and mislearning (Dworkin et al., 2004).

While aware of the different types of disorders potentially leading to VPD, it is important to know how the normal VP mechanism works in order to fully understand the effects of the anatomical, physiological, and neurological problems leading to such disorders. There is a relative paucity of information in the literature about the normal VP mechanism and the majority of that literature presents data collected from adults. There are few studies of the VP mechanism of normally developing children.

The ability as clinicians to diagnose and treat the speech problems associated with VPD must be based on a firm understanding of VP anatomy and physiology in normal adults as well as children. Knowing typical functional properties (e.g. kinematics) of the child's VP mechanism and the effects of VP movements on speech aerodynamics and acoustics should be expected to improve a clinician's ability to evaluate the speech of a child using age appropriate normative data.

Bell-Berti and Krakow (1991) investigated the velar kinematics of 3 native speakers of American English. The participants produced nasal utterances and oral utterances in the carrier phrase "It's ___ again". A Velotrace (Horiguchi & Bell-Berti, 1987) was used to track the time-varying position of the velum. The results demonstrated that velar lowering occurred in consonant-vowel sequences whether there was a nasal or oral consonant following the sequence. Also, the velum lowered in close temporal proximity to the nasal murmur for the production of the nasal consonant.

Kuehn and Moon (1998) measured VP closure force in varying phonetic contexts in typical adults. The effects of place and manner of articulation, voicing, and constant sequencing were investigated. The VP closure was transduced with a silastic force bulb (Moon, Kuehn & Huisman, 1994). As expected, the non-nasal sounds had greater VP closure force than the nasal sounds. High vowels had greater closure than low vowels. Additionally, the males had more significant differences than the females, although there was not a significant difference between genders. In the high back vowel environment, lingual dorsal consonants had greater closure force than lingual apical consonants for males. Males also had greater closure force for voiceless sounds than voiced sounds, but online within the /i/ and /u/ environments. These results demonstrated that typical VP closure force during speech is a versatile process and it varies to meet the demands of the phonetic context.

Furthermore, Moon and Jones (1991) measured normal adult speaker's ability to voluntarily control their VP positioning. The participants were given visual feedback using a phototransducer while they produced the vowels /a/ and /i/ at 50% and 75% of complete VP closure. They observed evidence for both motor flexibility and plasticity to a novel speaking condition. The results, although there was a lot of variability, displayed that the speakers were able to phonate at intermediate levels of closure demonstrating control over the VP mechanism. The results of this study supported Folkins (1985) that the VP organization is flexible and can adapt to changes in movement parameters.

One approach used in part to assess functional properties of the VP mechanism has been to alter speech rate and observe the effect of increasing or decreasing speech rate on velar movements as reflected in nasal and oral air flows and pressures, as well as in perceived nasality. For example, Brancewicz and Reich (1989) investigated the effect of speaking rate on the nasal accelerometric vibrational index (NAVI) during the production of nasal and non-nasal sentences of adults. The speakers produced a carrier paragraph with a semi-vowel loaded sentence, an obstruent loaded sentence, and a sentence with a single nasal consonant embedded within it. The rates used by speakers included normal, half of normal, and as slowly as possible. No effects of speaking rate variations were observed in nasal oral acoustic ratios as evidenced in the NAVI signals. However, a very small effect on the perception of nasality was observed such that the perceived nasality increased at slow speaking rates.

Goberman, Selby and Gilbert (2001) investigated the effect of speaking rate variations (self- and metronome-controlled) on peak nasal airflow rate, percentage of nasal airflow and perception of nasalance during the production of schwa in a non-nasal sentence. Healthy adults, ages 21-34 years, repeated the non-nasal sentence at slow, normal, and fast rates. Increases in peak nasal airflow, percentage of nasal airflow, and perception of nasalance were observed at slow rates compared to normal and fast rates. It was concluded that contact between the velum and pharyngeal walls decreased during the slow speaking rates, leading to higher airflow rates. Additionally, the males were perceived to produce utterances with greater nasalance than the females.

Jones and Folkins (1985) studied the effect of increasing speaking rates on the perception of disordered speech for children with repaired cleft palate (ages 7-10 years).

Each child produced 3 sentences that excluded pressure consonants at a normal rate and then gradually increased the rate with subsequent productions. Fifteen judges rated each production according to the perceived severity of disordered speech. The judges rated nasality, nasal distortions, nasal emission, glottal stops, and pharyngeal fricatives. The results of the study demonstrated that the perception of disordered speech did not increase with increased speaking rate for these children with repaired cleft palate.

More recently, Gauster, Yunusova and Zajac (2010) investigated the effect of speaking rate variations on a number of aerodynamic and acoustic measures related to VP function in adults. The study included 27 healthy adults between the ages of 41 and 87 years. Participants repeated "hamper, "Buy Bobby a puppy", and "Mama made lemon jam" at four different self-regulated rates (normal, fast, slow and slowest). Their data analysis revealed that in healthy adults, variations in speaking rate were not associated with significant changes in any of the aerodynamic (intraoral pressure, nasal pressure, nasal airflow and VP orifice area) or acoustic measures (nasalance and nasalance distance). The authors suggested that the aerodynamic and acoustic measures associated with VP function were not affected by variation in speaking rate in healthy adult males and females.

While there exists some literature on the VP mechanism of adults, it is also important to understand the anatomy and physiology of the VP mechanism, as well as other articulators, of young normally developing children, and how they may be different than that of adults. This is important given that clinically, speech-language pathologists were primarily working with children with disorders of the VP mechanism. It may not be appropriate to extrapolate data obtained from adults to children with respect to velopharyngeal function. This has already been shown in the body of literature that compares children to adults with respect to control and the development of control of speech structures other than the velum.

Smith and McLean-Muse (1987) investigated the kinematic characteristics of children’s speech (ages 4-5 years, 7-8 years and 10-11 years) and adult’s speech in three different speaking conditions: normal rate, fast rate and with a bite block. A head mounted strain gauge transduction system was used to measure inferior and superior movements of the mandible, upper lip and lower lip. Participants produced repetitions of consonant-vowel-consonant words beginning with a bilabial sound that was embedded in a carrier phrase. The younger children (ages 4-5 years) exhibited more variation in the movement of articulators on repeated trials as compared to the children (7-8 years and 10-11 years) as well as adults. Even slightly older children (7-8 years old) continued to produce more variability in articulatory displacement than adults. It was concluded that articulatory development continues until at least 10-11 years old. The children also had decreasing duration of movements from age 4 to age 12, and 14 year olds had greater durations than the adults. The children exhibited articulatory cycles, closing/opening phases and occlusion phases that were longer than adults. Additionally, the children’s overall maximum velocity of the articulators was less than that of the adults (Smith & McLean-Muse, 1987).

Smith and Zelaznik (2004) evaluated children aged 4, 5, 7, 12 and 14, and adults aged 20-22 years. The movements of the upper lip, lower lip and jaw were studied in the repetition of two separate sentences, “Buy Bobby a puppy” and “Mommy bakes pot pies” at a normal rate and loudness. The younger children tended to have more variability in the coupling (using combinations of the upper lip, lower lip, and jaw together) of the articulators between the repetitions of the utterances. Based on their results, Smith and Zelaznik suggested that speech motor control processes were not adult like until after 14 years of age. Additionally, the durations of the productions were compared in a post hoc analysis. There were differences between durations such that there was a decrease in duration with an increase in age from 4 to young adulthood with an exception between 12 and 14 year olds (Smith & Zelaznik, 2004).

As previously mentioned, young children were learning how to produce correct articulation, while adults have often mastered it. Likely due to learning articulation, it has also been demonstrated that children aged 4-5 years old produce more variable articulatory movements than adults (Goffman, Smith, Heisler & Ho, 2008). In this study, children ages 4-5 years and adults produced rounded and unrounded vowels embedded in the medial position of words in a carrier phrase. The researchers used infrared light emitting diodes (IREDs) to track the upper lip, lower lip and jaw. The spatiotemporal index (STI) is a measure used to assess the variability across conditions and groups by quantifying the stability underlying the movement patterns when absolute differences were eliminated (Smith, Goffman, Zelaznik, Ying & McGillem, 1996; Smith, Johnson, McGillem & Goffmen, 2000). The children had greater STI values demonstrating that they were relatively more variability in lip rounding than the adults.

Smith and Gartenberg (1984) used a head mounted strain gauge transduction system the inferior and superior displacement of the upper lip, lower lip and mandible as participants repeated utterances in a carrier phrase with /p/, /b/, and /f/ with a front /i/ or /I/ or back /a/. The investigators measured the max oral opening, vertical distance from the temperomandibular joint (TMJ) to the angle of the mandible and the angle of the mandible to the mental symphasis. The children (ages 4;6-7;0) tended to move their articulators (upper lip, lower lip and mandible) more slowly than adults. Furthermore, the children produced segment durations that were longer than adults (Smith & Gartenberg, 1984).

In a later study conducted by Smith and Goffman (1998), three groups of speakers (4 year olds, 7 year olds and young adults) produced the utterance “Buy Bobby a puppy” at their perceived normal rate and loudness as measurements of stability and patterning of the speech movements were made to compare movement ranges and trajectories. IREDs were placed on the lower lip and forehead, and 3-dimentional measurements of displacement were measured. The 4 year old children had STI values that were approximately twice that of the 7 year old children and the adults, demonstrating that the 4 year old children produced less reliable or stable patterns than the older children and adults. The children produced speech movements that were of similar amplitude as adults; however, the movements of the children occurred at a slower velocity. The authors concluded that by age 7, children still do not have adult-like performance in articulation movements, and they were still developing control for speech This demonstrated that even at 7 years of age children were still developing their motor speech behaviors.

Smith (1978) studied speech development by looking at temporal properties during the repetitions of nonsense words including the consonants /b/, /d/, /t/ and the vowel /a/. Comparing young children ages 2.5-3 and 4-4.5 years, as well as adults, Smith discovered that the younger children produced more variability in word and segment duration than adults, suggesting that the children had less precise neuromotor control.

Green, Moore, Higashikawa and Steeve (2000) investigated the development of lip and jaw coordination during speech as well as the possible influence that speech motor development may have on phonological development. Children (with age groups of 1, 2 and 6 years) and adults (with a mean age of 29;5 years) repeated “baba”, “papa” and “mama” while a video-based movement tracking system was used to measure the movement of the upper lip, lower lip and jaw. Compared to the adults, the 1 year olds had an increased jaw displacement and excessive compression of their lips as well of an increased variety of lip configurations. The 2 year old children had increased displacement of the upper lip and lower lip and decreased jaw displacement when compared to the adult group. The 6 year old children were similar to the adults, but had an increase in variability of displacement. The contribution to oral closure also differed significantly. The 1 year olds had greater jaw contribution than all other groups, and the 2 year olds had greater lower lip contribution than the 6 year olds. Additionally, the order of closure differed between the groups. The 1 and 2 year old groups had jaw as the greatest contribution, then the lower lip, followed by the upper lip. However, the 6 year olds and the adults had the greatest closure from the lower lip followed by the jaw, lower lip and jaw similarly and then the upper lip. Spatial and temporal coupling was also significantly different between age groups. Upper lip and lower lip coupling was relatively high in the younger children, and the coordination between the lips and jaw was lower in the youngest age group; however, it increased gradually with age. Overall, these results demonstrated that organization of articulation changes significantly during early childhood and continues to be refined after 6 years of age.

To investigate the development of speech motor skills, Sharkey and Folkins (1985) measured the lower lip and jaw movements using a strain gauge system of adults and children ages 4, 7 and 10 years. The duration of the lip opening movements, jaw opening movements, lip opening postures, and the timing between the onset of the lower lip opening and the jaw opening differed from the children to the adults. Their results demonstrated that there were no significant differences in the variability of jaw displacement in the children's groups; however the variability of lower lip displacement decreased significantly from the 4 year olds to the 7 year olds. The authors hypothesized that different developmental motor processes affect the variability of the speech movements at different ages: early, intermediate and older. Additionally, they concluded that children use variability to enhance learning or refine the precision of developmental habits, while adults do not have this same need since they were comfortable with their habits. The researchers concluded that a decrease in variability seen between the older age groups was indicative of changes in the motor system from around 4 years and below differed from that of older children.

Using spectral analysis, Singh and Singh (2008) investigated the developmental changes in articulatory features in language in children ages 4-8 years. The children participated in a picture naming task as well as phrase repetitions of two separate phrases. Spectrogram and modulation spectrums were examined, and the features investigated include syllabicity (associated with the long time scale), formant transitions and the place of articulation. Researchers concluded that with an increase in age, there was improvement in speech-motor skills. While at age 4, children exhibit syllabicity similar to adults, as children get older, their articulatory signatures were associated with shorter time scales. The researchers concluded that by age 8, only half of the children exhibit adult-like articulatory signatures demonstrating that children's speech continues to mature in young childhood and past 8 years of age. Furthermore, children indicate maturing fine motor control as they get older, including fine motor skills required for articulation.

A recent study conducted by Zharkova, Hewlett and Harcastle (2011) examined the lingual coarticulatory properties using ultrasound tongue imaging. The researchers investigated children (6-9 years) and adults that were speakers of standard Scottish English. Synchronized ultrasound and acoustic data was collected from each participant while they produced /ʃu/, /ʃi/ and /ʃa/ in a carrier phrase. The results demonstrated that although adults and children did have some similar coarticulation patterns, the extent of the coarticulation was significantly greater in the children than the adults. The consonants adapted to the vowel more in the children's speech than the adults'. Additionally, the children had more within speaker variability than the adults such that the tongue positions were more variable for the children.

Lofqvist, Frid and Schotz (2011) investigated lip movement variability across repetitions of the same utterance in 41 typically-developing children and adults (ages 5-31 years). The participants repeated the short Swedish phrase "Mamma papa barn" ("mummy daddy kids"). Upper and lower lip movements were recorded using the Carstens AG500 system. The researchers concluded that temporal (phase) and spatial (amplitude) variability of the lip movements decrease with age, but there was a greater reduction of amplitude variability than phase variability.

Based on previous research of speech motor performance variations in childhood, teens and young adults discussed by Smith (2006), it is expected that adults and children will differ greatly in their speech motor performance. It has been demonstrated that children up to their teenager years produce noisier, less reliable, less consistent and slower speech movements as compared to young adults (Walsh and Smith, 2002). In the study conducted by Walsh and Smith (2002), teenagers (ages 12, 14, and 16 years old) and young adults (mean age 21.2 years) repeated the utterance “Buy Bobby a puppy” while IREDs were on the upper lip, lower lip and jaw of each participant to measure the reflection of the spatiotemporal consistency in the movement trajectories for repeated productions. These results demonstrated that while the jaw variables were less variable than the upper lip and lower lip, even the teenagers as old as 16 years of age produced more variable articulatory trajectories of the upper lip, lower lip and jaw, longer segment durations, smaller displacements, and lower velocities than the younger adults. This helps to give a more comprehensive model of speech development.

As evidenced above, a significant body of previous research has demonstrated differences in speech motor performance between children and adults. The research previously described demonstrates that children aged 4-7 have greater variability in articulation than adults. Additionally, rates and durations of the movements of the articulators also differ between children and adults. However, there is little to no information in the literature regarding the motor control of the VP mechanism in normal children and how that might differ from adults. Since the velum is considered one of the articulators used in the production of speech, results seen for other articulators might suggest that differences in VP function could be expected when comparing normally developing children to adults. Further, it would be important to fully understand the nature of control of VP function in normal children, opposed to extrapolating performance characteristics seen in adults down to children as engaged in the assessment of the speech of children with suspected VP dysfunction.

Children do appear to differ from adults from a motor perspective and that these differences may appear in the control of VP articulatory gestures. One method of looking at articulatory control and motor organization is to vary speech rate.

Present Study

While Gauster, et al. (2010) examined healthy adults, to this date there has been no research conducted on the effect of variation of speaking rate on VP function of children. The present study aimed to assess the effects of speaking rate variations on VP function in normal children. Children as young as 4 and 5 years of age, including those with repaired palatal clefts, may present with aerodynamic and/or acoustic speech patterns suggestive of velopharyngeal dysfunction if compared to the more adult like patterns typical of older children or adults. It is therefore important to document patterns of aerodynamic and acoustic events associated with the speech of typically-developing children within that age range.

The following research questions were addressed:

(1) Will variations in speaking rates, gender or age of children affect aerodynamic measures of velar function during speech, as evidenced by differences in

nasal pressure, intraoral pressure, nasal airflow and calculated velopharyngeal orifice area?

(2) Will variation in speaking rates, gender or age of children affect acoustic measures velar function during speech, as evidenced in differences in nasal versus oral tract acoustic energy (nasalance) and nasalance distance?

(3) Will speech rate effects observed in children differ from previously published findings from adults (Gauster et al., 2010)?

METHOD

Nineteen healthy, typically-developing children (9 males, 10 females) participated in the present study. As displayed in Table A1, participants' ages ranged from 4;1 to 7;11 years (mean= 6;3, SD= 1.27), and were recruited from the Iowa City and Coralville area. The children were divided into two age groups; a younger group from 4;11 years to 6;3 years (mean=5;3, SD=0;9) and an older group from 6;11 years to 7;11 years (mean=7;7, SD=0;4). According to parent report, the children (1) spoke English as their primary language, (2) were typically-developing with no known speech, language or hearing concerns, (3) had no maxillofacial abnormalities and (4) had not received any prior therapy for speech or language. Voice, resonance and articulation were informally judged by the primary examiner (a masters student in speech pathology and audiology) to be within normal limits.

The protocol was completed within a one-hour visit to the Speech Physiology Laboratory in the Wendell Johnson Speech and Hearing Center at the University of Iowa. Participants were motivated with age-appropriate activities such as beads and stickers. Two researchers collaborated to complete the protocol with each participant. The same primary researcher gave instructions, managed signal digitization and gave directions, while a second researcher assisted with the instrumentation and motivation of the child. Approval for the present study was obtained by the University of Iowa Institutional Review Board (HawkIRB). Additionally, prior to participation the researchers obtained written informed consent from the participant's legal parent/guardian as well as verbal consent from the participant.

Speech Sample

The protocol used by Gauster et al. (2010) was adapted to accommodate for the young age of the subjects. Participants repeated the utterances “hamper” (HAMPER), “Buy Bobby a puppy” (BBP), and “Momma made lemon jam” (MMJ) 5 times each at 4 different, self-regulated speaking rates. The speaking rates included normal, fast, slow and slowest.

For the normal rate, children were prompted to talk as they do every day, as if talking to their mother or father. For the fast rate, speakers were asked to speak as fast as possible while still saying all of the sounds in each word. For the slow rate, speakers were asked to produce their speech slower than normal speaking rate. The children were often reminded that this was not their *slowest* but just *slow* or *medium slow.* The slowest rate was elicited by prompting the speakers to produce speech at their slowest possible rate. In the slow and slowest rates, the participants were encouraged to connect the words and not pause during the production of the sentence. Throughout the five trails within each condition, the participants were reminded to maintain the appropriate rate and models were given if needed. To augment these directions, the children were provided with age appropriate visual cues. The visual cues included a picture of a continuum with a bunny on one end to elicit the fast rate, a turtle on the other end to elicit the slowest rate and a star in the middle representing normal talking. Each child was given an opportunity to practice each rate before trials were recorded.

The entire protocol was completed twice, once for the collection of aerodynamic measures and once for the collection of acoustic measures. The order of protocol repetition (beginning with the acoustic or aerodynamic instrumentation) was counterbalanced. The order of the rates examined remained constant for each speech task for each child, similar to previous studies (Gauster et al., 2010; Brancewicz & Reich, 1989; Goberman et al., 2001). For each word or utterance, the participants began at the normal speaking rate, increased to the fast rate, decreased to the slow rate and finished with the slowest rate. The order of utterance production also remained constant; HAMPER followed by BBP and then MMJ.

Procedures

Aerodynamic Measures

Aerodynamic measures included nasal airflow, oral airway pressure, and nasal airway pressure. The PERCI-SAR system (Microtronics Corp., Chapel Hill, NC) was used to obtain aerodynamic data (see Figure B1). A small nasal mask with attached pneumotachograph was placed over the subject's nose to capture nasal airflow. The nasal facemask was held to the subjects face by the experimenter to assure proper placement. A small tube fixed in the mask was used to sense nasal airway pressure. Oral airway pressure was sensed by a small 1.5 mm diameter polyethylene tube positioned in the oral cavity with the inlet approximately 1 cm behind the front teeth and held in place by the experimenter as the subject spoke. A microphone was attached to the outside of the nasal mask. Both air pressure and air flow transducers were calibrated on a weekly basis throughout the experimentation period. The pressure transducer was calibrated using a U-tube water manometer. The airflow pneumotachograph was calibrated using a Fisher-Porter rotameter (Fischer and Porter, Co, Ltd, Hong Kong).

Using PERCI-SAR software, measurements were collected during the first consonant /p/ in ‘a puppy’ of BBP, the consonant /m/ in ‘momma made’ of MMJ, and the consonant cluster /mp/ in HAMPER. Measurements of peak intraoral pressure (Po), the corresponding nasal pressure (Pn), nasal flow (Vn), sound pressure level (SPL) and calculated VP orifice area were collected for the /p/ of BBP and /m/ of MMJ. An example of the measurement display for one token of BBP is displayed in Figure B2. Measurements of Po, Pn, Vn, SPL and VP area were taken at the peak Po for /p/ and peak Vn for /m/ in HAMPER. All aerodynamic measurements were taken from the middle 3 productions within each rate condition.

To document differences in speech rate between the rate conditions, the time intervals between the pressure peaks for the two /p/ consonants in “puppy” (BBP) and between the acoustic offset of the second /m/ in “mama” and /m/ offset for “made” (MMJ) were calculated. Duration for BBP was measured between peak oral pressures of the /p/’s in “puppy”, similar to Gauster et al. (2010). Duration for MMJ was measured between the second /m/ in “mama” and the offset of the /m/ in “made”. Duration of HAMPER was not measured because a consistent method of attaining a duration measurement could not be established using the PERCI-SAR software and the data collected.

Unfortunately, an equipment malfunction resulted in the microphone audio signal being recorded for only for 4 of the 19 subjects. As a result, durations could not be analyzed during MMJ for the 15 participants without acoustic recordings. Since there was no audio signal recorded for 15 (the majority) of the participants, SPL measurements for all speech tasks and the aerodynamic measurements for MMJ were only collected from the 4 subjects. This data will not be discussed. The aerodynamic measurements were collected for BBP and HAMPER based on the plosive peaks displayed, not the acoustic location.

Acoustic Measures

A Nasometer II (Model 6400, KayPentax, Pine Brook, NJ) was used to sense oral and nasal acoustic energy. The device uses a headset with a small horizontal plate that rests against the face just below the participant's nose. Microphones on either side of the plate capture the acoustic signals coming from the nasal and oral cavities, respectively. These signals were used to calculate a "nasalance" value representing the ratio of the nasal amplitude to the total amplitude (nasal plus oral amplitudes). The Nasometer was calibrated on a weekly basis following the protocol provided by the manufacturer.

The Nasometer data was collected through the entirety of the middle 3 productions of BBP and MMJ within each rate condition. The overall utterance duration was also measured for each of these productions. A "nasalance distance" value was calculated for each subject by subtracting the mean nasalance for the oral utterances (BBP) from that of the nasal utterances (MMJ). According to Bressmann, Sader, Whitehill, Awan, Zeilhofer and Horch (2000), calculating nasalance distance can help control individual variability in the mean nasalance scores as well as be used as a clinical measurement for oral-nasal resonance.

Statistical Method

Multi-level mixed model regressions were adopted as the means of examining the data. This approach was selected in part to replicate the previous paper. Unlike Gauster, et al. (2010), the present study used mixed effects, which allows the maximization of data retention and power of the analysis (Baayen, Davidson & Bates, 2008; Dixon, 2008; Jaeger, 2008; Quene & van den Bergh, 2008). This meant that instead of computing means and medians, each value for each production was used as a data point. This is important because, unlike standard ANOVA methods, multi-level mixed model regression estimates by item and by subject effects simultaneously, reducing the possibility of type I error.

For Po, nasalance, nasalance distance, Fn of /m/ and VP area of /m/ variables, which were continuous, linear mixed effect models were employed. For Fn and VP area for /p/ variables which were categorical, logistic mixed models were used instead. The categorical dependent variables were necessary because Fn and VP orifice area for the /p/ productions had non-normal distributions due to a large number of zeros. Comparable to Gauster et al. (2010), the raw data was converted to binary scores of “0” or “1”. The Fn values below 20 ml/sec were replaced with a “0” and the values above 20 ml/sec were replaced with a “1”. There were no values equal to 20 ml/sec. Previous research has demonstrated that the value of 20 ml/sec is the average Fn during /p/ productions in a group of normal speakers, and a value of 20 ml/sec or less reflected a complete VP seal in the normal speakers (Zajac and Mayo, 1996; Zajac, 2000). Additionally, studies conducted by Zajac and Mayo (1996) and Zajac (2000) demonstrated that at a value of $1mm^2$ or lower for VP area was present for oral stops produced by healthy speakers.

Being cognizant of the literature, the VP area binary cut-off value was 1 mm^2. Values below 1 mm^2 were replaced with a “0” and values equal to or greater than 1 mm^2 were replaced with a “1”. Logistic regression l treats changes between extreme points as more important than changes near those points (Jaeger, 2008), thus correcting for distributional issues in the variables.

Analysis

Logistic mixed effect models were carried out with the binary values for Fn and VP area for /p/ as the dependent variables. Rate (fast, normal, slow and slowest), age group (young and old age) , and gender (male and female) were all treated as categorical fixed factors and subject and item were treated as random factors.

Linear mixed effect models (LME) were carried out using the data points for Po, nasalance, nasalance distance, Fn for /m/ and VP area for /m/ as the dependent variables. Rate (fast, normal, slow and slowest), age group (young and old age), and gender (male and female) were all treated as categorical fixed factors and subject and item were treated as random factors.

RESULTS

As discussed in the Method, the participants were typically-developing children without previous speech-language therapy. Per parent report, one male subject in the young age group (5m05p) had previously undergone an adenoidectomy. When comparing his data to others, this subject did not differ greatly from the others, and so his data were included in the analysis.

Reliability

To assess measurement reliability, the author repeated the data extraction blindly for two subjects, one young male and one old female. Values for Pn, Fn, Po and VP area were collected for BBP and HAMPER, and nasalance was collected for BBP and MMJ for each of the rates. The test-retest reliability revealed correlations ranging from 0.981 to 0.984.

Rate

The mean speech rate was calculated using durational measures from BBP and MMJ for nasalance data and from BBP for aerodynamic (pressure) data. Table A2 displays the mean and standard deviations for the duration measurements for the younger and older children. As demonstrated in Table A2, the children in both groups did increase and decrease rate as anticipated. On average, the fast speaking rate was 56%-69% faster than the normal speaking rate. On average, the slow speaking rate was 66%-75% slower than the normal speaking rate. The slowest speaking rate was 51%-64% slower than the slow speaking rate.

Nasal Pressure (Pn)

Table A3 displays nasal pressure (Pn) data for each utterance. Pn for /p/ in BBP was significantly greater for the fast rate than the slowest (β= -0.00, p=0.01). There was no main effect between fast and normal (p= 0.07) or slow (p= 0.10). Following visual examination of the data, no further rate analyses were completed. There was a main effect of gender, such that males had greater pressures than females (β= 0.00, p= 0.01). There was no main effect of age group (p= 0.95).

With respect to the /p/ in HAMPER, there was no main effect of rate between the fast and normal (p= 0.05), slow (p= 0.81) or slowest (p= 0.78) rates. There was also no main effect for gender (p= 0.09), although there was a main effect for age group such that the older group had significantly greater pressures than the younger group (β= -0.01, p= 0.03).

For the /m/ in HAMPER, there was a rate effect such that the fast rate was associated with significantly greater Pn than the normal (β= -0.19, p< 0.001), slow (β= -0.21, p< 0.001) and slowest (β= -0.25, p< 0.001) rates. Further, the normal rate was associated with significantly greater Pn than the slowest (β= 0.06, p= 0.01) rate. There was no significant difference in pressure between the normal and slow (p= 0.39) or the slow and slowest (p= 0.10) rates. There was no effect of gender (p= 0.94), but Pn was found to be greater in the older group than the younger group (β= -0.07, p= 0.01).

Nasal Flow (Fn)

Nasal flow data is summarized in Table A4. Based on the binary scores for the /p/ in BBP, there was no significant difference between the fast and normal (p= 0.08), slow

(p= 0.08) or slowest (p= 0.08) rates. Following a visual examination of the data, no further rate analyses were conducted. There was no main effect for gender (p= 1.00) or for age group (p= 0.73).

Table A4 also displays Fn values for the /p/ in HAMPER. Based on binary scores, the fast rate yielded significantly greater flow rates than the normal (β= -2.04, p= 0.02) and slowest (β= -2.04, p= 0.02) rates. There was no significant difference between the fast rate and the slow rate (p= 0.07), normal and slow (p= 0.05) or slowest (p= 1.00), or between slow and slowest (p= 0.41). There was no main effect of gender (p= 0.06) or age group (p= 0.93).

For the /m/ in HAMPER (Table A4), there was a main effect for rate such that the fast rate yielded statistically greater Fn values than the normal (β= -144.10, p< 0.001), slow (β= -178.10, p< 0.001) and slowest (β= -191.02, p< 0.001) rates. Following visual examination of the data, no further rate analyses were completed. There no main effect for gender (p= 0.57). Fn was found to be statistically greater for the older children than for the younger children (β= -46.37, p= 0.02).

Oral Pressure (Po)

Table A5 summarizes the Po data for each utterance. For the /p/ in BBP, Po was significantly greater in the fast rate than the normal (β= -4.89, p< 0.001), slow (β= -5.41, p< 0.001) and slowest (β= -6.15, p< 0.001) rates. Po for the normal rate was significantly greater than the slowest rate (β= -1.26, p= 0.01), but there was no significant difference between the normal and the slow rate (p= 0.24). Furthermore, there was no significant difference between the slow and slowest (p= 0.10) rates. There was no main effect of gender ($p = 0.54$). There were no significant differences between the younger and older children ($p = 0.09$).

In the production of /p/ in HAMPER, there was main effect for rate such that such that Po was greater for the fast rate compared to the normal ($\beta = -6.81$, $p < 0.001$), slow ($\beta = -7.45$, $p < 0.001$) and slowest ($\beta = -7.66$, $p < 0.001$) rates. Following visual examination of the data, no further rate analyses were run. There were no main effects for gender ($p = 0.77$) or for age group ($p = 0.23$).

Po recorded during the /m/ in HAMPER was significantly greater for the fast rate compared to the normal ($\beta = -1.20$, $p < 0.001$), slow ($\beta = -1.68$, $p < 0.001$) or slowest ($\beta = -1.76$, $p < 0.001$) rates. Following visual examination of the data, no further rate analyses were completed. Po for the /m/ in HAMPER did not differ significantly by gender ($p = 0.19$) or by age group ($p = 0.53$).

VP Area

VP area data for each utterance is summarized in Table A6. Based on an analysis of binary data values, the VP area associated with the /p/ in BBP did not differ between the fast and normal ($p = 1.00$), slow ($p = 1.00$) or slowest ($p = 1.00$) rates. Following visual examination of the data, no further rate analyses were completed. There were no significant gender ($p = 0.37$) or age group ($p = 0.43$) effects.

For the /p/ in HAMPER, there were no significant differences in VP area between the fast and normal ($p = 1.00$), slow ($p = 0.69$) or slowest ($p = 0.72$) rates. Additionally, there were no significant differences in VP area between the slowest rate and the normal

(p= 0.72) or slow (p= 0.45) rates. There was no main effect for gender (p= 0.11) or age group (p= 0.87).

There was a significant rate condition difference in the VP area values for the /m/ in HAMPER such that areas for the fast rate were greater than slow (β= -0.18, p= 0.02) and slowest (β= -0.28, p< 0.001), while areas for the normal rate were greater than slow (β= -0.16, p= 0.04) and slowest (β= -0.26, p< 0.001) rates. There was no significant difference between the fast and normal (p= 0.82) rates or between the slow and slowest (p= 0.18) rates. VP area values for the /m/ in HAMPER did not vary as a function of gender (p= 0.73) or by age group (p= 0.78).

Nasalance

Nasalance values for BBP and MMJ are summarized in Table A7. For BBP, the fast rate was associated with higher nasalance than the normal (β= -5.12, p< 0.001), slow (β= -6.97, p< 0.001) and slowest (β= -5.74, p< 0.001) rates. Following visual examination of the data, no further rate analyses were completed. Females produced higher nasalance values than males (β= -3.32, p= 0.04). There was no main effect of age group (p= 0.06).

For MMJ, there was a main effect for rate such that the slow rate had greater nasalance than fast (β= 1.98, p= 0.04) and slowest (β= 1.91, p= 0.05) rates. However, nasalance values for the slow rate were not significantly different from the normal rate (p= 0.88). There were no significant difference between fast and normal (p= 0.83), fast and slowest (p= 0.94), or normal and slowest (p= 0.15). There was no main effect of gender (p= -1.61) or age group (p= -1.48).

Nasalance Distance

Table A8 summarizes the nasalance distance data. Values for the slow rate were greater than fast (β= 8.00, p< 0.001), normal (β= 3.61, p= 0.0174) and slowest (β= -3.14, p= 0.04). The fast rate was associated with significantly lower nasalance distance values than the normal (β= 4.29, p< 0.01) and slowest (β= 4.86, p< 0.01) rates. There was no significant difference between normal and slowest (p= 0.75). There was no main effect of gender (p= 0.39). The older group had significantly greater nasalance distance scores than the younger group (β= -7.17, p< 0.01).

DISCUSSION

The purpose of this study was to investigate the effect of speaking rate variations on the aerodynamic and acoustic measurements of VP function in typically-developing children ages 4-7 years old. The children repeated the stimuli “hamper”, “Buy Bobby a puppy”, and “Mama made lemon jam” at normal, fast, slow and slowest rates. In a similar study conducted previously with adults, Gauster et al. (2010) found that Po decreased with a decrease in rate, but no other significant effects of speaking rate or of speaker gender in aerodynamic indices of VP function were found. Similarly, there were no differences of VP function, measured by acoustic measures, with rate; however there were differences observed between males and females.

The results of this study will be discussed below, organized by research question and by the utterance that was produced. Since the utterances posed different demands on the VP mechanism, this will the discussion of VP function with the varying task demands.

Aerodynamic Measures

The first research question asked “Will variations in speaking rates, gender or age of children affect aerodynamic measures of velar function during speech, as evidenced by differences in nasal pressure, intraoral pressure, nasal airflow, and calculated velopharyngeal orifice area?”. Based on an analysis of the results, it may be concluded that, for the children studied, VP function did not differ by rate, gender or age for the /p/ in BBP and HAMPER. For the /m/ in HAMPER, there were no differences by gender. However, observed rate and age group effects may be indicative of differences in the maturation of the articulatory system involving the velum. Below, the findings will be discussed further by utterance.

Utterance BBP

The utterance BBP consisted of only oral consonants, specifically bilabial plosives requiring higher levels of intra oral air pressure. These oral consonants required the VP mechanism to be elevated to close the VP port in order to avoid nasal resonance and/or nasal air emission. As expected, Pn, Fn and VP area values were relatively low and Po values were relatively high as compared to that of the /m/ in HAMPER. The observed Fn values fell below 20 ml/sec, and VP area values were lower than $1mm^2$. As suggested by Zajac and Mayo (1996) and Zajac (2000), this result was indicative of a complete VP seal.

Statistically, variations in speaking rate appeared to have an effect on one of the aerodynamic measures of BBP. While Fn and VP area values did not differ significantly as a function of rate, the children produced statistically higher Pn values during the slow rate than other rates. However, after examining the data, these differences were very small and were likely meaningless in relation to the degree of functioning of the VP mechanism. Therefore, this demonstrated that rate did not have an effect on VP function during these tasks, although Pn was statistically significant. These results supported previous research conducted by Brancewicz and Reich (1989) that there was no change in VP function with a change in rate for an obstruent loaded sentence as measured in nasal oral acoustic ratios with the NAVI. However, it contradicted Goberman et al. (2001) since they concluded that the degree of closure of the velum decreased during slow rates.

This difference may be attributed to the differences in the measurements in the speech stimuli. The participants in Goberman et al. (2001) produced the non-nasal utterance “It’s a story about a zoo”. While this stimuli was similar to BBP since it didn’t contain nasals, measurements were taken at different points in the utterances for each study. In Goberman et al. (2001), the measurements were taken on a vowel, and the measure was taken during the consonant /p/ in the present study. It is possible that rate has a different effect on vowels than consonants since consonants tend to have a greater buildup of pressure, and further investigation of these differences would be beneficial.

Additionally, Po was greater in the fast production as compared to the other rates and the normal rate was greater than the slowest rate. However, since the other aerodynamic measures (Fn, Pn and VP area) did not change with rate, it might be concluded that there was no effect of rate on the VP function. This trend for an increase in Po with an increase in rate may be due to the children speaking louder with an increase in rate. With an increase in SLP, it is likely to see an increase in Po since it has been demonstrated that SPL can have an effect on aerodynamic measures (Warren, Dalston, Morr, et al., 1989a; Warren, Morr, Rochet & Dalston, 1989b; Holmberg, Hillman, Perkell & Gress, 1994; Zajac, 1997; Dromey & Ramic, 1998; Zajac, Mayo & Kataoka, 1998). Specifically, Po has been demonstrated to increase with an increase in vocal intensity (Isshiki, 1964; Subtelny, Worth & Sakuda, 1966; Hixon, Minifie & Tait, 1967; Brown, 1969; Stathopoulos, 1986).

In BBP, there were no significant gender differences in Pn, Fn, Po or VP area when collapsed across all rates. Therefore, it was concluded that both the males and the females have similar VP functioning with the task demands required for BBP. Similarly, when Stathopoulos and Weismer (1985) investigated oral airflow and Po in young children ages 4-12, there was no difference in gender. This suggests that both genders have similar degrees of VP function.

Similar to gender, when collapsed across all rate conditions there were no significant differences between the younger children and the older children in Pn, Fn, Po, or VP area. Since the measures of Pn, Fn or VP area didn't have significant differences and there were no differences found in the oral measure of Po, this demonstrates that there were no differences in the VP functioning between the age groups. While other studies have not investigated the control of the velum of children, many previous studies have compared the ability to control other articulators. Results of these studies often show that younger children (approximately 4-5 years old) move their articulators more slowly than older children (7 years old) and/or adults (Smith & Gartenberg, 1984; Smith & McLean-Muse, 1987; Smith & Goffman, 1998; Smith & Zelaznik, 2004), and thus it would be predicted the velum to move slower as well. However in BBP, the velum was required to move to close the VP port, but no further movement was needed. Therefore, it makes sense that there were no differences found between these ages.

Overall, it was concluded that rate, gender and age have no effect on VP function for these children during the production of BBP. BBP includes only pressure consonants in a fully oral environment that didn't require rapid raising and lowering of the soft palate during the utterance. Although a difference Po was found by rate, this difference was possibly a related to vocal intensity, not VP function. Therefore, regardless of rate, gender or age, the children had similar VP function.

Utterance HAMPER

Overall, the task demands of HAMPER were different than that of BBP. BBP, as previously mentioned, only contains oral consonants and vowels, and the velum was required to remain closed throughout the production. HAMPER had slightly more complex task demands because it contains the nasal phoneme /m/ that requires the velum to open. Since the beginning of HAMPER contained an oral consonant, the VP mechanism should be closed. Then the velum should open for the /m/ and quickly close again for the /p/ and the remainder of the utterance.

Phoneme /p/

The task demands for the /p/ in HAMPER may be considered greater than those of BBP. In BBP, the VP should remain sealed for the production of all of the oral sounds, both vowels and consonants. HAMPER, on the other hand, required VP opening for the /m/ immediately preceding the /p/ that required a velar seal. Since the demands were greater for HAMPER, it could be predicted that velar function could decrease compared to BBP especially if the mechanism isn't mature. Even with an immature system, it would be predicted that the velum would be able to achieve some level of closure for the /p/. Similar to the /p/ in BBP, the present study found relatively low Pn, Fn and VP area values and higher Po values than the /m/ in HAMPER even when demands were increased. The Fn values were below 20 ml/sec and the VP area values were less than $1mm^2$, reflecting a complete VP seal and healthy oral stops production (Zajac & Mayo, 1996; Zajac, 2000).

There were many significant aerodynamic variable differences associated with speaking rate. The children produced the highest Pn, Fn and Po values at the fast rate. However, there were no differences between the other rates, and there were no differences in VP area as a function of rate. With the greater overall Pn and Fn values, one could conclude that there was a decrease in the degree of VP closure at the fast rate. However, similar to Pn values discussed previously in BBP, the differences were very minimal, and the Pn significant differences were viewed as not important in relation to the degree of functioning of the velum. When examining the Fn (Table A4) and Po (Table A5) data, it was demonstrated that the fast rate tended to have greater Fn in the older children and Po values for all of the children than the other rates. If there was a significant enough decrease in the extent of VP closure, it might be expected to see an inverse relationship between Fn and Po; as Fn increased, Po would decrease. That was not the case. Additionally, since calculated VP area did not decrease at the faster rate, it might be concluded that the observed increase in Po was due to increasing SPL and not a variation in the functioning of the VP mechanism. Similar to BBP, the children may have been speaking louder during the fast rate. A greater SPL could be a result of greater aerodynamic measures of Fn and Po, as SPL has been demonstrated to be affected by aerodynamic measures (Warren, Dalston, Morr, et al., 1989a; Warren, Morr, Rochet, & Dalston, 1989b; Holmberg et al., 1994; Zajac, 1997; Dromey & Ramic, 1998; Zajac, Mayo, & Kataoka, 1998).

Overall, there were no significant gender based differences in the aerodynamic measurements made during the /p/ in HAMPER. Therefore, it was concluded that similar to the /p/ in BBP, gender did not have an effect on the velar functioning of the children even with more complex demands placed on the system. Similar to BBP, these results were supported by results of the investigation of the oral airflow and Po of children ages 4-12 years that found no differences in gender (Stathopoulos & Weismer, 1985). This demonstrates that the children (both male and female) in the present study closed their velum similarly and adequately during the /p/ directly following an /m/.

With respect to age, Fn, Po and VP area did not differ significantly between the two groups. However, Pn was greater overall for the older children than the younger children. However, when looking at the data, the differences of Pn between the ages were minimal with the exception of a higher mean for the older males in the normal rate that also had a very high value of variability. This suggested that although there was a statistically significant difference, the difference in age found for Pn did not reflect a difference in the VP function. Therefore, it could be concluded that age did not have an effect on the VP function in the children examined. This was somewhat surprising since it was expected the velum to move more slowly for the younger children based on previous research demonstrating that younger children often move their articulators more slowly during the production of bilabial consonants embedded in sentences (Smith & Gartenberg, 1984; Smith & McLean-Muse, 1987; Smith & Goffman, 1998; Smith & Zelaznik, 2004). Thus it would be expected to see greater Fn, Pn and VP area for the high pressure oral consonant /p/ following the /m/ since the velum is required to quickly close for the /p/. However, the results of this study demonstrated that between the ages of 4-7 the children had similar abilities in VP function for high pressure oral consonants, even when rapid movement is required. However, it may not be able to be concluded that this would be true for all oral consonants following a nasal consonant. It is possible that since the following consonant was a high pressure consonant, the velum was able to attain closure. The same may not be true for low pressure consonants like /r/ or /l/ following a nasal consonant. This is an area where future research will be beneficial.

Overall, it can be concluded that for production of the /p/ of HAMPER, VP function did not differ with rate, gender or age. While there were some statistical differences between rates in Pn, Fn and Po, these differences were not attributed to variations in velar function. Instead, the Pn was viewed as not important since the differences were so minimal. The observed increases in Fn and Po within the fast rate were attributed to a possible increase in vocal intensity.

Phoneme /m/

As previously mentioned, for the production of HAMPER, the velum must move from a closed posture to open for the /m/ and immediately close again for the /p/. This placed increased demands on the velum to open and close rapidly. For the nasal consonant /m/ the velum was opened, and it was expected to see higher nasal values such as Pn, Fn and VP area. As expected, the Fn values were above 20 ml/sec, indicating an opening in the VP seal (Zajac & Mayo, 1996; Zajac, 2000). Furthermore, the VP area values were greater than $1mm^2$, indicating an open VP port since values less than $1mm^2$ were expected for the oral stops of healthy speakers (Zajac & Mayo, 1996; Zajac, 2000). Additionally, the Po values were lower during the /m/ in HAMPER than the /p/ in HAMPER or BBP, and it would be expected to see lower Po values during the /m/ based on the open velum during the nasal consonant.

Rate seemed to have an effect on the VP functioning of children, as measured by the aerodynamic measures, for the /m/ in HAMPER. The fast rate had greatest Pn, Fn, Po and VP area. Additionally, the normal Pn was greater than slow and the normal VP area was greater than slow and slowest. These results demonstrated that the VP mechanism was open, as expected, during the /m/, and the degree of opening may have varied as an effect of rate. One explanation for these differences was that the VP may have had a greater opening due to an increase in nasality in the "ha" of HAMPER due to coarticulation in the fast rate. Since the children's system had the complex task of closing the velum preceding the /m/, open for /m/ and then close again for the remainder of the word, it was possible that the children were unable to meet the timing demands of the utterance during the faster rate. Instead, the children may have kept the velum wider open until the required closure for the /p/. However, for the slower rates, the children were able to meet the close-open-close demands of the system. Since children have demonstrated a great extent of lingual coarticulation to help meet the demands of the system (Zharkova et al., 2011), it is very plausible that children were using coarticulation with the velum since previous research has demonstrated that anticipatory nasal coarticulation often occurs on vowels preceding a nasal consonant (Thompson & Hixon, 1979; Zajac, et al., 1998)

Another explanation was that with an increase in Pn, Fn and Po for the fast rate, it could be postulated that the children spoke louder when speaking fast leading to greater aerodynamic values. However, the VP area also increased. It is possible that talking louder could be associated with greater VP opening to allow more acoustic energy to pass through the nasal passage more easily. The field of speech-language pathology could benefit from research on if an increase in intensity has an effect on VP area.

Similar to previous discussion with BBP and the /p/ in HAMPER, there were no statistical differences in VP function, measured aerodynamically, found between males and females for the /m/ in HAMPER. Again, this is contradictory to Goberman et al., (2001) that found that adult males had decreased degree in velar function in the schwa vowel of a non-nasal sentence. This suggested that both genders have similar VP functioning during the production of the /m/ in HAMPER, similar to BBP and the /p/ in HAMPER. However, this may not be a valid comparison given that the present study investigated the effects on VP function during the production of a consonant by children and Goberman et al., (2001) investigated VP function during the production of a vowel by adults.

Moreover, while there were no differences between age groups for Po or VP area, the older children produced higher Pn and Fn than the younger children. With an increase in Pn and Fn values with the older children in the nasal production of /m/, it could be presumed that the velum was in a more opened position and it is possible that VP function was altered. It was expected the velum to be open during the production of the /m/, and it is possible that the velum could open to a greater degree for the younger children. However, there were no differences in the VP area and since, contradicting that there were no differences in VP function. Instead, another explanation for the variations between age groups may be due to an increase in respiratory drive. When looking at the data in Table A3 and Table A4, it was apparent (especially with the males) that the older children have greater Pn and Fn values across rates, including the normal rate. Additionally, the older children may be speaking more loudly across rates leading to an increase in Pn, Fn and Po values; however only an increase in Pn and Fn were observed in the results. This was contrary to what was expected. It would be anticipated that the younger children would have greater loudness because Susser (1980) demonstrated that children have a greater "comfortable loudness" than adults and it could be expected that the trend would be present between older and younger children as well. However, the opposite trend seemed to be present.

Another explanation for these differences in Pn and Fn may lie in the manner in which HAMPER was produced by the older children compared to the younger children. After listening to the speech samples for which an audio signal was recorded, a slight difference in the productions of HAMPER was observed to occur between the older children and the younger children. The older children inconsistently produced the /m/ longer during the slow rates (for example, "hammmmper") while the younger children prolonged the vowel (i.e., "haaaamper"). The differences in the slow productions may just simply be a variation in the preference of how to prolong the word. With an increase in the duration of the /m/, there was more time for the velum to assume the lower positions before having to elevate for the plosive, leading to greater Pn and Fn values.

Additionally, during the fast rates, the older children included the /m/ sound (i.e., "hamper"), while the younger children tended to eliminate or minimize the /m/ (ie., "ha_per"). The difference in productions in the fast rate supported a notion that the older children participating in this study may have more mature systems, demonstrating the ability to put the nasal sound immediately preceding the high pressure oral consonant /p/ in the complex demands of the fast rate. Previous studies have demonstrated that lip and jaw coordination increase from 1 to 6 years (Green et al., 2000), lip and jaw variability decreased from 4 to 7 years (Sharkey & Folkins, 1985), and that half of children have adult-like articulation by age 8 (Singh & Singh, 2008). This demonstrated that the children from 4 to 7 years were refining their motor skills required for articulation, and therefore supporting the notion that older children have more refined control of their velum to meet the demands of the system when speech rate was increased. Nevertheless, as previously mentioned, only four participants have acoustic recordings during the aerodynamic tasks and it cannot firmly be concluded that these changes in Pn and Fn were due to different productions of HAMPER based on the tendencies of four children.

Overall, there was an increase in Pn, Fn, Po and Vp area with an increase in rate. The differences were possibly due to an increase in vocal intensity or a change in manner of production. While the change in manner of production may just be a difference in the preference of varying rate, it may also be an indication of increased control over the velum and other articulators since some of the younger children deleted the /m/ in HAMPER in the fast rate. Gender did not have an effect on VP function. Additionally, while the older children had greater Fn and Pn than the younger children, it was concluded that these differences were likely due to respiratory drive, loudness or how the target item was produced. However, the variations in stimuli productions may be indicative of differences in maturation or control of the system. Therefore there it was concluded that the younger and older children don’t demonstrate differences in the functional status of the VP mechanism.

Acoustic Measures

To answer the second research question, the effects of variations in speaking rates, gender or age of children on acoustic measures of velar function during speech were studied, as evidenced in differences (including variability) in nasal versus oral tract acoustic energy (nasalance) and nasalance distance. Based on the results obtained in this portion of the study, it can be concluded that rate and gender did have an effect on velar function during the production of BBP. VP function decreased in the fast rate in BBP; however a similar effect was not seen with MMJ. Additionally, nasalance distance increased with an increase in rate. Below, the findings will be further discussed, organized by utterance.

Utterance BBP

As anticipated, nasalance values recorded during the fully oral production BBP were less than half the values observed during MMJ, a phrase loaded with nasal consonants. Additionally, the nasalance values were below the “cutoff” range of 28-32 for an oral production, in which values above the “cutoff” were perceived as hypernasal (Peterson-Falzone, Trost-Cardamone, Karnell, & Hardin-Jones, 2006). Nasalance scores falling below the 28-32 thresholds can be interpreted as indicative of normal VP function.

In BBP, there appeared to be an effect of rate on VP function. The fast rate was produced with significantly greater nasalance than the normal, slow and slowest rates, suggesting that the VP mechanism did not acoustically separate the oral and nasal cavities to the same extent as rate increased. It is possible that with an increase in the rate of production, the velum had difficulty achieving complete closure, but it has greater closure with slower rates because it has more time to achieve closure. Previous studies have demonstrated that children move their articulators more slowly (Smith & McLean-Muse, 1987; Smith & Zelaznik, 2004; Smith & Gartenberg, 1984; Smith & Goffman, 1998), so with slower movement of the VP port, the velum had difficulty meeting the task demands with the increased speed.

While the results of this study were supported by previous research on articulators and motor development, the results of this study contradicted a study conducted with adults by Fletcher and Daly (1976) that found an increase in nasalance in the slower rates during the production of the “Zoo Passage” (a passage containing only oral consonants). In an additional study conducted with adults, Goberman, et al. (2001) found that perceived nasality were greater at the slow rate as compared to normal and fast rates. These previous studies were supported by the normative data provided by KayPentax that states that vowels were characterized with greater nasalance than consonants, and therefore in slow rates when vowels were prolonged, the nasalance would increase. Also contradictory to the current finding, Brancewicz and Reich (1989) found no change in nasal oral acoustic ratios during the production of obstruent loaded utterances by adults. These differences may be due to different speech stimuli, since BBP was not used for each of these studies, and it is possible that participants prolong vowels to different degrees for different utterances. An increase in the duration of vowels in an utterance containing oral consonants may increase the nasalance of the overall utterance. Also, it is possible that the children have decreased control of their velum or slower movements of the velum, leading to an increase in nasalance in the fast rate.

This difference in VP function was not likely due to differences in loudness, since nasalance is a ratio of nasal versus nasal plus oral acoustic amplitudes. Additionally, Watterson, York and McFarlane (1994) investigated the effects of loudness on nasalance in adults with both oral and nasal stimuli. They concluded that there was no difference in nasalance measures across the levels of loudness (soft, conversational and loud). The results from Watterson and colleagues (1994) support that the present study's findings of an increase in nasalance with in the fast rate were in fact due to a decrease in the degree of VP closure.

Additionally, there was an effect of gender on VP function during BBP. The females produced greater nasalance during BBP than the males. This suggests that the males have a greater degree of VP closure and possibly more control of their velum than the females during BBP. This is contradictory to findings from Goberman and colleagues (2001) that found that adult males were perceived to have greater nasalance than females during the production of non-nasal utterances. However, the results of Goberman et al. (2001) were based on *perceived* nasalance (the nasalance subjectively judged by listeners) and the present study was *measured* nasalance, which could have led to a difference in findings. The perceived nasalance may vary from the measured nasalance. Additionally, there might be differences between adults and children in the function of the VP, such that the children have an immature VP system.

However, there were no statistically significant differences between age groups. Therefore, it was concluded that children aged 4-7 years old have similar VP abilities during the production of BBP at varying rates. These results were similar to what was found for the aerodynamic measures of /p/ in BBP and HAMPER. While children were refining motor control with other articulators (Sharkey & Folkins, 1985; Green et al., 2000; Singh & Singh, 2008), it would appear that during a speech task where the velum is not required to move from a closed to open to closed position during the execution of the task, no differences in performance were observed between a group of 4 year old and 7 year old children.

Overall, this demonstrates that while other articulators were still refining control from age 4-7 (Sharkey & Folkins, 1985; Green et al., 2000; Singh & Singh, 2008), the control velum remained stable in this age group. However, when the system was taxed during the fast rate, there was a decrease in the degree of functioning of the velum. Therefore it is possible that significant development in velar function occurs after the age range of 4-7. Since it is an articulator that is not easily visible during the production of speech, it may be less concrete to the children and therefore refine later in development. Furthermore, the males had a decreased degree of VP function than the females suggesting that during the ages of 4-7, the females may be in the process of refining the movements and control of the velum.

Utterance MMJ

In contrast to BBP, MMJ was loaded with nasal consonants. As expected, nasalance values recorded during MMJ were higher than for BBP. In addition, the nasalance values were greater than 50, indicating appropriate nasal resonance for a nasally loaded utterance; below 50 usually denotes denasality in nasal utterance (Peterson-Falzone, et al., 2006).

Different from BBP, the slow rate was associated with greater nasalance than the fast and slowest rates. One explanation was that the children produced greater nasalance by opening the velum wider since they have more time, thus allowing airflow to pass more easily as rate decreased. Having the ability to pass airflow more easily at slower rates could decrease the amount of effort placed on the speaker. However, it would be expected that this trend with the slow rate would continue through the slowest rate, but the slowest rate did not have greater nasalance. Since, the nasalance appeared to be different for only the slow rate, it appeared as though the increased opening of the velum only occurred during that rate. Another explanation was that the children produced MMJ differently for the slow than the slowest rate. After listening to the audio recordings of the productions of MMJ, some of the children prolonged the phoneme /m/ more during the slow rate (ie., “mmmaa mmmaa”) and then prolonged the vowels more during the slowest rate (ie., “maaaaa maaaaa”). A longer prolongation of /m/ would lead to a greater nasalance for the overall utterance, as supported by the results. Therefore the differences between slow rate and other rates were likely due to the manner of production rather than degree of velar function.

Setting aside the difference in production in the slow rate, there were no differences between rates in MMJ. This supports findings by Brancewicz and Reich (1989) that investigated the effect of speaking rate on the nasal accelerometric vibrational index (NAVI) during the production of nasal sentences of adults. The researchers found no change in acoustic ratios, measured by NAVI, in nasal loaded utterances. It is likely that the lack of VP differences between the fast, normal and slowest rates were because the velum remained lowered for most of the utterance, leading to a minimal change in the nasalance (Ushijima & Sawashima, 1972).

There were no statistically significant differences between age groups or genders, suggesting that there was no effect of age or gender on the nasalance during the production of MMJ. This showed that children, regardless of age or gender, were able to open and keep their velum open similarly during the nasal production. This demonstrated that while children were refining motor control with other articulators (Sharkey & Folkins, 1985; Green et al., 2000; Singh & Singh, 2008), the velum had no significant changes in function between ages 4 to 7 when the task required the velum to open and remain opened for the majority of the utterance. While development is required to gain the ability to control the velum to keep it lowered and open, such development appeared to be similar between genders and age groups.

In summary, during the production of MMJ, it was expected to see high values of nasalance. Interestingly, the slow rate had the greatest nasalance, but it cannot be concluded that this difference is due to a difference in VP function. Instead, it was speculated that it was a difference in how the utterance was produced. Moreover, the children performed similarly regardless of gender or age, thus demonstrating that between the age groups and genders, the children have similar refinement of the velum required for this task.

Nasalance Distance

Nasalance distance is a value calculated by subtracting the mean nasalance for BBP from that of MMJ. According to Bressmann et al. (2000), nasalance distance is correlated with individual range in the nasalance scores. It allows “each speaker to serve as his or her own reference”.

When collapsed across age and gender, the nasalance distance statistically differed with rate variations (Table A8). The nasalance distance was greatest for the slow rate, and the normal and slowest rates were greater than the fast rate. The increase in nasalance distance during the slow rate suggests that there was a greater difference between the nasalance of BBP and MMJ. These results of the increase in nasalance distance were supported by previous results indicating an increase in the nasalance of MMJ during the slow rate. Additionally, there was a relatively low nasalance distance for the fast rate as compared to other rates. This supports the nasalance results previously discussed, since the nasalance of BBP increased with the fast rate, decreasing the nasalance distance. Furthermore, the results of nasalance distance support the results found and discussed for the nasalance of BBP and MMJ. The nasalance distance results further demonstrate that the increases in nasalance were not across the tasks, but were task-dependent. For example, when the children increased nasalance in the fast rate of BBP, it was not also increased for MMJ. Thus, while rate appears to affect velar function, the effects of rate were different for the different tasks.

There were no significant differences in nasalance distance between the genders. This suggested that the male and female children had similar ranges in nasalance across the two tasks (BBP and MMJ).

However, the older children had greater nasalance distance than the younger children. These results demonstrated that the older children had a greater range in nasalance across the two tasks. This suggested that the older children had greater differences between the nasalance scores of BBP and MMJ, supporting the notion that the older children may have less nasalance for BBP and/or more nasalance for MMJ. However, these trends were not seen in either BBP or MMJ.

Overall, nasalance distance and rate helped to confirm results found with the nasalance of BBP and MMJ. Males and females had similar nasalance distance values, suggesting similar VP control abilities. Finally, the older children had greater nasalance distance than the younger children, suggesting that the older children had greater control over the velum. Physiologically, this showed that although males and females have similar control of the velum, the older children were able to have a greater degree of difference in velar function between the utterances. This suggested that the older children have refined their control of the velum by demonstrating a greater degree of opening for the nasal utterances and closure for the oral utterances.

Children vs Adults (Gauster et al., 2010)

The third research question involved comparing the results of the present study to Gauster et al. (2010). Specifically, the question states: Will speech rate or gender effects observed in children differ from previously published findings from adults (Gauster et al., 2010)? The results of the present study conducted with children ages 4-7 were compared to the results of the study conducted by Gauster et al. (2010) with adults. Comparisons of the statistical differences across the two studies were made. Table A9 through TableA13 display a summary of significant differences by rate and gender found in both studies.

Aerodynamic Measures

During the aerodynamic measures, Gauster et al. (2010) found significant differences in Po of the /p/ in HAMPER as a function of rate. However, they did not find statistical differences due to variations in rate when SPL was corrected for. This varied greatly from previous studies and the present study. However, this differed from some previous studies that reported greater Po (Zajac & Mayo, 1996; Zajac, 1997), greater oral airflow (Stathopoulos & Weismer, 1985), and greater Fn (Hoit & Watson, 1994) in male adult speakers than female adult speakers. In the present study, Pn and Po (Table A9, Table A11 respectively) varied by rate for all utterances. Fn varied by rate for both the /p/ and /m/ in HAMPER (Table A10), and VP varied by rate only during the /m/ in HAMPER (Table A12). However, the differences in Pn in the present study were not indicative of varying VP function since the differences were so minimal. One explanation for this difference between adults and children was that children did indeed have differences of aerodynamic values displayed in Tables 9-12 due to rate, likely due to immature motor systems. Additionally, SPL was not controlled for in the present study or the previous studies mentioned, and if the children's changes by rate were actually changes due to loudness differences, this may be another explanation for the differences between the groups. A final explanation was that the children produced the speech stimuli in a different manner than the adults did, such as "ha_per" in the fast rate or prolonging vowels and consonants differently. It was difficult to determine which factor was actually leading to these differences. It is not known how the children's productions compare to the adults'. Therefore, it is suggested that future research be conducted to determine the causal factor or factors while controlling for SPL and regulating the manner of production.

Acoustic Measures

During the acoustic measures, again Gauster et al. (2010) did not report statistical differences in rate; however the present study did in the nasalance of BBP and MMJ as well as in nasalance distance (Table A13). Variations in loudness would not explain the differences between the adults and the children in nasalance since nasalance is a ratio. These results demonstrate that the children did have some variations in nasalance and nasalance distance that the adults did not. This was especially apparent in the nasalance measures of BBP, since there was an increase in nasalance in the fast rate for the children and not for the adults. However, the significant differences in MMJ due to rate were likely due to differing manners of production.

Gender

Additionally, the adults did not have any differences by gender (Gauster et al., 2010) in the aerodynamic measures. Similarly to Gauster et al. (2010), the children in the present study didn't have any effects of gender during the aerodynamic measures. This demonstrated that across both studies using the same measurements and stimuli, the males and females perform similarly when compared to similar aged subjects.

However, in the acoustic measures, gender differences were found for both children and adults. The adults had significant differences in the nasalance of BBP and MMJ as well as nasalance distance. Similar to Gauster et al. (2010), females have been found to have greater nasalance scores on nasal sentences than adult males (Hutchinson, Robinson & Nerbonne, 1978; Seaver, Dalston, Leeper & Adams, 1991). However, the children only differed by gender for the nasalance of BBP. These differences between adults and children demonstrated that it is possible that maturation of the VP system and coordination occurs differently between adult males and females. While the difference becomes more apparent in adulthood, it is minimally evident in childhood. This may be due to immature VP systems in childhood that were equally similar between young males and females.

Variability

In addition to difference in rate and gender, the children and adults also differed in the variability across measures. When comparing standard deviations and interquartile ranges with the adults in Gauster et al., (2010), the children of the present study often had increased values and ranges of variability. Frequently, the ranges were greater for the children than the adults, thus demonstrating that in general, the children were more variable than the adults. These results were supported by many previous studies that have demonstrated that children were more variable than adults in a variety of different measures (Bernthal & Buekelman, 1978; Smith, 1978; Smith & Gartenberg, 1984; Sharkey & Folkins, 1985; Smith & McLean-Muse, 1987; Walsh & Smith, 2002; Smith & Zelaznik, 2004; Goffman et al., 2008; Zharkova, et al., 2011; Lofqvist et al., 2011). Furthermore, an increase in the variability in children suggested that the children have immature articulatory systems (including the velum) as compared to adults. The immaturity may include imprecise movements leading to increased variability in the VP function from task to task. With these differences between children and adults, it can be concluded that between the ages of 4-7, the velum has not yet reached adult-like control.

Overall, to answer the third research question, there were many differences between children and adults in reference to velar function. The children differed from the adults in rate and gender, demonstrating that like other articulators, children's velar abilities and control varied from that of adults. The children appeared to be more affected by rate than the adults in both the acoustic and aerodynamic measures, suggesting that the children have immature systems.

Limitations

There were limitations with the present study. Not having the SPL measurements or audio recordings for many of the speech tasks was the first limitation of the present study. Without the audio recordings, aerodynamic data could not be confidently extracted from MMJ. Also, the present study was unable to control for SPL or determine whether rate or SPL was the causal factor for some changes observed. Additionally, productions could not be listened to in order to determine if the manner of production was varying consistently and possibly leading to variations in VP function.

A small sample size of participants was another limitation of the present study. While it was felt that with the current sample some conclusions may be confidently made with the present study's results, a larger sample size would increase the confidence and could determine whether trending differences were significant or not significant. Additionally, only three samples for each child were examined rather than five for each participant in Gauster et al., (2010). Since the participants were children and attention was limited, getting more samples per participant would have been challenging but would benefit the study.

The field of speech-language pathology would benefit from additional research on VP function with variations in articulatory rate. Further studies should make audio recordings and measure SPL for all samples to determine if rate and/or loudness affect VP function. Having some control over SPL and the manner of productions could help determine causal factors as well. Future studies would also benefit from a variety of ages of children and adults as well as a large sample size to determine at what age the children have more adult-like VP function.

Clinical Implications

This study was conducted to determine if variations in speech rate, gender or age has an effect on VP function of typically-developing children. Following the Gauster et al. (2010) investigation with adults, there was a need for a similar investigation with children. The results from this study can be applied to the clinical practice of children with VP dysfunction and/or children with cleft palate. The present study highlights that clinicians should take rate of speech into effect when treating children with VP disorders, especially since there was a broad effect of a decrease in the degree of velar function during oral consonants or utterances containing mostly oral constants. Clinicians need to be cognizant that the speaking rate of the child may be playing a role on the function of the velum and the ability for the child to meet the demands on the system. In addition to rate, clinicians should be mindful of the other demands placed on the system that may be taxing the system leading to changes in the production, coarticulation, and possibly changes in the VP function.

Conclusion

The present study investigated the effect of variations in speaking rate, gender or age had on the function of the VP mechanism. To answer the first research question of the study, only the aerodynamic measures in the /m/ of HAMPER were affected by speaking rate. While SPL may have increased with an increase in rate making the appearance of a change in VP function, the differences were a likely indication for differences/maturation on the articulatory system, including the velum. For the second research question, it did appear that rate, gender and age had an effect on the VP function; however, it was affected differently for each utterance and for the nasalance distance across utterances. Rate affected the nasalance measures of BBP and MMJ and nasalance distance. However, the differences in MMJ may be due to a difference in manner of production or greater opening of the velum. Gender affected the nasalance of BBP, and age affected nasalance distance. To answer the final research question, children varied from the adults in Gauster et al. (2010) in differences in rate, gender and variability. Determining the causal factors (such as loudness, manner of production or velar opening) would be beneficial in future research. In summary, rate, gender and age group had various effects on the measures relating to VP function. Therefore, these variables should be considered when examining and treating children with VP dysfunction.

APPENDIX A: TABLES

Table A1: Means (*M*) and standard deviations (SD) of participants' age.

Participant Age			
	n	*M* (years)	SD (years)
young male	5	4.93	.63
old male	4	7.67	.30
young female	4	5.50	.69
older female	6	7.25	.55

Table A2: Means (*M*) and standard deviations (SD) of durational measures at each rate.

	Duration (seconds)							
	Fast		Normal		Slow		Slowest	
	M	SD	*M*	SD	*M*	SD	*M*	SD
BBP								
young male	1.03	.25	1.48	.23	1.99	.66	2.45	.49
older male	.83	.13	1.53	.54	2.43	1.19	7.79	7.54
young female	.90	.13	1.74	.37	2.44	.73	3.68	1.05
older female	.93	.13	1.38	.36	2.47	.78	4.08	.87
MMJ								
young male	1.26	.33	2.34	.43	3.04	.70	3.86	.97
older male	1.14	.15	2.06	.42	3.30	.89	5.48	2.78
young female	1.45	.24	2.39	.21	2.68	.21	4.55	1.74
older female	1.25	.18	2.19	.33	3.02	.72	4.94	1.88
BBP segment								
young male	.21	.05	.26	.07	.42	.22	.73	.50
older male	.16	.03	.27	.10	.36	.13	1.02	.52
young female	.21	.06	.29	.10	.46	.08	.54	.16
older female	.19	.04	.24	.04	.51	.24	.77	.21

Table A3: Means (*M*) and standard deviations (SD) of nasal pressure (Pn) at each rate.

	Pn (cm H2O)							
	Fast		Normal		Slow		Slowest	
	M	SD	*M*	SD	*M*	SD	*M*	SD
BBP /p/								
young male	-.00	.01	-.00	.01	-.00	.01	-.01	.01
older male	-.00	.01	-.00	.01	-.00	.01	-.00	.01
young female	-.01	.01	-.01	.00	-.01	.00	-.01	.01
older female	-.01	.01	-.01	.01	-.01	.01	-.01	.01
HAMPER /p/								
young male	-.01	.02	-.00	.01	.00	.02	-.02	.03
older male	-.00	.02	.09	.20	.00	.01	-.00	.02
young female	-.01	.01	-.00	.01	.00	.02	-.00	.01
older female	.00	.02	-.00	.01	-.00	.01	.00	.01
HAMPER /m/								
young male	.38	.15	.13	.07	.09	.05	.11	.06
older male	.44	.16	.23	.07	.17	.05	.14	.06
young female	.29	.22	.19	.11	.12	.06	.09	.07
older female	.38	.21	.20	.04	.25	.30	.14	.04

Table A4: Medians and interquartile ranges (IQR) and means (*M*) and standard deviations (SD) of nasal flow (Fn) at each rate.

	Fn (ml/s)							
	Fast		Normal		Slow		Slowest	
	Median	IQR	Median	IQR	Median	IQR	Median	IQR
BBP /p/								
young male	5.60	7.10	6.92	5.19	7.36	5.50	4.55	7.02
older male	11.20	6.54	5.79	2.65	2.28	3.78	6.05	7.83
young female	4.33	4.79	2.86	7.63	4.42	2.02	3.27	2.07
older female	6.68	1.71	4.32	7.72	7.34	4.73	5.93	4.07
HAMPER /p/								
young male	3.84	10.80	7.80	14.71	6.04	15.49	5.45	5.71
older male	10.98	20.04	9.34	11.82	7.20	7.29	4.25	8.37
young female	3.75	4.51	6.33	4.76	5.18	8.31	3.05	3.57
older female	10.32	5.08	6.35	2.70	7.89	4.95	7.97	2.96
	M	SD	*M*	SD	*M*	SD	*M*	SD
HAMPER /m/								
young male	312.66	106.20	116.56	57.80	88.14	44.45	107.99	41.57
older male	373.32	98.18	195.09	47.81	146.58	36.39	123.73	33.18
young female	236.56	163.61	162.97	83.62	110.30	50.05	97.14	41.84
older female	302.41	158.53	177.44	31.25	159.42	40.48	127.47	43.47

Table A5: Means (*M*) and standard deviations (SD) of oral pressure (Po) at each rate.

	Po (cm H2O)							
	Fast		Normal		Slow		Slowest	
	M	SD	*M*	SD	*M*	SD	*M*	SD
BBP /p/								
young male	14.69	6.65	7.81	1.51	6.85	2.79	5.93	1.88
older male	9.43	2.90	5.94	1.42	6.02	.48	4.76	.89
young female	11.73	3.48	7.93	3.50	8.23	3.59	7.35	3.46
older female	11.96	4.07	7.06	1.63	5.96	1.32	5.81	1.33
HAMPER /p/								
young male	15.96	5.98	7.23	2.29	7.29	2.70	5.86	1.91
older male	15.63	6.47	7.27	2.14	5.24	1.59	6.69	1.87
young female	13.04	3.71	9.52	2.73	9.03	4.14	8.37	4.23
older female	13.30	5.33	6.92	1.05	6.53	1.14	6.54	1.43
HAMPER /m/								
young male	2.96	2.02	1.35	1.20	.78	.74	.44	.29
older male	2.55	2.29	1.25	.77	.72	.62	.54	.16
young female	2.36	1.10	1.03	.69	.35	.61	.63	.41
older female	1.56	1.63	.87	.59	.62	.33	.57	.27

Table A6: Medians and interquartile ranges (IQR) and means (*M*) and standard deviations (SD) of VP orifice area at each rate.

VP Orifice Area (mm2)								
	Fast		Normal		Slow		Slowest	
	Median	IQR	Median	IQR	Median	IQR	Median	IQR
BBP /p/								
young male	.23	.20	.29	.25	.34	.33	.23	.27
older male	.36	.21	.28	.15	.26	.33	.25	.23
young female	.07	.10	.15	.35	.21	.09	.17	.22
older female	.22	.03	.18	.18	.32	.19	.25	.24
HAMPER /p/								
young male	.33	.21	.30	.30	.57	.80	.26	.14
older male	.39	.65	.36	.54	.31	.25	.17	.45
young female	.12	.12	.26	.24	.22	.26	.12	.11
older female	.39	.20	.26	.14	.36	.26	.35	.16
	M	SD	*M*	SD	*M*	SD	*M*	SD
HAMPER /m/								
young male	17.99	9.82	11.09	8.51	9.64	8.80	9.05	11.23
older male	20.20	14.21	21.30	8.86	11.97	14.38	17.07	12.23
young female	18.95	11.05	14.86	12.29	5.99	7.66	8.56	8.43
older female	19.51	13.64	18.97	10.46	21.18	12.05	10.70	13.69

Table A7: Means (*M*) and standard deviations (SD) of nasalance at each rate.

	Nasalance (%)							
	Fast		Normal		Slow		Slowest	
	M	SD	M	SD	M	SD	M	SD
BBP								
young male	17.53	5.51	8.67	3.68	7.20	3.34	7.47	3.23
older male	12.00	2.41	10.75	1.96	9.58	1.31	9.50	2.02
young female	21.93	5.20	14.00	3.48	12.27	3.71	17.60	9.34
older female	10.50	1.99	13.40	5.58	11.73	3.74	8.87	2.80
MMJ								
young male	53.07	7.58	48.87	6.31	49.020	8.99	49.00	5.63
older male	57.33	7.23	58.67	10.36	59.83	7.16	58.25	7.26
young female	57.37	13.03	59.60	6.36	61.33	7.23	55.80	8.06
older female	56.67	7.18	58.27	8.00	62.00	5.01	61.73	5.46

Table A8: Means (*M*) and standard deviations (SD) of nasalance distance at each rate.

	Nasalance Distance (%)							
	Fast		Normal		Slow		Slowest	
	M	SD	M	SD	M	SD	M	SD
MMJ-BBP								
young male	35.53	7.02	40.20	4.47	42.00	7.24	41.53	5.37
older male	45.33	5.35	47.92	10.27	50.25	6.98	48.75	5.67
young female	38.93	6.04	45.60	3.58	49.07	8.95	38.20	4.78
older female	42.27	7.67	46.53	9.50	53.13	5.55	53.73	3.76

Table A9: Summary of statistical differences in the present study and Gauster et al. (2010) for nasal pressure (Pn).

Pn: Present vs Gauster et al. (2010)				
	Rate		Gender	
	Present Study	Gauster et al. (2010)	Present Study	Gauster et al. (2010)
BBP	Yes	No	No	No
HAMPER /p/	Yes	No	No	No
HAMPER /m/	Yes	No	No	No

Table A10: Summary of statistical differences in the present study and Gauster et al. (2010) for nasal flow (Fn).

Fn: Present vs Gauster et al. (2010)				
	Rate		Gender	
	Present Study	Gauster et al. (2010)	Present Study	Gauster et al. (2010)
BBP	No	No	No	No
HAMPER /p/	Yes	No	No	No
HAMPER /m/	Yes	No	No	No

Table A11: Summary of statistical differences in the present study and Gauster et al. (2010) for oral pressure (Po).

Po: Present vs Gauster et al. (2010)				
	Rate		Gender	
	Present Study	Gauster et al. (2010)	Present Study	Gauster et al. (2010)
BBP	Yes	No	No	No
HAMPER /p/	Yes	Yes/No*	No	No
HAMPER /m/	Yes	No	No	No

*Gauster et al. (2010) found a statistical difference between rates for the /p/ in HAMPER; however when the analysis was controlled for SPL, there was no significant difference.

Table A12: Summary of statistical differences in the present study and Gauster et al. (2010) for VP area.

VP Area: Present vs Gauster et al. (2010)				
	Rate		Gender	
	Present Study	Gauster et al. (2010)	Present Study	Gauster et al. (2010)
BBP	No	No	No	No
HAMPER /p/	No	No	No	No
HAMPER /m/	Yes	No	No	No

Table A13: Summary of statistical differences in the present study and Gauster et al. (2010) for nasalance and nasalance distance.

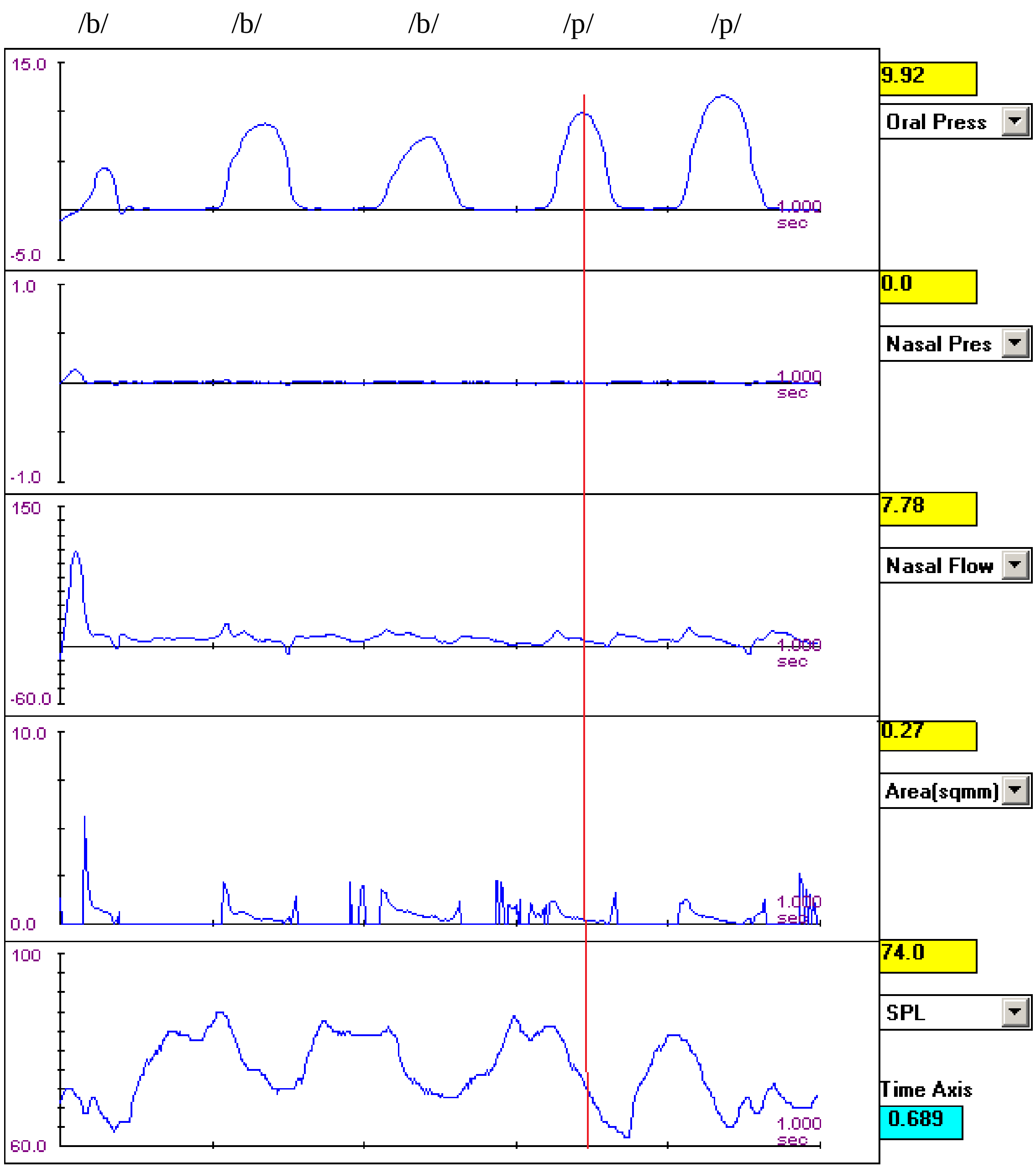
Nasalance and Nasal Distance: Present vs Gauster et al. (2010)				
	Rate		Gender	
	Present Study	Gauster et al. (2010)	Present Study	Gauster et al. (2010)
BBP	Yes	No	Yes	Yes
MMJ	Yes	No	No	Yes
Nasalance Distance	Yes	No	No	Yes

APPENDIX B: FIGURES

Figure B1: Aerodynamic Data Collection

Pictured above is the nasal mask, pneumotachograph, and air pressure sensing tubing portion of the PERCI-SAR system used to collect the aerodynamic measurements including oral pressure, nasal pressure, nasal flow, VP area, and SPL.

Figure B2: Perci Data Display



Above is a sample display of aerodynamic signals, derived VP orifice area, and voice intensity from the Perci software. Shown is the utterance of “Buy Bobby a puppy” with the consonants indicated above the display. The measurements (displayed in yellow on the right) were taken at the peak of the oral pressure for the first /p/ in “puppy”.

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