THE EFFECT OF SPEAKING RATE ON VELOPHARYNGEAL FUNCTION IN
HEALTHY SPEAKERS

by

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ABSTRACT

The Effect of Speaking Rate on Velopharyngeal Function in Healthy Speakers

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This study investigated the effect of speaking rate on aerodynamic and acoustic measures of velopharyngeal (VP) function in 27 adult speakers (14 M, 13 F). The pressure-flow method (Warren & Dubois, 1964) was used to collect aerodynamic data of /m/ and /p/ segments in the word “hamper” and the utterances “Mama made some lemon jam” (MMJ) and “Buy Bobby a puppy” (BBP). A Nasometer was used to collect nasalance scores and nasalance distance for MMJ and BBP. Measures were collected under 4 speaking rate conditions (normal, fast, slow, and slowest). Results indicated that nasal airflow and VP orifice area were unaffected by speaking rate whereas intraoral pressure decreased as speaking rate slowed. Nasalance was greater for BBP at slow speaking rates and nasalance distance (MMJ – BBP) decreased at slow rates. The data was interpreted with respect to expectations set forward in the literature on normal and disordered speech motor control.

“Curiosity has its own reason for existing”
- Albert Einstein

To everyone in my life who encouraged me to ask questions.

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TABLE OF CONTENTS

Abstract.....	ii
Acknowledgements.....	iv
Table of Contents.....	v
List of Tables and Figures.....	vii
Introduction.....	1
Velar Anatomy and Physiology.....	2
Segment Identity and Phonetic Context.....	4
Segment Position and Stress.....	5
Age Effects.....	6
Gender Effects.....	7
Speaking Rate Effects.....	8
Kinematic measures of VP function and rate manipulations: The phenomenon of movement undershoot.....	8
Acoustic measures of VP function and rate manipulations.....	10
Aerodynamic measures of VP function and rate manipulations.....	11
Questions of the Present Study.....	13
Hypotheses.....	13
Method.....	15
Participants.....	15
Speech Sample.....	16
Data Acquisition and Processing.....	17

Measurements.....	19
Data Analysis.....	23
Statistical Analysis.....	24
Results.....	25
Durational Measures.....	25
Sound Pressure Level.....	26
Intraoral Pressure.....	27
Nasal Airflow.....	28
Nasal Pressure.....	29
VP Orifice Area.....	30
Nasalance and Nasalance Distance.....	31
Discussion.....	32
VP Orifice Area.....	33
Nasal Airflow Rate.....	36
Intraoral Pressure.....	38
Mean Nasalance and Nasalance Distance.....	40
Gender Effects.....	42
Clinical Relevance.....	42
Conclusions.....	43
References.....	44

LIST OF TABLES AND FIGURES

Table 1	Participant demographics.....	16
Table 2	Durational measures of utterances used for aerodynamic measures.....	25
Table 3	Durational measures of utterances used for measures of nasalance.....	26
Table 4	Sound pressure level.....	27
Table 5	Intraoral pressure.....	28
Table 6	Nasal airflow for /m/ segments of interest.....	29
Table 7	Nasal airflow for /p/ segments of interest.....	29
Table 8	Nasal pressure.....	30
Table 9	VP orifice area for /m/ segments of interest.....	30
Table 10	VP orifice area for /p/ segments of interest.....	31
Table 11	Nasalance and nasalance distance.....	32
Figure 1	Equipment set up.....	19
Figure 2	Aerodynamic trace typical for the word HAMPER	20

INTRODUCTION

The purpose of this study was to investigate the effect of speaking rate on aerodynamic and acoustic measures of velopharyngeal (VP) function in healthy speakers. This study was motivated by the lack of a detailed investigation of this type in current literature and the need, particularly from a clinical perspective, to distinguish effects of disease on VP dysfunction from those related to speaking rate changes which are common in individuals with motor speech disorders.

The clinical impetus for studying the effects of speaking rate on VP function lies in the fact that both VP function *and* speaking rate may be simultaneously affected in speakers with neurologic conditions such as Amyotrophic Lateral Sclerosis (ALS) (Delorey, Leeper, & Hudson, 1999) or Traumatic Brain Injury (TBI) (McHenry, 1999). For example, a recent study reported that measures of VP function declined earlier than any other speech measures in a group of speakers with ALS, suggesting that measures of VP function could serve as a possible early behavioural biomarker of disease onset and progression in the bulbar form of the disease (Green, Yunusova, Ball, Mefferd, & Pattee, 2006). However, speaking rate was also found to be slower than baseline in these speakers and has been generally found to decline early in ALS (Ball, Willis, Beukelman, & Pattee, 2001; Ball, Beukelman, & Pattee, 2002; Yorkston, Strand, Miller, Hillel, & Smith, 1993). Thus the nature of the relationship between these two variables must be understood in order to distinguish the changes associated with muscular abnormalities (e.g., weakness) in the VP mechanism from those that are due to adjustments in speaking

rate that could be related to impairments across the speech system as a whole or could be compensatory in nature (Yorkston, Beukelman, Strand, & Bell, 1999).

Velar Anatomy and Physiology

The velum (velopharynx, soft palate) is a flexible extension of the hard palate composed of muscle, connective tissue, nerves, and blood vessels. The primary muscle responsible for elevating the velum is the levator veli palatini (Bell-Berti, 1976; Bell-Berti, 1993) which is innervated by the mandibular branch of the trigeminal nerve (cranial nerve V) (Seikel, King, & Drumright, 1997). The tensor veli palatini, musculus uvulae, palatoglossus, and palatopharyngeus muscles also play a role in changing the shape and position of the velum (Seikel et al., 1997). These muscles are innervated by the vagus nerve and/or accessory nerve (cranial nerves X and XI respectively) (Seikel et al., 1997). Correlations have been observed between levator veli palatini EMG potentials and velar height (Bell-Berti & Hirose, 1975) and between velar height and the degree of VP opening (Ushijima & Sawashima, 1972). At the same time, it has been debated whether velar lowering results from relaxation of the muscles responsible for velar elevation or from contraction of the palatoglossus and palatopharyngeus muscles (Seikel et al., 1997). Regardless of how velar movement is controlled, it is clear that complex interplay between various muscles is required for proper functioning of the velum during speech.

The velum plays a vital role in speech, breathing and swallowing. It functions as a valve which, when elevated, blocks the nasal cavity and nasopharynx from the oral

cavity and lower portions of the pharynx (Seikel et al., 1997). In this position, the velum and pharyngeal walls create a seal necessary for deglutition and sucking (Barlow, Finan, Andreatta, & Paseman, 1997). In its lowered position, the velum allows for nasal breathing to occur (Barlow et al., 1997). Pharyngeal wall movement may play a role in VP valving. The contribution of the pharyngeal wall to VP closure has been observed in a number of studies (Iglesias, Kuehn, & Morris, 1980; Magen, Kang, Tiede, & Whalen, 2003; Minifie, Hixon, Kelsey, & Woodhouse, 1970; Zagzebski, 1975). Four different patterns of VP closure which involve movement of the lateral and/or posterior pharyngeal walls (e.g. the velum and pharyngeal walls move equally to close the VP port at the midline) have been described in normal speakers (see Croft, Shprintzen, & Rakoff, 1981).

During speech, the velum acts as an articulator and distinguishes nasal from non-nasal sounds by varying the degree of oral-nasal coupling (Bell-Berti, 1980). In English, nasal sounds include the consonants /m/ (bilabial), /n/ (alveolar) and /ŋ/ (velar). In order to properly produce these sounds, the velum must assume a lowered position in order for proper nasal resonance to be achieved. All other sounds in English are considered non-nasal. Obstruent consonants such as /p/ are produced with the velum in an elevated position, allowing for the adequate build up of intraoral pressure. The degree of velar elevation differs for specific sounds (Bell-Berti, 1980) and is also dependent on phonetic context (Kuehn & Moon, 1998), prosodic factors such as position in an utterance and stress (Krakow, 1993), and speaking rate (Bell-Berti & Krakow, 1991a; Bell-Berti, Krakow, Gelfer, & Boyce, 1995; Bzoch, 1968; Kent, Carney, & Severeid, 1974; Kuehn, 1976; Moll & Shriner, 1967). VP function might also be influenced by age and gender

(Hoit, Watson, Hixon, McMahon, & Johnson, 1994; Hutchinson, Robinson, & Nerbonne, 1978; McKerns & Bzoch, 1970; Seaver, Dalston, Leeper, & Adams, 1991; Thompson & Hixon, 1979; Zajac & Mayo, 1996; Zajac, 1997). A brief description of how each of these factors affects VP function and a detailed literature review on the effects of speaking rate on VP function follows.

Segment Identity and Phonetic Context

In the early years of studying VP function in speech, its presumed simplicity (i.e., opening and closing states of the VP port) led to the description of velar function in terms of binary control (Denes & Pinson, 1973; Moll & Daniloff, 1971). In this view, the velum had two specified positions: elevated for non-nasal sounds [-nasal] and lowered for nasal sounds [+nasal] (Chomsky & Halle, 1968). This view, however, was not confirmed by empirical tests. Movement studies have shown that velar position for vowels seems to decrease through the series /i/, /u/, /o/, /e/, /a/ (see Bell-Berti, 1980 for a review; Krakow, 1993; Ushijima & Sawashima, 1972). Similarly, a measure of velar-to-pharyngeal wall contact force during the production of sustained vowels revealed that velar closing force was higher for high (/i/ and /u/) versus low (/æ/ and /ɑ/) vowels (Kuehn & Moon, 1998; Moon, Kuehn, & Huisman, 1994). Velar position differed for consonants as well and was sensitive to place of articulation, voicing, and manner of production (Bell-Berti, 1980; Krakow, 1993; Kuehn & Moon, 1998). For example, Kuehn and Moon (1998) discovered that, in a high-back vowel context, VP closure may be tighter for dorsal /k/ versus apical /t/ in males. Males also exhibited less velar closing force for voiced as compared to voiceless alveolar fricatives in a high-vowel context (Kuehn & Moon,

1998). Nasal airflow, a measure sensitive to the presence of VP opening, was observed more frequently in voiced compared to voiceless consonants (Hoit et al., 1994).

Expectedly, velar closure force and levator veli palatini EMG potentials were greater for a plosive /t/ and fricative /s/ than for a nasal /n/ (Kuehn & Moon, 1998).

Velar position and nasal airflow differed for isolated sounds as compared to the same sounds when they were produced in connected speech (Hoit et al., 1994; Moll, 1962; Moll & Shriner, 1967). Velar closing force and nasal airflow was observed to be less for non-nasal consonants preceding a nasal consonant than for those following a nasal consonant (Hoit et al., 1994; Krakow, 1993). Furthermore, nasal airflow increased for obstruent consonants which followed a nasal consonant in the /mp/ blend in the word “hamper”, as compared to the same consonant produced in an oral environment or in isolation (Warren, Dalston, Morr, Hairfield, & Smith, 1989). Additionally, velar closing force and EMG potentials of the levator veli palatini revealed greater muscle activity for various consonants produced in high (/iCi/ and /uCu/) as compared to low (/aCa/) vowel contexts (Kuehn & Moon, 1998). In sum, velar position appears to be important for segment distinction in isolation and in the speech stream.

Segment Position and Stress

A segment’s position within a word or sentence affects velar function. For example, Krakow found that velar lowering began earlier and reached lower positional extremes during word final as compared to word initial nasals (1993). Velar position for vowels preceding word-final nasals was also lower, making them more likely to be

nasalized than their word-initial counterparts (Krakow, 1993). Obstruent consonants at the end of a sentence have decreased velar elevation in comparison to obstruent consonants at the beginning of a sentence; a phenomenon known as declination (Bell-Berti & Krakow, 1991b). Intraoral pressure, another aerodynamic measure associated with VP function, has been affected by the declination effect as well (Zajac, 1997).

Syllable stress appears to enhance velar elevation (Krakow, 1993). Velar height increased for stressed oral consonants and reached lower positions for stressed nasal consonants in comparison to their unstressed counterparts (Vaissière, 1988 cited in Krakow, 1993). Syllable stress appears to affect temporal patterns of velar movement as well. Velar elevation has been shown to be initiated later for stressed as compared to unstressed syllables (Krakow, 1987).

Age Effects

Studies on the effect of age on velar function have been inconclusive at best. “Abnormally high” nasalance, an acoustic measure of VP function, has been reported in oral utterances for adults over 50 years of age (Hutchinson et al., 1978). Increased nasalance has been suggested to be the result of age-related neuromuscular weakness of the velum (Hutchinson et al., 1978). On the contrary, aerodynamic studies have revealed no effect of age on nasal airflow rate across various age groups including individuals over 80 years of age (Hoit et al., 1994; Zajac, 1997). Higher than normal intraoral pressure, however, has been reported for obstruent consonants produced by older adults (68 – 83 years) (Zajac, 1997). This was interpreted as the result of differences in respiratory effort

levels rather than VP function per se or possibly increased vocal intensity due to age-related hearing loss (Zajac, 1997). Note that elderly speakers are also known to speak at slower speaking rates than younger speakers (Hoit et al., 1994). Speaking rate was not controlled for in any of the aforementioned studies.

Gender Effects

Although velar anatomy and function may differ between females and males, empirical evidence of the gender effect is equivocal at this point. Velar length and mean height of elevation is known to be generally greater in males (McKerns & Bzoch, 1970). In females however, the angle of velar orientation toward the pharynx is more acute and velar contact with the pharyngeal wall appears to be greater (McKerns & Bzoch, 1970).

Males have also been reported to produce greater intraoral pressure levels during obstruent consonants (Zajac & Mayo, 1996; Zajac, 1997) and greater nasal airflow during nasal consonants (Hoit et al., 1994). Females on the other hand, have been reported to show greater nasalance scores on nasal sentences (Hutchinson et al., 1978; Seaver et al., 1991). Anticipatory nasal coarticulation has been suggested to occur earlier in females as demonstrated by the earlier onset of nasal airflow on vowels preceding a nasal consonant (Thompson & Hixon, 1979). Interestingly, Zajac and Mayo (1996) found no difference in anticipatory nasal airflow or volume between males and females but reported that females required a longer time period to reach peak intraoral pressure than males (Zajac & Mayo, 1996). Kuehn and Moon (1998) reported no gender differences in velar closing

force across experimental conditions (i.e., place and manner of articulation, voicing, and consonant sequencing in different vowel contexts).

It is clear that many factors must be taken into consideration when studying VP function. One additional factor might be speaking rate. A detailed literature review regarding what is known about the effect of speaking rate on VP function follows.

Speaking Rate Effects

Kinematic measures of VP function and rate variations: The phenomenon of movement undershoot

Most of what is known regarding VP function at different speaking rates in healthy speakers stems from movement studies which have provided information regarding the position and timing of VP movements during speech (Bell-Berti & Krakow, 1991a; Bell-Berti et al., 1995; Kent et al., 1974; Krakow, 1993; Kuehn, 1976; Moll & Shriner, 1967).

One of the findings across published movement studies is articulatory undershoot - the decrease in velar displacement - at fast as compared to normal and slow speaking rates (Kent et al., 1974; Kuehn, 1976; Moll & Shriner, 1967). For example, Moll and Shriner (1967) reported a decrease in velar lowering for nasal consonants and a decrease in velar elevation for vowels at fast (4 syllables per second) as compared to slow (1 syllable per second) speaking rates in the syllables /ma/ and /mu/ in two participants. Other movement studies have highlighted the between speaker variability in the extent

and direction of velar undershoot however, as well as the mechanism through which individuals may change their speaking rate. Kent and colleagues (1974) for example, described velar undershoot for one participant during the sentence “Soon the snow began to melt” produced at fast as compared to normal speaking rates. This study revealed decreased velar elevation for consonants and increased velar elevation for nasals during fast speaking rates in one speaker. The second participant in this study showed minimal velar undershoot during the same utterance at the fast speaking rate and achieved similar velar positions by increasing the velocity of velar movements (Kent et al., 1974). Kuehn (1976) also reported velar undershoot patterns during fast speaking rate conditions in two participants during VCNV and VNCV utterances. The direction of velar undershoot was different between participants however. One participant achieved similar velar minimums for nasals at both fast and normal speaking rates, but decreased the amount of velar elevation for oral consonants at fast speaking rates (Kuehn, 1976). The second participant in this study did the opposite, and achieved similar velar elevation for oral consonants during both speaking rates but decreased the amount of velar lowering for nasals at fast speaking rates (Kuehn, 1976). These early reports of velar undershoot at fast as compared to normal speaking rate conditions were confirmed in more recent work by Bell-Berti and colleagues examining velar movements using the Velotrace in three speakers (Bell-Berti & Krakow, 1991a; Bell-Berti et al., 1995).

The effect of speaking rate on VP function has been predominantly studied using kinematic measures. Minimal evidence exists in the literature regarding speaking rate effects on other, less invasive and perhaps more clinically applicable, objective measures

of VP function such as acoustic and aerodynamic measures. The following section highlights what is known about speaking rate effects on these measures in healthy speakers.

Acoustic measures of VP function and rate variations

To my knowledge, only two studies have assessed the effects of speaking rate on measures of nasal resonance (Brancewicz & Reich, 1989; Fletcher & Daly, 1976). Fletcher and Daly (1976) analyzed the effect of speakers' habitual speaking rate on the acoustic measure of nasalance in 50 speakers with impaired hearing and 64 control participants using the "Zoo Passage" (a passage without any nasal consonants). Nasalance data was obtained using the Quan-Tech TONAR II system. This study revealed that nasalance scores were higher for speakers with slower habitual speaking rates as compared to those with faster habitual speaking rates in control participants (Fletcher & Daly, 1976).

Brancewicz and Reich (1989) investigated the effect of self-controlled and computer-paced speaking rate variations on nasal and voice accelerometric measures in 10 healthy speakers. Accelerometers were placed on the participants' noses and necks. Participants were asked to speak at their self-controlled normal speaking rate, half their normal speaking rate, and as slowly as possible. They also spoke at rates that were paced at 1, 2 and 3 syllables per second. In this study, a vowel and semi-vowel loaded sentence, an obstruent loaded sentence, and a sentence with a single nasal consonant were embedded in a carrier paragraph. The study revealed no effect of speaking rate on the

nasal accelerometric vibrational index (NAVI), “an estimate of the degree of nasal resonance” (Brancewicz & Reich, 1989; p. 839), for any of the utterances.

Aerodynamic measures of VP function and rate variations

To my knowledge, only one study investigated the effect of speaking rate manipulation on aerodynamic measures of VP function in healthy speakers (Goberman, Selby, & Gilbert, 2001). The authors studied the effect of self-controlled and metronome-controlled speaking rate variation on peak nasal airflow rates and percent nasal airflow during schwa in the non-nasal sentence “it’s a story about *a* park” in 19 healthy speakers. The study revealed an increase in peak nasal airflow and percent nasal airflow at slow as compared to normal and fast speaking rate conditions (Goberman et al., 2001).

While it is clear that kinematic events must relate to aerodynamic events (pressures and flows) during speech sound production, the findings of the two types of studies seem contradictory. Kinematic work seems to show that velar height varies with speaking rate variation (Bell-Berti & Krakow, 1991a; Kent et al., 1974; Kuehn, 1976; Moll & Shriner, 1967). One may therefore expect nasal airflow to change at different speaking rates as well, due to the change in VP opening available for nasal air escape. While the difference in test utterances used between studies makes comparisons difficult, results from the two studies which assessed the effect of speaking rate on vowels are conflicting (Goberman et al., 2001; Moll & Shriner, 1967). Work by Moll and Shriner (1967) showed that velar elevation decreased for vowels at fast speaking rates due to velar undershoot. Based on this observation, nasal airflow might be expected to increase

at fast speaking rates due to the presumable increase in VP opening available for nasal air escape. The opposite occurred in the one published aerodynamic study however, in which nasal airflow did not differ between normal and fast speaking rates but increased at *slow* speaking rates (Goberman et al., 2001). Note that only one study has examined the effect of purposefully slowed speech on kinematic measures of VP function (Moll & Shriner, 1967).

No study to date has investigated the effect of speaking rate manipulations on aerodynamic measures of VP orifice area and intraoral pressure, both of which are commonly associated with VP function in healthy speakers and in pathologic conditions (Dalston, Warren, Morr, & Smith, 1988; Laine et al., 1988; Laine, Warren, Dalston, Hairfield, & Morr, 1988; Warren, 1979). However, there might be reason to expect a direct relationship between the measures of VP orifice area and kinematic measures. For example, one kinematic study showed that velar distance, the distance between the velum and the posterior pharyngeal wall as measured by fiberoptic observation, was directly related to velar height, with lowering of the velum resulting in an increase in velar distance (Ushijima and Sawashima, 1972).

The effect of speaking rate on intraoral pressure is important to examine as this measure has been viewed as a controlled parameter in speech (Kim, Zajac, Warren, Mayo, & Essick, 1997; Klechak, Bradley, & Warren, 1976; Putnam, Shelton, & Kastner, 1986; Warren, Hall, & Davis, 1981; Warren, 1982; Warren, 1986; Warren et al., 1989; Warren, Morr, Rochet, & Dalston, 1989). Based on the increased oral airflows observed

at greater VP port openings in normal speakers and in those with open bite, Warren hypothesized that respiratory adjustments serve to maintain adequate levels of intraoral pressure during speech (Klechak et al., 1976; Warren et al., 1981; Warren, 1982). This was supported by the observed increase in respiratory effort in healthy speakers with perturbed speech conditions designed to mimic VP inadequacy (Warren et al., 1989) and in individuals with cleft palate (Warren, 1986). Mechanical models of the vocal tract developed to predict changes in oral pressure due to VP inadequacy provided further support for this hypothesis. Intraoral pressure in these models decreased to levels well below 3.0 cmH₂O when the orifice area was set to 0.5 cm² whereas the loss of oral pressure below 3 cmH₂O was rarely observed in individuals with equal VP orifice areas (Kim et al., 1997; Warren et al., 1989; Laine et al., 1988; Warren, 1986). Understanding how speaking rate affects intraoral pressure may therefore provide important information relevant to understanding basic principles of speech motor control.

Questions of the Present Study

The following questions will be addressed in this study: (1) Does speaking rate affect measures of intraoral pressure, nasal airflow, and VP orifice area? and (2) Does speaking rate affect the acoustic measure of nasalance in a large group of healthy adult speakers?

Hypotheses

Due to the limited amount of data available in the literature regarding speaking rate effects on other measures of VP function, the following hypotheses were based

primarily on movement studies and the theory that intraoral pressure is a regulated parameter in speech. Specifically, it was expected that at a fast rate of speech the velum would lower to a lesser extent for nasal consonants than it would at normal or slow speaking rates (Moll & Shriner, 1967). This was expected to result in a decrease in VP orifice area. Conversely, slow speaking rates would result in an increase in VP orifice area for nasal consonants (as a result of the expected increase in velar lowering at slower speaking rates) (Moll & Shriner, 1967). VP orifice area for oral consonants was expected to remain unaffected by speaking rate as participants in the present study had intact VP mechanisms and were therefore expected to achieve adequate VP closure regardless of change in velar height.

Changes in VP orifice area in a nasal context might elicit responses in respiratory effort which would serve to maintain stable levels of intraoral pressure (Klechak et al., 1976; Warren et al., 1981; Warren, 1982). Thus, nasal airflow was expected to increase if VP orifice area increased and decrease if VP orifice area decreased whereas intraoral pressure was expected to remain stable across speaking rate conditions for both nasal and oral consonants.

Based on Fletcher and Daly's finding that nasalance increased as speaking rate slowed (1976) and the consistent reports that perceived nasality increased at slow speaking rates (Brancewicz & Reich, 1989; Colton & Cooker, 1968; Goberman et al., 2001), it was expected that nasalance may increase as speaking rate slows for both oral and nasal sentences in the present study.

METHOD

Participants

27 healthy adult speakers (14 males and 13 females) participated in this study. Participants were recruited through advertisement. Table 1 lists demographic and dialect information for each participant. The average age of speakers in the male group was 54.1 years (SD = 14.1, range = 41 - 87). The average age of speakers in the female group was 58.2 years (SD = 11.2, range = 48 - 86). The age range of participants corresponded with that of a typical population affected by ALS (Brooks et al., 1991). All but 4 participants (N012, N016, N020, N023) grew up in English speaking Canada or the United States. The remaining 4 participants immigrated to Canada as adults but spoke English fluently. The diverse pool of speakers reflected the ethnic diversity of the Greater Toronto Area. All participants were free of maxillofacial anomalies and reported a negative history of speech problems, speech therapy, and condition or use of medication that may affect speech. Voice and resonance were judged informally by a speech-language pathologist to be within normal limits for all participants. Adequate hearing for speech and normal nasal patency was reported by each participant. All participants gave their informed consent to participate in the study, which was approved by the Research Ethics Board at the Sunnybrook Health Science Centre and the University of Toronto.

Table 1. Participant ID, age, gender, and dialect base

ID	Age (years)	Gender	Dialect Base*
N02	65	M	Ontario
N03	69	F	Ontario
N05	50	F	Ontario
N06	56	M	Ontario
N07	50	M	Ontario
N08	48	M	Quebec
N09	47	M	Nova Scotia
N010	55	F	Ontario
N011	44	M	Ontario
N012	52	F	China (Cantonese)
N013	41	M	Ontario
N014	54	F	Michigan
N015	51	F	Ontario
N016	54	F	South Africa (Gujarati)
N017	48	F	Ontario
N018	58	F	Ontario
N020	86	F	England (British)
N021	87	M	Ontario
N022	81	M	Ontario
N023	55	F	South Africa (Afrikaans)
N024	74	F	Ontario
N025	44	M	Ontario
N026	52	F	Newfoundland
N027	47	M	Ontario
N028	56	M	Ontario
N029	45	M	Ontario
N030	47	M	Nova Scotia

*Note. When not North American English, language of dialect base is indicated in brackets

Speech Sample

Participants were seated in a comfortable chair and asked to read the utterances “hamper” (HAMPER), “Buy Bobby a puppy” (BBP) and “Mama made some lemon jam” (MMJ). Each utterance was read with normal loudness and was repeated 5 times at four, self-controlled speaking rates (i.e., normal, fast, slow and slowest). Like in previous rate studies (Brancewicz & Reich, 1989; Goberman et al., 2001), the order of speaking rate condition was held constant for all participants. This was done to circumvent variability in speaking rate associated with order of presentation (Goberman et al., 2001) and to ensure that all speakers slowed their speaking rate (see Brancewicz & Reich, 1989). At the fast rate, the speakers were asked to produce speech at twice the speed of one’s

normal speaking rate. Slow rate was defined as half one's normal speaking rate, and slowest rate was as slowly as possible while still producing intelligible speech. Speakers were discouraged from pausing between words during slow rate productions. The protocol was performed twice by each participant: once for the aerodynamic recording and once using the Nasometer. Recordings were performed on the same day, one protocol immediately following the other for each participant. The order of each recordings varied between participants.

Consonants /p/ in “a puppy” of BBP, /m/ in “mama made” of MMJ, and the sound combination /mp/ in HAMPER were studied. These sound stimuli are commonly used in the literature to investigate VP function in healthy speakers and speakers with VP abnormalities (Zajac, 2000). Three repetitions of each syllable in the middle of the string of repetitions were used for the analyses.

Data Acquisition and Processing

Aerodynamic, acoustic and nasometric data were recorded directly onto the hard drive of a PC. Aerodynamic signals including intraoral air pressure (P_o), nasal air pressure (P_n), and nasal airflow (V_n) were collected using the MP150 Data Acquisition System (Biopac Systems, Inc.) and AcqKnowledge software (Figure 1, a). Flexible polyethylene pressure catheters (1.7 mm internal diameter) were used to collect P_o and P_n (mmH₂O). Catheters were coupled to the positive side of two differential pressure transducers (TSD160A) referenced to the atmosphere. The P_o catheter was hand-held perpendicular to airflow in the oral cavity approximately 10mm behind the central

incisors. The Pn catheter sensed pressure inside the nasal mask (Ultra Mirage II, Resmed) which was used to collect V_n (ml/s). The mask was placed on each participant in such a way that ensured a tight seal and no air leakage. The nasal mask was coupled to a pneumotachograph (Fleisch #1). The pressure drop across the pneumotachograph screen was monitored by means of a pressure transducer (TSD160A). The aerodynamic equipment was calibrated once prior to each recording day following manufacturer specifications. Aerodynamic channels were digitized at 200 Hz. Differential pressure (P_{o-n}) was derived by subtracting the nasal pressure trace from the oral pressure trace. All aerodynamic data was then low pass filtered at 30 Hz. Aerodynamic data collection replicated methods reported in the literature (Andreassen, Smith, & Guyette, 1992; Hoit et al., 1994; Mayo, Warren, & Zajac, 1998; Stathopoulos, 1986; Warren, Dalston, Trier, & Holder, 1985; Zajac & Mayo, 1996).

Sound pressure level (dB) was collected in synchrony with acoustic and aerodynamic data using the MP150 Data Acquisition System at a sampling rate of 25 kHz and displayed in the AcqKnowledge software. The high quality microphone was positioned approximately 15 cm from the speaker's mouth. The channel was calibrated using an SPL meter (Extech Instruments) prior to each recording.

Speech samples were digitally recorded at 25 kHz synchronously with the aerodynamic and SPL channels using the MP150 Data Acquisition System. A high quality headset microphone (Countryman E6) was used to obtain the recordings. The microphone was placed laterally approximately 5 cm from the speaker's mouth.

Nasalance for each utterance was obtained using the Nasometer II (Model 6400; Kay Elemetrics, Pine Brook, NJ, USA; see Figure 1, b). The headset-like device was placed on participants with its plate resting on the upper lip, parallel to the floor. Oral and nasal acoustic energy were recorded separately at a pre-set sampling rate of 11025 Hz by two microphones situated on opposite sides of the plate.

Figure 1. a) aerodynamic set-up

b) Nasometer KayPentax

Aerodynamic traces were inspected to ensure that there were measurable P_o and V_n peaks in each segment of interest. Intervals containing segments of interest were parsed based on the speech waveform.

Measurements

(1) Acoustic durations were measured using the speech waveform. The goal of these measures was to ensure that participants changed their speaking rate accordingly for each rate category (e.g., spoke faster in the fast speaking rate condition compared to normal). Because durational measures were not used as independent variables and were important in the global sense only, reliability measures were not performed. The intervals for

measurement were chosen based on ease of boundary identification and remained the same for each utterance across all 4 speaking rates. They included:

Figure 2. Representation of an aerodynamic trace typical for the word HAMPER. Vertical lines A and B represent interval boundaries used to make temporal measurements. Arrows and the numbers 1 - 4 indicate where P_o and V_n measurements were taken for each /m/ and /p/ segment.

(a) the interval between the offset of the vowel preceding the initial /p/ in “puppy” to offset of the vowel following the initial /p/ in “puppy”

(b) the interval between the onset of the vowel preceding /m/ in “made” to the offset of the vowel [diphthong] following /m/ in “made”

(c) the interval between the onset of the vowel /ae/ to onset of the vowel /ε^/ for /mp/ in HAMPER (this interval is marked as horizontal lines A and B in Figure 2).

(d) Sentence durations as a whole were measured for the utterances recorded using the Nasometer

Measures 2 to 6 were obtained automatically using a custom-written algorithm.

(2) **Average SPL** (dB) was obtained from the SPL trace for each parsed data interval.

This measure was recorded because vocal intensity has been shown to affect aerodynamic measurements (Holmberg, Hillman, Perkell, & Gress, 1994; Stathopoulos, 1986).

(3) **Po max** for /p/ was obtained at the maximum value of the oral pressure during the measured interval (marked as “4” in Figure 2). For /m/, Po was taken at the point of maximum nasal flow during the nasal consonant (marked as “2” in Figure 2).

(4) **Vn max** for /m/ was obtained at the point of maximum nasal flow during /m/ (marked as “1” in Figure 2); for /p/, Vn was measured at the point of Po maximum (marked as “3” in Figure 2).

Po max and Vn max were measured in this study because they have been shown to describe accurately normal VP function and to be sensitive to VP dysfunction (Dalston et al., 1988; Laine et al., 1988; Laine et al., 1988; Warren, 1979).

(5) **Pn** for /m/ was obtained at the point of maximum Vn. For /p/ Pn was obtained at the point of maximum Po. Pn was used to calculate differential pressure (intraoral pressure minus nasal pressure; Po-n) which was used to calculate VP orifice area (see below).

(6) **VP orifice area** was calculated for each /m/ and /p/ segment of interest using the hydrokinetic equation (Warren & DuBois, 1964):

$$Area = \frac{Vn}{k \sqrt{\frac{2(Po - n)}{D}}}$$

where Vn = the airflow through the nasal orifice (ml/s), $Po-n$ = differential pressure (cmH₂O), $k = 0.65$ and D = density of air (0.001 g/cm³). Calculations were made using measurements taken at the time of the oral pressure peak for /p/ and at the time of the nasal flow peak for /m/. Units were converted when necessary for the purpose of VP orifice area calculation. VP orifice area is a common measure of VP function (Warren, 1979; Zajac & Mayo, 1996).

(7) Mean nasalance was estimated for each recorded utterance. The intensity of the oral and nasal signals was measured directly by the two microphones as described above and then converted into a ratio (nasal/nasal+oral) which was, after multiplication by 100, expressed as percent nasalance. Nasalance reflects the relative proportion of nasal to nasal + oral acoustic energy in the speech stream. Nasalance measures were included in this study as they have been found to most accurately reflect listener perception of nasality (McHenry, 1999).

(8) Nasalance distance (MMJ-BBP) was derived by subtracting the mean nasalance calculated across oral sentences (BBP) from the mean nasalance calculated for the nasal sentences (MMJ). Nasalance distance was included in this study because it has been said to allow for the better control of within speaker variability and has been shown to be a useful clinical measure (Bressmann et al., 2000) .

Data Analysis

Data were examined visually prior to performing any analyses. Slightly negative Vn values were observed in 16.4% of data for /p/ in HAMPER ($M = -3.23$ ml/s; $SD = 3.11$) and 42.6% of the data in BBP ($M = -2.74$ ml/s; $SD = 1.10$). These negative values were suspected to be due to velar bounce produced during plosives (Hoit et al., 1994). These data points were replaced by zeros to indicate complete VP closure and used to generate summary statistics and to calculate VP orifice area.

Pn values were slightly greater than Po for 9.5 % of /m/ in HAMPER and 17.4% of data in MMJ resulting in a negative Po-n ($M = -0.31$ cmH₂O, $SD = 0.23$ for /m/ in HAMPER; $M = -0.30$ cmH₂O, $SD = 0.24$ for MMJ). Because negative values could not be used in the calculation of VP orifice area, they were converted to absolute values.

The data distribution for each variable was checked visually and with the One-Sample Kolmogorov-Smirnov test for normalcy. Distributions for SPL, Po, Nasalance, and Vn (the latter measures for /m/ only) were normal for each utterance. VP orifice area for /m/ was non-normally distributed and thus log-transformed prior to statistical analyses. Means and standard deviations (SD) are reported for normally distributed variables. Vn and VP orifice area for /p/ revealed non-normal distributions due to a large amount of zero values. Medians and interquartile ranges (IQR) are reported for these two variables.

Outliers (data points that were 3 SD above the mean) were removed from the statistical analyses. For /p/ in BBP, the outliers included: 2 data points of Vn for N030 (normal and slowest rate productions) and 2 data points for VP orifice area for N014 (fast and slowest speaking rate productions). For /p/ in HAMPER, outliers included: Vn and VP orifice area for N030 during the normal speaking rate condition, and VP orifice area for N018 during the fast speaking rate condition.

Statistical analysis

Two methods of statistical analysis were used in this study. A linear mixed effect model (LME) with gender and rate as fixed factors and subject as a random factor was used to test speaking rate effects on the majority of variables. Because significant correlations of SPL with Po and Vn were observed across utterances ($r = 0.22 - 0.99$, $p < 0.05$), SPL was included as a covariate in the Po and Vn models. When the effect of rate was significant for the LME analyses, pairwise comparisons between speaking rates were performed.

29.5 % of Vn and VP orifice area data for the /p/ segments contained zeros, indicating the absence of nasal flow and a completely sealed VP port for the oral consonant. Because of the large proportion of zeros, a binary logistic regression was performed to test the probability of dependent variables to vary with speaking rate. The logistic regression required the data to be categorical in nature. Numerical data was therefore converted to “0s” and “1s” prior to analysis. For Vn, all values below 20 ml/s were replaced with 0 and all values above 20 ml/s were replaced with 1. The cut-off

value of 20 ml/s was used based on the average Vn during the production of /p/ observed in a large group of normal speakers and the finding that a complete VP seal is reflected by values of Vn equal to or lesser than 20 ml/s during /p/ in healthy speakers (Zajac & Mayo, 1996; Zajac, 2000). For VP orifice area, a categorical variable was created by replacing all values below 1 mm² with 0, and all other values with 1. This value was chosen based on mean VP orifice area values reported in the literature for the production of oral stops by healthy speakers (Zajac & Mayo, 1996; Zajac, 2000). For both LME and logistic regression, main effects were tested at a 0.05 *p*-value. Pairwise comparisons were performed using Tukey's Honestly Significant Differences.

RESULTS

Durational Measures

Durational measures computed across speakers for each utterance used for the aerodynamic and nasometric recordings are reported in Tables 2 and 3, respectively. They revealed that participants changed their speaking rate accordingly for each speaking rate condition. Fast speaking rate was, on average, 20 – 38% faster than the normal speaking rate condition. Slow speaking rate was approximately 68 – 128 % slower than normal and slowest speaking rate was approximately 206 - 363 % slower than normal.

Table 2. Means (M) and standard deviations (SD) of the durational measures of utterances used for aerodynamic measures during fast, normal, slow, and slowest speaking rates

	Durational Measures (ms)							
	Fast		Normal		Slow		Slowest	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HAMPER	242.82	44.96	319.75	51.25	732.34	241.89	1473.11	589.28
BBP	172.43	23.58	210.81	33.26	360.96	172.71	711.55	399.05
MMJ	280.67	47.12	460.28	102.25	885.99	271.99	1682.92	658.09

Table 3. Means (M) and standard deviations (SD) of the durational measures of utterances used for measures of nasalance during fast, normal, slow, and slowest speaking rates

	Durational Measures (ms)							
	Fast		Normal		Slow		Slowest	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BBP	1058.09	160.89	1458.52	264.31	3118.26	1338.50	5703.38	2797.17
MMJ	1485.96	217.14	2198.81	427.49	4000.55	1577.24	6744.85	2955.62

Sound Pressure Level

Table 4 summarizes the SPL results for each utterance and rate. On average SPL was 67.7 dB (SD = 4.8) for the production of HAMPER in the normal speaking rate condition. SPL was higher than normal in the fast speaking rate condition but not in the slow and slowest speaking rate conditions. LME revealed a significant main effect of speaking rate on SPL in HAMPER ($F_{3,25} = 42.067, p < 0.000$). Paired samples t-tests revealed that SPL was significantly higher in the fast compared to normal ($t_{22} = 5.164, p < 0.000$), slow ($t_{23} = 6.368, p < 0.000$), and slowest ($t_{26} = 5.943, p < 0.000$) speaking rate conditions.

LME revealed a significant main effect of speaking rate on SPL for BBP ($F_{3,22} = 43.54, p < 0.000$) and MMJ ($F_{3,7} = 10.952, p < 0.004$) utterances as well. Paired samples t-tests for BBP revealed that SPL was significantly higher in the fast as compared to normal ($t_{18} = 3.607, p < 0.001$), slow ($t_{24} = 6.724, p < 0.000$), and slowest ($t_{32} = 7.927, p < 0.000$) speaking rate conditions, and the normal compared to slow ($t_{23} = 3.117, p < 0.000$) and slowest ($t_{36} = 4.320, p < 0.000$) speaking rate conditions. For MMJ, pairwise comparison revealed that SPL was higher for fast compared to slow ($t_{25} = 2.927, p < 0.000$) and slowest ($t_{26} = 3.278, p < 0.001$) speaking rates and for normal compared to slow ($t_{28} = 1.848, p < 0.018$) and slowest ($t_{28} = 2.199, p < 0.037$) speaking rates. There was no effect of gender on SPL.

Table 4. Means (M) and standard deviations (SD) of SPL for each utterance used for aerodynamic measurements

	SPL (dB)							
	Fast		Normal		Slow		Slowest	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HAMPER	72.3	5.4	67.7	4.8	66.6	5.1	67.0	5.3
BBP	74.0	4.0	71.0	4.5	68.2	4.3	67.0	5.2
MMJ	70.5	4.2	69.4	4.2	67.1	4.1	67.4	5.7

Intraoral Pressure

Nasal Consonants. Table 5 provides a summary of Po calculated across speakers for each utterance. Mean Po for /m/ in HAMPER produced at the normal speaking rate was 1.33 cm H₂O (SD = 0.60). This value increased in the fast speaking rate condition and decreased during both slow speaking rate conditions. LME revealed a main effect of rate on Po in /m/ during HAMPER ($F_{3,30} = 9.735, p < 0.000$). Pairwise comparisons revealed a significant difference between the fast speaking rate condition and the normal ($t_{24} = 0.624, p < 0.026$), slow ($t_{22} = 0.932, p < 0.000$), and slowest ($t_{21} = 0.878, p < 0.001$) speaking rate conditions.

Mean Po for /m/ in MMJ during the normal speaking rate condition was 0.61 cm H₂O (SD = 0.33) and remained similar across all speaking rate conditions. LME revealed no main effect of rate on Po of /m/ during MMJ.

Oral Consonants. Mean Po for /p/ in HAMPER during the normal speaking rate was 6.06 cm H₂O (SD = 1.22). This value tended to increase during the fast speaking rate condition and decrease during both slower speaking rate conditions. LME revealed a main effect of rate on Po of /p/ during HAMPER ($F_{3,27} = 12.206, p < 0.000$). Pairwise comparisons revealed a significant difference between the fast speaking rate condition

and the normal ($t_{13} = 0.965, p < 0.025$), slow ($t_{28} = 1.512, p < 0.000$), and slowest ($t_{32} = 1.723, p < 0.000$) speaking rates, and between the normal and slowest ($t_{34} = 0.758, p < 0.021$) speaking rate conditions.

Mean Po for /p/ in BBP during the normal speaking rate condition was 6.44 cm H₂O (SD = 1.19). This value was similar for the fast speaking rate condition but appeared to decrease during both slower speaking rate conditions. LME revealed a main effect of rate on Po of /p/ during BBP ($F_{3,20} = 8.262, p < 0.001$). Pairwise comparisons revealed a significant difference between the fast speaking rate condition and the slow ($t_{22} = 0.798, p < 0.021$) and slowest ($t_{37} = 1.186, p < 0.002$) speaking rate conditions, and between the normal speaking rate condition and the slow ($t_{28} = 0.538, p < 0.027$) and slowest ($t_{28} = 0.926, p < 0.006$) speaking rate conditions. Gender was not a significant factor in any of the models with Po as a dependent variable.

Table 5. Means (M) and standard deviations (SD) of Po for each segment of interest

	Intraoral Pressure (cmH ₂ O)							
	Fast		Normal		Slow		Slowest	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HAMPER /m/	1.91	0.88	1.33	0.60	1.03	0.54	1.09	0.48
HAMPER /p/	6.90	1.57	6.06	1.22	5.54	1.41	5.33	1.52
BBP	6.56	1.46	6.44	1.19	5.82	1.23	5.51	1.43
MMJ	0.72	0.36	0.61	0.33	0.59	0.28	0.53	0.33

Nasal Airflow

Nasal Consonants. Mean Vn for /m/ in HAMPER during the normal speaking rate condition was 229.21 ml/s (SD = 123.14). This value showed a tendency to decrease at fast and slower speaking rates (see Table 6). Mean Vn for /m/ in MMJ during the normal speaking rate condition was 206.07 ml/s (SD = 120.56) and showed a tendency to

decrease only during slower speaking rates. LME revealed no main effect of rate or gender on Vn in either /m/ segment.

Table 6. Means (M) and standard deviations (SD) of Vn for each /m/ segment of interest

	Nasal Airflow (ml/s)							
	Fast		Normal		Slow		Slowest	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HAMPER /m/	201.40	99.46	229.21	123.14	208.71	120.03	204.47	115.05
MMJ	206.52	121.10	206.07	120.56	174.96	99.63	189.96	104.34

Oral Consonants. Median Vn for /p/ in HAMPER during the normal speaking rate condition was 11.22 ml/s (IQR = 12.70; Table 7). Median Vn for /p/ in BBP during the normal speaking rate condition was small, only 2.98 ml/s (IQR = 5.79). These values showed a tendency to decrease at fast and slower speaking rates. Logistic regression revealed no main effect of rate or gender on Vn for either /p/ segment.

Table 7. Median and interquartile range (IQR) of Vn for each /p/ segment of interest

	Nasal Airflow (ml/s)							
	Fast		Normal		Slow		Slowest	
	Median	IQR	Median	IQR	Median	IQR	Median	IQR
HAMPER /p/	9.35	11.97	11.22	12.70	4.64	6.01	7.90	9.09
BBP	1.10	4.39	2.98	5.79	1.77	6.29	1.90	4.90

Nasal Pressure

Nasal Consonants. Summary statistics for Pn are reported in Table 8. Pn for /m/ in HAMPER remained similar across rate conditions whereas Pn for /m/ in MMJ appeared to decrease in the slower rate conditions.

Oral Consonants. Pn for /p/ in HAMPER and BBP remained similar across all speaking rate conditions.

Table 8. Means (M) and standard deviations (SD) of Pn for each segment of interest

	Nasal Pressure (cmH ₂ O)							
	Fast		Normal		Slow		Slowest	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HAMPER /m/	0.41	0.19	0.47	0.25	0.44	0.25	0.42	0.24
HAMPER /p/	0.03	0.03	0.04	0.05	0.02	0.02	0.03	0.03
BBP	0.02	0.05	0.02	0.03	0.02	0.03	0.02	0.03
MMJ	0.42	0.25	0.41	0.23	0.35	0.19	0.39	0.21

VP Orifice Area

Nasal Consonants. Table 9 shows the across-speaker averages for VP orifice area during the production of utterances containing /m/ segments of interest. In HAMPER, the measure remained relatively stable across all speaking rate conditions. In MMJ, the measure showed a tendency to decrease at fast and slower speaking rates compared to normal. LME revealed no main effect of rate on VP orifice area for either /m/ segment of interest. There was no main effect of gender on VP orifice area for either /m/ segment.

Table 9. Means and standard deviations (SD) of VP orifice area for each /m/ segment of interest

	VP Orifice Area (mm ²)							
	Fast		Normal		Slow		Slowest	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HAMPER /m/	27.61	27.10	32.62	22.25	31.68	20.30	35.32	29.44
MMJ	41.63	27.75	48.09	30.79	36.62	21.85	42.50	20.00

Oral Consonants. Median VP orifice areas for /p/ in HAMPER and BBP are reported in Table 10. During the normal speaking rate condition VP orifice area was 0.48 mm² (IQR = 0.55) for HAMPER. This value remained similar to normal during the fast speaking rate condition but showed a tendency to decrease somewhat during the slower speaking rate conditions. Logistic regression revealed no main effect of rate on VP orifice area for /p/ in HAMPER.

Median VP orifice area for /p/ in BBP during the normal speaking rate condition was 0.13 mm² (IQR = 0.23). This value seemed to decrease during the fast speaking rate

condition. However, the regression analysis revealed no main effect of rate on VP orifice area for /p/ in BBP. The effect of gender was not significant on VP orifice area measurements of all /p/ segments of interest.

Table 10. Median and interquartile range (IQR) of VP orifice area for each /p/ segment of interest

	VP Orifice Area (mm ²)							
	Fast		Normal		Slow		Slowest	
	Median	IQR	Median	IQR	Median	IQR	Median	IQR
HAMPER /p/	0.42	0.57	0.48	0.55	0.21	0.29	0.36	0.48
BBP	0.05	0.18	0.13	0.23	0.10	0.31	0.10	0.36

Nasalance and Nasalance Distance

Summary statistics for nasalance values from each utterance and for mean nasalance distance between MMJ and BBP (MMJ – BBP) are reported in Table 11. Nasalance for BBP increased as speaking rate slowed. LME revealed a main effect of rate on nasalance for BPP ($F_{3,20}=5.134, p < 0.008$). Pairwise comparisons revealed a significant difference between the fast speaking rate condition and the slow ($t_{34} = -3.130, p < 0.041$) and slowest ($t_{39} = -4.637, p < 0.003$) speaking rate conditions.

For MMJ, nasalance appeared to decrease at slower speaking rates. LME revealed no main effect of rate on nasalance for MMJ. There was no main effect of gender on nasalance values for any of the utterances.

Nasalance distance decreased at slower speaking rates. LME revealed a main effect of rate ($F_{3,27}=7.945, p < 0.001$) and gender ($F_{1,8}=12.036, p < 0.007$) on nasalance distance. Pairwise comparisons revealed a significant difference between the fast speaking rate condition and the slow ($t_{28}=4.063, p < 0.023$) and slowest ($t_{25}=6.696,$

$p < 0.001$) speaking rate conditions. Females had higher nasalance distance scores than males.

Table 11. Means and standard deviations (SD) of nasalance (%) values for each utterance and for nasalance distance

	Nasalance (%)							
	Fast		Normal		Slow		Slowest	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BBP	14	7	15	7	17	7	19	8
MMJ	59	6	60	7	58	7	57	8
MMJ - BBP	45	7	44	8	41	10	39	10

DISCUSSION

The purpose of this study was to investigate the effect of altered speaking rate on aerodynamic and acoustic measures of VP function in healthy adult speakers. 27 participants were asked to produce the word HAMPER and the sentences MMJ and BBP at 4 different speaking rates (fast, normal, slow, and slowest). Aerodynamic measures of maximum intraoral pressure (P_o), nasal airflow (V_n), and VP orifice area were collected for /m/ and /p/ segments of these utterances. Mean percent nasalance of the entirety of BBP and MMJ was measured using a Nasometer. Based on previous studies, it was hypothesized that VP orifice area would be affected by changes in speaking rate for the nasal consonant /m/ (Bell-Berti & Krakow, 1991a; Bell-Berti et al., 1995; Kent et al., 1974; Krakow, 1993; Kuehn, 1976; Moll & Shriner, 1967). The absence of literature on the effect of speaking rate manipulations on V_n or P_o for nasal consonants, in combination with previous work which has speculated that P_o is a controlled parameter in speech (e.g., Warren, 1986), led to the hypothesis that either V_n or P_o would change across speaking rate conditions for nasal consonants while the other parameter would remain stable. VP orifice area for oral consonants was expected to remain stable across

speaking rate conditions leaving Vn and Po unchanged. Nasalance was expected to increase for nasal and oral sounds as speaking rate slowed based on previous work which reported that rate of speaking is related to nasalance (Fletcher & Daly, 1976) and the consistent findings that perceived nasality increases at slow speaking rates (Brancewicz & Reich, 1989; Colton & Cooker, 1968; Goberman et al., 2001).

The results of this study indicated that VP orifice area and Vn were largely unaffected by changes in speaking rate, regardless of the consonant (nasal or oral) or utterance/context. Po changed with speaking rate and was generally higher for fast as compared to normal and slower speaking rates across contexts (BBP and HAMPER). Po remained the same across varying speaking rates for /m/ in a nasal sentence context (MMJ). Nasalance scores were generally higher during slower speaking rates for oral sentences but not for MMJ. Nasalance distance was greater at fast compared to slower speaking rate conditions and females had greater nasalance distance than males. A detailed discussion of these results follows.

VP Orifice Area

A modification of the pressure-flow technique (Warren & DuBois, 1964) was used to measure VP orifice area in this study. This measure was used because VP orifice area has been found to be sensitive to varying degrees of VP inadequacy (Warren, 1979). Unlike Po and Vn, VP orifice area has also been said to be unaffected by differences in respiratory effort and nasal resistance (Warren et al., 1989; Zajac, 2007). VP orifice area values obtained in the present study for oral and nasal consonants produced at normal rates were in agreement with those reported in the literature for healthy adults

(Andreassen et al., 1992; Zajac & Mayo, 1996; Zajac, 2000). VP orifice area was not affected by changes in speaking rate. This was in accordance with hypotheses for oral consonants but not for nasal consonants.

Movement studies have reported differences in velar height for oral and nasal consonants at fast as compared to normal and slower speaking rates (Bell-Berti & Krakow, 1991a; Bell-Berti et al., 1995; Kent et al., 1974; Kuehn, 1976; Moll & Shriner, 1967). It was anticipated that VP orifice area would increase as rate slowed from the fast to the slowest speaking rate condition for nasal consonants. The disagreement in findings between measures of VP orifice area used in the present study and kinematic measures of velar height at different speaking rates reported previously may perhaps be explained by differences in the method of measurement used, phonetic context, or small participant number (and therefore low generalizability) of previous kinematic studies.

Differences between kinematic and aerodynamic measures of velar height and VP orifice area, respectively, may be explained by the nature of what each measure is actually measuring (e.g. position of a marker on the surface of the velum vs. VP port area). The velum is a fleshy structure which lengthens and thickens in the midsagittal plane during speech compared to at rest (Bzoch, 1968). Measures of velar height do not necessarily take into account such changes. It is therefore possible that a sealed VP port may be attained while surface positions of the velum continue to change. In the case of /p/, participants in this study had functioning VP mechanisms and were therefore

expected to achieve proper VP closure across speaking rate conditions. This is not to say that measures of velar height, had they been taken, would not have changed.

Although VP orifice area has been found to be a good estimate of VP function (Warren & DuBois, 1964; Zajac, 2007), it must be considered that it is a derived measure calculated at the point of peak Vn for nasal consonants and peak Po for oral consonants. Velar position at the time of these measures may not necessarily correspond with maximum velar lowering and/or elevation for nasal and oral consonants, respectively. If peak Vn and Po occur at any time other than when the velum is in its most extreme positions, speaking rate effects on VP orifice area may not necessarily be measurable by aerodynamic methods as the velum would be in an intermediate position.

Furthermore, pharyngeal wall displacement may have occurred at the level of the velum during speech (Zagzebski, 1975). Such movement would necessarily affect measures of VP orifice area but not those of velar height. Thus, the relationship between kinematic and aerodynamic measures of VP orifice might not be direct.

The lack of speaking rate effect on VP orifice area in the present study could also lie in the measured segments and their phonetic context. Previous work has shown that the velum maintains an elevated position when in an oral consonant environment, and a lowered position when in a nasal environment (Ushijima & Sawashima, 1972). In the case of BBP and MMJ, it is therefore possible that VP orifice areas for measured segments would be largely unaffected by speaking rate because the velum remained in a

relatively stable position for the total duration of these utterances (i.e. lowered during nasal MMJ and elevated during oral BBP). From this perspective, a more obvious change in VP orifice area would be expected for HAMPER, as this utterance stresses the palatal mechanism to both positional extremes. This, however, did not occur in the present study.

Finally, it is also possible that velar height and VP orifice area are not affected by speaking rate for some individuals. The small number of movement studies that were used to generate the hypotheses for this study (Bell-Berti & Krakow, 1991a; Kent et al., 1974; Kuehn, 1976; Moll & Shriner, 1967) were conducted on a very limited number of participants (1 – 3). While results from these studies point toward a trend of decreased velar displacement at fast speaking rates, other strategies (e.g. increased velar movement velocity) have also been reported (Kent et al., 1974). When individual data was considered in this study, some participants showed a variable response to speaking rate variation. A handful of participants showed a tendency to increase VP orifice area as speaking rate slowed while another subgroup of participants showed a tendency to decrease VP orifice area as speaking rate slowed. Further exploration of individual performance might be necessary to understand strategies used by different speakers to change speaking rate.

Nasal Airflow Rate

The present study measured V_n during nasal and oral consonants. The general differences between these two sound classes were apparent in the data and corresponded

with the results reported in the literature (Mayo et al., 1998; Zajac, 2000). However, our results for Vn in /m/ of HAMPER were somewhat higher (229 ml/s, SD = 123 versus 149 ml/s, SD = 73) than those reported (Zajac & Mayo, 1996; Zajac, 1997). Vn was unaffected by changes in speaking rate for either consonant class in this study. This finding was in disagreement with Goberman and colleagues (2001) who found significantly greater Vn during their slow compared to normal and fast speaking rate conditions.

The discrepancy between the results of this study and Goberman et al. (2001) may lie in the speech sample used in each study. Goberman, Selby, and Gilbert studied Vn during the vowel /ə/ in “it’s a story about *a* park”. The present study focused on oral and nasal consonants. It is therefore possible that changes in speaking rate have a different effect on velar position for different sound classes, especially since velar positions might be specified in a more strict way for consonants as compared to vowels (Moll & Daniloff, 1971).

The finding that Vn was unaffected by speaking rate may also be explained by the relationship between Vn and VP orifice area. In the introduction, it was hypothesized that Vn might change at different speaking rates in response to changes in VP orifice area. In this case, changes in Vn would reflect modifications in respiratory effort which serve to regulate Po. In this study however, VP orifice area remained stable across speaking rate conditions. Thus alterations in respiratory effort (or Vn) might not have been necessary.

Intraoral Pressure

Po was the only aerodynamic parameter which changed significantly with speaking rate. Po measurement was made because it has been shown to be sensitive to VP dysfunction (Warren & Ryon, 1967; Zajac, 1997) and is also used to calculate VP orifice area (Warren & DuBois, 1964). However, it is known that Po is affected by respiratory effort, nasal resistance, and the degree of oral cavity constriction (Zajac, 2007). Care must therefore be taken when using Po as an indicator of VP function (Zajac, 2007). In this study, Po was measured for oral as well as nasal consonants. Its values were similar to what has been reported in the literature, showing distinction for the two sounds classes studied (i.e., higher Po for oral as compared to nasal consonants; (Zajac & Mayo, 1996; Zajac, 1997). This study found that Po tended to decrease as speaking rate slowed. This was contrary to what was expected based on the model proposed in the beginning of this study. No other study has examined the relationship between speaking rate and Po.

Warren and his colleagues (1986 & 1989) have suggested that increases in respiratory effort serve to regulate Po in the face of decreased velar resistance (due to changes in VP orifice area for example). It was therefore hypothesized that (a) Po would remain unaffected by changes in speaking rate for oral consonants (for which no change in VP orifice area was expected) and (b) Po would change for nasal consonants only if VP orifice area was affected and no compensatory adjustments in airflow occurred, otherwise Po would remain stable. The findings of this study contradicted the proposed

hypotheses, as neither a change in VP orifice area or V_n were observed in this study yet P_o was affected by speaking rate.

One explanation for this finding may be that individuals used greater respiratory effort during fast speaking rate conditions than during slower speaking rate conditions. This is supported by our finding that SPL was greater during fast speaking rate conditions. SPL might be used in a broad way as a measure of respiratory effort and has been shown to affect aerodynamic measures (Dromey & Ramig, 1998; Holmberg et al., 1994; Warren et al., 1989; Warren et al., 1989; Zajac, 1997; Zajac, Mayo, & Kataoka, 1998). The effect of speaking rate, however, was beyond SPL since its effect was statistically controlled in this study.

Perhaps other muscular effort (e.g., interlabial force) or changes in articulation were responsible for the observed rate effect on P_o . Dromey and Ramig (1998) reported increased articulatory lip displacements and peak velocity at fast speaking rates. These findings may correspond with extended effort during speech at fast speaking rates if a uni-dimensional frictionless dynamic model of speech movement is assumed (Perkell, 1997). P_o has been found to be affected by oral cavity constriction therefore changes in movement amplitude of the lips at fast speaking rates may have influenced P_o (Zajac, 2007).

Very little information exists in the literature regarding the effect of speaking rate on the aerodynamic properties of speech. No data has been reported on the effects of

speaking rate on Po. Based on kinematic studies, it was therefore predicted that aerodynamic measures of VP orifice area would change at least for nasal consonants resulting in smaller VP orifice areas at fast speaking rates and larger VP orifice areas at slow speaking rates. The lack of rate effect on VP orifice area and the presence of a speaking rate effect on Po was surprising. Previous work has suggested that Po is a controlled parameter in speech which, in the presence of altered velar resistance, is regulated by compensatory adjustments in respiratory effort (Kim et al., 1997; Warren, 1986; Warren et al., 1989; Warren et al., 1989). It is however possible that any changes in VP function due to altered speaking rate in the present study may not have been extreme enough to evoke responses reported in previous studies which assessed individuals with VP inadequacy or perturbed conditions (e.g. bite block, lip valves, purposefully lowered VP) designed to mimic VP inadequacy. Thus, this study was not designed to prove or disprove previous theories regarding compensatory mechanisms, but rather used such models to develop hypotheses regarding speaking rate effects on parameters which have not otherwise been studied.

Mean Nasalance and Nasalance Distance

Our measures of nasalance during normal speaking rates corresponded to results reported by the manufacturing company (KayPentax) for the Nasometer. Nasal sentences had high nasalance values and oral sentences had comparatively low nasalance values. Nasalance varied significantly with speaking rate in this study, increasing in the utterance BBP at slower as compared to fast and normal speaking rates. The increase in nasalance with rate during the oral sentence in our study seems to agree with Fletcher and Daly's

study (1976) which found greater nasalance scores in habitually slower speakers during the Zoo passage. A possible explanation for this finding may be the tendency for individuals to disproportionately increase the length of vowels and not consonants at slower speaking rates (vowels are characterized by higher nasalance than oral consonants; see KayPentax for normative data). If this occurred during BBP, the proportion of time when the VP was supposedly closed (i.e., for plosives) would therefore decrease at slow in comparison to fast speaking rates. There was no significant effect of speaking rate on nasalance in the nasal sentence MMJ. A possible explanation for this could be that the velum remained in a lowered position for the majority of the utterance length (Ushijima & Sawashima, 1972). The ratio of nasal to nasal + oral energy would therefore change minimally across speaking rates for this utterance.

Bressmann and colleagues (2000) suggested that nasalance distance may be an important addition to measures of nasalance alone, because “each speaker serves as his or her own reference”. The within speaker sensitivity of this measure was confirmed by this study which revealed that nasalance distance was sensitive to variations in speaking rate *and* gender. Nasalance distance decreased as speaking rate slowed. This was due to the tendency for nasalance to decrease for MMJ as rate slowed and increase for BBP as rate slowed. The combined effect of these two trends yielded as significant result whereas nasalance for MMJ alone was not significantly affected by speaking rate. The finding that nasalance distance was greater for females than for males will be discussed in the next section.

Gender Effects

The present study found no gender effects on aerodynamic measures of VP function. Some studies have reported greater Po (Zajac & Mayo, 1996; Zajac, 1997) and Vn (Hoit et al., 1994) in male as compared to female speakers. Neither Po or Vn were affected by gender in this study.

Females have been found to have greater nasalance scores on nasal sentences than males (Hutchinson et al., 1978; Seaver et al., 1991). Nasalance distance was the only measure statistically affected by gender in the present study however. The reason for this gender difference became evident upon closer inspection of the data, which revealed that women were generally more nasal than men for MMJ (supporting previous findings) and less nasal for BBP. Thus, although the tendency for females to be more nasal than males for nasal sentences was not statistically significant in the present study, it was revealed by the measure of MMJ-BBP. This finding also supported previous studies which have reported greater speech intelligibility (and presumably increased articulatory distinction) in female speakers (Marguiles, 1979; Markham & Hazan, 2004).

Clinical Relevance

While it is clear that the mechanism through which individuals with pathology change their speaking rate may be different than in healthy speakers (Yorkston et al., 1999), this study highlights the need to take speaking rate into account when assessing velar function in individuals with pathology and concomitant altered speaking rate. This is based on the present study's findings that nasalance and Po were affected by changes

in speaking rate. Specifically, it may be important to consider speaking rate when assessing Po for oral consonants in individuals with dysarthria who are more likely to slow their rate, as these were the only segments for which Po differed in the slow compared to normal speaking rates. Po also differed from normal at fast speaking rates for both /m/ and /p/ segments indicating the need to consider speaking rate when assessing velar function in individuals who may speak faster than normal (e.g. Parkinson's Disease; (Duffy, 2005).

Conclusions

This study investigated the effect of speaking rate on various measures of VP function. Only two measures, Po and Nasalance, were affected by variations in speaking rate. The findings of this study highlighted the need to consider speaking rate when assessing velar function using measures of Po and nasalance in individuals with pathology, but also the need to delineate the relationship between various measures of VP function. Linking velar movements to the presently used measures of VP function would be beneficial in future research.

REFERENCES

- Andreassen, M. L., Smith, B. E., & Guyette, T. W. (1992). Pressure-flow measurements for selected oral and nasal sound segments produced by normal adults. *The Cleft Palate-Craniofacial Journal*, 29(1), 1-9.
- Ball, L. J., Beukelman, D., & Pattee, G. L. (2002). Timing of speech deterioration in people with amyotrophic lateral sclerosis. *Journal of Medical Speech-Language Pathology*, 10(4), 231-235.
- Ball, L. J., Willis, A., Beukelman, D., & Pattee, G. L. (2001). A protocol for identification of early bulbar signs in amyotrophic lateral sclerosis. *Journal of Neurological Sciences*, 191(1-2), 43-53.
- Barlow, S. M., Finan, D. S., Andreatta, R. D., & Paseman, L. A. (1997). Kinematic measurement of the human vocal tract. In M. R. McNeil (Ed.), *Clinical management of sensorimotor speech disorders* (pp. 107-147). New York: Thieme.
- Bell-Berti, F. (1976). An electromyographic study of velopharyngeal function in speech. *Journal of Speech and Hearing Research*, 19(2), 225-240.
- Bell-Berti, F. (1980). Velopharyngeal function: A spatial-temporal model. *Speech and language: Advances in basic research and practice* (pp. 291) Academic Press, Inc.
- Bell-Berti, F. (1993). Understanding velic motor control: Studies of segmental context. *Phonetics and Phonology*, 5, 63-85.

- Bell-Berti, F., & Hirose, H. (1975). Palatal activity in voicing distinctions: A simultaneous fiberoptic and eletromyographic study. *Journal of Phonetics*, 3, 69-74.
- Bell-Berti, F., & Krakow, R. A. (1991a). Anticipatory velar lowering: A coproduction account. *The Journal of the Acoustical Society of America*, 90(1), 112-123.
- Bell-Berti, F., & Krakow, R. A. (1991b). Velar height and sentence length: Declination? *The Journal of the Acoustical Society of America*, 89, 1916.
- Bell-Berti, F., Krakow, R. A., Gelfer, C. E., & Boyce, S. E. (1995). Anticipatory and carryover effects: Implications for models of speech production. *Producing speech: Contemporary issues* (pp. 77). New York: AIP Press.
- Brancewicz, T. M., & Reich, A. R. (1989). Speech rate reduction and "nasality" in normal speakers. *Journal of Speech and Hearing Research*, 32(4), 837-848.
- Bressmann, T., Sader, R., Whitehill, T. L., Awan, S. N., Zeilhofer, H. F., & Horch, H. H. (2000). Nasalance distance and ratio: Two new measures. *The Cleft Palate-Craniofacial Journal*, 37(3), 248-256.
- Brooks, B. R., Sufit, R. L., DePaul, R., Tan, Y. D., Sanjak, M., & Robbins, J. (1991). Design of clinical therapeutic trials in amyotrophic lateral sclerosis. *Advances in Neurology*, 56, 521-546.

Bzoch, K. R. (1968). Variations in velopharyngeal valving: The factor of vowel changes.

The Cleft Palate Journal, 5, 211-218.

Chomsky, N., & Halle, M. (1968). *The sound pattern of english*. New York: Harper &

Row.

Colton, R. H., & Cooker, H. S. (1968). Perceived nasality in the speech of the deaf.

Journal of Speech and Hearing Research, 11(3), 553-559.

Croft, C. B., Shprintzen, R. J., & Rakoff, S. J. (1981). Patterns of velopharyngeal valving

in normal and cleft palate subjects: A multi-view videofluoroscopic and

nasendoscopic study. *The Laryngoscope*, 91(2), 265-271.

Dalston, R. M., Warren, D. W., Morr, K. E., & Smith, L. R. (1988). Intraoral pressure

and its relationship to velopharyngeal inadequacy. *The Cleft Palate Journal*, 25(3),

210-219.

Delorey, R., Leeper, H. A., & Hudson, A. J. (1999). Measures of velopharyngeal

functioning in subgroups of individuals with amyotrophic lateral sclerosis. *Journal*

of Medical Speech-Language Pathology, 7(1), 19-31.

Denes, P. B., & Pinson, E. N. (Eds.). (1973). *The speech chain; the physics and biology*

of spoken language. Garden City, NY: Anchor Press.

- Dromey, C., & Ramig, L. O. (1998). Intentional changes in sound pressure level and rate: Their impact on measures of respiration, phonation, and articulation. *Journal of Speech, Language, and Hearing Research, 41*(5), 1003-1018.
- Duffy, J. R. (2005). Motor speech disorders, substrates, differential diagnosis, and management. (2nd ed., pp. 187) Mayo Foundation for Medical Education and Research.
- Fletcher, S. G., & Daly, D. A. (1976). Nasalance in utterances of hearing-impaired speakers. *Journal of Communication Disorders, 9*, 63-73.
- Goberman, A. M., Selby, J. C., & Gilbert, H. R. (2001). The effects of changes in speaking rate on nasal airflow and the perception of nasality. *Folia Phoniatrica Et Logopaedica, 53*(4), 222-230.
- Green, J. R., Yunusova, Y., Ball, L. J., Mefferd, A. S., & Pattee, G. L. (2006). Comprehensive instrumental analysis of bulbar function over time in persons with ALS., Poster Presentation in Yokohama, Japan.
- Hoit, J. D., Watson, P. J., Hixon, K. E., McMahon, P., & Johnson, C. L. (1994). Age and velopharyngeal function during speech production. *Journal of Speech and Hearing Research, 37*(2), 295-302.
- Holmberg, E. B., Hillman, R. E., Perkell, J. S., & Gress, C. (1994). Relationships between intra-speaker variation in aerodynamic measures of voice production and

variation in SPL across repeated recordings. *Journal of Speech and Hearing Research*, 37(3), 484-495.

Hutchinson, J. M., Robinson, K. L., & Nerbonne, M. A. (1978). Patterns of nasalance in a sample of normal gerontologic subjects. *Journal of Communication Disorders*, 11(6), 469-481.

Iglesias, A., Kuehn, D. P., & Morris, H. L. (1980). Simultaneous assessment of pharyngeal wall and velar displacement for selected speech sounds. *Journal of Speech and Hearing Research*, 23(2), 429-446.

Kent, R. D., Carney, P. J., & Severeid, L. R. (1974). Velar movement and timing: Evaluation of a model for binary control. *Journal of Speech and Hearing Research*, 17(3), 470-488.

Kim, J. R., Zajac, D. J., Warren, D. W., Mayo, R., & Essick, G. K. (1997). The response to sudden change in vocal tract resistance during stop consonant production. *Journal of Speech, Language, and Hearing Research*, 40(4), 848-857.

Klechak, T. L., Bradley, D. P., & Warren, D. W. (1976). Anterior open bite and oral port constriction. *The Angle Orthodontist*, 46(3), 232-242.

Krakow, R. A. (1987). Stress effects on velic gestures. *The Journal of the Acoustical Society of America*, 82, S17.

- Krakow, R. A. (1993). Nonsegmental influences on velum movement patterns: Syllables, sentences, stress, and speaking rate. *Phonetics and Phonology*, 5, 87-116.
- Kuehn, D. P. (1976). A cineradiographic investigation of velar movement variables in two normals. *The Cleft Palate Journal*, 13, 88-103.
- Kuehn, D. P., & Moon, J. B. (1998). Velopharyngeal closure force and levator veli palatini activation levels in varying phonetic contexts. *Journal of Speech, Language, and Hearing Research*, 41(1), 51-62.
- Laine, T., Warren, D. W., Dalston, R. M., Hairfield, W. M., & Morr, K. E. (1988). Intraoral pressure, nasal pressure and airflow rate in cleft palate speech. *Journal of Speech and Hearing Research*, 31(3), 432-437.
- Magen, H. S., Kang, A. M., Tiede, M. K., & Whalen, D. H. (2003). Posterior pharyngeal wall position in the production of speech. *Journal of Speech, Language, and Hearing Research*, 46(1), 241-251.
- Marguiles, M. (1979). Male-female differences in speaker intelligibility; normal and hearing-impaired listeners. *The Journal of the Acoustical Society of America*, 65(S1), S99.
- Markham, D., & Hazan, V. (2004). The effect of talker- and listener-related factors on intelligibility for a real-word, open-set perception test. *Journal of Speech, Language, and Hearing Research*, 47(4), 725-737.

- Mayo, R., Warren, D. W., & Zajac, D. J. (1998). Intraoral pressure and velopharyngeal function. *The Cleft Palate-Craniofacial Journal*, 35(4), 299-303.
- McHenry, M. A. (1999). Aerodynamic, acoustic, and perceptual measures of nasality following traumatic brain injury. *Brain Injury*, 13(4), 281-290.
- McKerns, D., & Bzoch, K. R. (1970). Variations in velopharyngeal valving: The factor of sex. *The Cleft Palate Journal*, 7, 652-662.
- Minifie, F. D., Hixon, T. J., Kelsey, C. A., & Woodhouse, R. J. (1970). Lateral pharyngeal wall movement during speech production. *Journal of Speech and Hearing Research*, 13(3), 584-594.
- Moll, K. L. (1962). Velopharyngeal closure on vowels. *Journal of Speech and Hearing Research*, 5, 30-37.
- Moll, K. L., & Daniloff, R. G. (1971). Investigation of the timing of velar movements during speech. *The Journal of the Acoustical Society of America*, 50(2), 678-684.
- Moll, K. L., & Shriner, T. H. (1967). Preliminary investigation of a new concept of velar activity during speech. *The Cleft Palate Journal*, 4, 58-69.
- Moon, J. B., Kuehn, D. P., & Huisman, J. J. (1994). Measurement of velopharyngeal closure force during vowel production. *The Cleft Palate-Craniofacial Journal*, 31(5), 356-363.

- Perkell, J. S. (1997). Articulatory processes. In W. J. Hardcastle, & J. Laver (Eds.), *The handbook of phonetic sciences* (pp. 333-370). Oxford, UK: Blackwell Publishers.
- Putnam, A. H., Shelton, R. L., & Kastner, C. U. (1986). Intraoral air pressure and oral air flow under different bleed and bite-block conditions. *Journal of Speech and Hearing Research*, 29(1), 37-49.
- Seaver, E. J., Dalston, R. M., Leeper, H. A., & Adams, L. E. (1991). A study of nasometric values for normal nasal resonance. *Journal of Speech and Hearing Research*, 34(4), 715-721.
- Seikel, J. A., King, D. W., & Drumright, D. G. (1997). *Anatomy and physiology for speech, language, and hearing* (Expanded ed.). San Diego: Singular Publishing Group, Inc.
- Stathopoulos, E. T. (1986). Relationship between intraoral air pressure and vocal intensity in children and adults. *Journal of Speech and Hearing Research*, 29(1), 71-74.
- Thompson, A. E., & Hixon, T. J. (1979). Nasal air flow during normal speech production. *The Cleft Palate Journal*, 16(4), 412-420.
- Ushijima, T., & Sawashima, M. (1972). Fiberscopic observation of velar movements during speech. *Annual Bulletin no. 6. University of Tokyo: Research Institute of Logopedics and Phoniatrics*, 6, 25-38.

- Vaissière, J. (1988). Prediction of articulatory movement of the velum from phonetic input. *Phonetica*, 45, 122-139.
- Warren, D. W. (1979). Perci: A method for rating palatal efficiency. *The Cleft Palate Journal*, 16(3), 279-285.
- Warren, D. W. (1982). Aerodynamics of speech. In N. J. Lass, L. V. McReynolds, J. L. Northern & D. E. Yoder (Eds.), *Speech, language, and hearing: Normal processes* (pp. 219-245). Philadelphia: W. B. Saunders.
- Warren, D. W. (1986). Compensatory speech behaviors in individuals with cleft palate: A regulation/control phenomenon? *The Cleft Palate Journal*, 23(4), 251-260.
- Warren, D. W., Dalston, R. M., Morr, K. E., Hairfield, W. M., & Smith, L. R. (1989). The speech regulating system: Temporal and aerodynamic responses to velopharyngeal inadequacy. *Journal of Speech and Hearing Research*, 32, 566-575.
- Warren, D. W., Dalston, R. M., Trier, W. C., & Holder, M. B. (1985). A pressure-flow technique for quantifying temporal patterns of palatopharyngeal closure. *Cleft Palate Journal*, 22(1), 11-19.
- Warren, D. W., & DuBois, A. B. (1964). A pressure-flow technique for measuring velopharyngeal orifice area during continuous speech. *Cleft Palate Journal*, 1, 52-71.

- Warren, D. W., Hall, D. J., & Davis, J. (1981). Oral port constriction and pressure-airflow relationships during sibilant productions. *Folia Phoniatrica Et Logopaedica*, 33(6), 380-394.
- Warren, D. W., Morr, K. E., Rochet, A. P., & Dalston, R. M. (1989). Respiratory response to a decrease in velopharyngeal resistance. *The Journal of the Acoustical Society of America*, 86(3), 917-924.
- Warren, D. W., & Ryon, W. E. (1967). Oral port constriction, nasal resistance, and respiratory aspects of cleft palate speech: An analog study. *The Cleft Palate Journal*, 4, 38-46.
- Yorkston, K. M., Beukelman, D., Strand, E., & Bell, K. (1999). *Management of motor speech disorders in children and adults* (2nd ed.). Austin, Texas: PRO-ED, Inc.
- Yorkston, K. M., Strand, E., Miller, R., Hillel, A., & Smith, K. (1993). Speech deterioration in amyotrophic lateral sclerosis: Implications for the timing of intervention. *Journal of Medical Speech-Language Pathology*, 1(1), 35-46.
- Zagzebski, J. A. (1975). Ultrasonic measurement of lateral pharyngeal wall motion at two levels in the vocal tract. *Journal of Speech and Hearing Research*, 18(2), 308-318.
- Zajac, D. J. (1997). Velopharyngeal function in young and older adult speakers: Evidence from aerodynamic studies. *The Journal of the Acoustical Society of America*, 102(3), 1846-1852.

- Zajac, D. J. (2000). Pressure-flow characteristics of /m/ and /p/ production in speakers without cleft palate: Developmental findings. *The Cleft Palate-Craniofacial Journal*, 37(5), 468-477.
- Zajac, D. J. (2007). Speech aerodynamics. In A. Krummer (Ed.), *Cleft palate and craniofacial anomalies: Effect on speech and resonance* (2nd ed., pp. 415-445). San Diego: Singular Thomson Learning.
- Zajac, D. J., & Mayo, R. (1996). Aerodynamic and temporal aspects of velopharyngeal function in normal speakers. *Journal of Speech and Hearing Research*, 39(6), 1199-1207.
- Zajac, D. J., Mayo, R., & Kataoka, R. (1998). Nasal coarticulation in normal speakers: A re-examination of the effects of gender. *Journal of Speech, Language, and Hearing Research*, 41(3), 503-510.