Oral Air Pressure, Nasal Air Flow and Velopharyngeal Area in the Speech of Young Children

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Stephanie Marcia Rauls
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Jeffrey P. Searl, PhD
Chairperson

Mary A. Carpenter, PhD

Debra B. Daniels, PhD

Date defended

The Thesis Committee for Stephanie Marcia Rauls certifies that this is the approved version of the following thesis:

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Jeffrey P. Searl, PhD
Chairperson

Date approved

ABSTRACT

There are limited data regarding velopharyngeal (VP) aerodynamics for children younger than six years of age. Aerodynamic data can serve as evidence in the decision-making process regarding adequacy of VP function. Data available for older populations support the conclusion that VP aerodynamics do differ across the age ranges.

Velopharyngeal aerodynamics from 32 children with typically developing speech were assessed. The purposes of the study were to describe VP aerodynamic measures in preschool-aged children, evaluate variables other than age as influential factors on these measures, describe stability over two recordings sessions, and compare preschool-aged to school-aged children.

Findings were that preschool-aged children had VP aerodynamic measures similar to those from school-aged children. Body size measurements of height, weight, head circumference, chest circumference and cross-sectional VP area were not strong correlates to the VP measures. Nasal flow measures were stable over two recordings, but oral pressure was higher at the second recording.

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INTRODUCTION

Children with a cleft palate typically undergo primary surgical repair of the cleft at about 12 months of age in most regions of the United States (Hardin-Jones & Jones, 2005). The central purpose of this primary repair is to create a functioning velopharyngeal (VP) mechanism that is able to close off the nasal from the oral cavity during swallowing and speech (Morris, Shelton & McWilliams, 1973). Whether or not that goal is accomplished cannot be determined with certainty until the child has a relatively wide phonemic repertoire and sufficient verbal output that can be judged. Typically, at approximately age three years, children should be generating enough speech that a speech-language pathologist (SLP) can begin to make judgments regarding the adequacy of VP function. Primary surgical repair of the palate results in a VP mechanism that functions adequately for the majority of those undergoing the procedure. However, not all children acquire normal speech after primary palatal surgery (Jones, Chapman & Hardin-Jones, 2003). Approximately 20% of individuals who undergo primary palatal repair will still have VP dysfunction (Shprintzen & Bardach, 1995).

When VP incompetency persists after primary surgical repair, there are additional surgical options, referred to collectively as secondary procedures or pharyngoplasty, as well as prosthetic and behavioral interventions that can be pursued. Most research studies have suggested that completing a secondary surgery at a younger rather than an older age results in better speech outcomes. A number of studies have documented better articulation and resonance outcomes from secondary pharyngoplasty surgery when it is performed before the child is six years of age compared to repair beyond six years (Leanderson, Korlof, Nylen, & Eriksson, 1974; Riski, 1979; Riski, Serafin, Riefkohl, Georgiade & Georgiade, 1984; Riski, Ruff, Georgiade, Barwick, & Edwards, 1992; Seyfer, Prohazka & Leahy, 1988). To maximize surgical and behavioral interventions, earlier rather than later identification of VP incompetency should be targeted.

Perceptual ratings of resonance and articulation as well as visual inspection of the palate and pharynx are frequently completed when determining whether a child has adequate VP function for speech. In addition, a host of instrumental assessments of VP structure and function are available for use in this diagnostic process. Aerodynamic assessment of VP function has been utilized for both clinical and research purposes. Warren and DuBois (1964) described an aerodynamic assessment procedure that is widely referred to as the pressure-flow (PF) technique. This procedure utilizes a pneumotachometer and pressure transducers to simultaneously measure oral air pressure (Po), nasal air pressure (Pn) and nasal air flow (Vn). These values can be used individually to provide information regarding VP function, particularly Po and Vn, or they can be applied to a modified hydraulic equation to derive an estimate of the VP orifice area. The PF technique is particularly attractive for use with children compared to other instrumental options for VP assessment. The aerodynamic approach does not require radiation exposure like cineradiography or fluoroscopy. PF is also non-invasive, unlike flexible endoscopic evaluations of VP function, which may allow for greater compliance from very young clients. However, as with any diagnostic tool, the usefulness of the PF technique is dependent upon adequate normative data that can help guide clinical decision-making. Unfortunately, there is little available normative data on VP aerodynamic measures for children below the age of six years.

At present, clinicians evaluating the VP function of preschool age children must rely on pressure-flow data acquired from older children when trying to decide on a youngster's VP competency. There is evidence, however, that both Po and Vn may vary as a function of speaker age. In the absence of normative VP aerodynamic data for children younger than six years, it is unknown whether clinicians are justified in using values from early school age children (six-eight years old) when evaluating preschoolers. Young children presumably have a less mature neurological system controlling the motor speech system which may result in a unique pressure-flow profile, making it inappropriate to apply normative values from older children and adults (Zajac, 2000; Zajac & Hackett, 2002; Smith, Patil, Guyette, Brannan & Cohen, 2004). The present study focused on describing velopharyngeal aerodynamics for children between the ages of 3;0-8;11. Data obtained can serve as a preliminary set of normative values for clinicians evaluating children with possible VP incompetency. This type of data is needed to assist clinicians utilizing the PF technique when evaluating the speech of young children with suspected VP incompetency.

REVIEW OF THE LITERATURE

Oral Air Pressure

To produce a stop consonant, expiratory airflow is obstructed by the articulators resulting in build-up of oral air pressure (Po). Release of this Po creates a burst of acoustic energy that helps mark the production as a stop consonant (Stevens & Blumstein, 1978). Fricatives also require approximation of articulators to create a constriction in the vocal tract. Oral air pressure builds behind the articulatory constriction forcing air through the narrowing to create turbulent airflow (Stevens, 1971). Affricates involve a combination of pressure burst release followed by turbulent airflow through a constriction. For stops, fricatives and affricates, generation of Po is dependent on several factors, one of which is the ability to close the VP mechanism. In the presence of incomplete or poorly timed VP closure, air pressure cannot build orally to expected levels unless the speaker makes exceptional compensations with the respiratory system (i.e., increased expiratory force). It is not unusual for an individual with a history of cleft palate or a neuromotor condition affecting the VP mechanism to produce oral consonants with significantly reduced Po (Dalston, Warren, Morr & Smith, 1988; Warren, 1986). Reductions in Po are associated with perceptions of weak or distorted stops, fricatives and affricates (Schoenbrodt, 2004).

Peak Po during oral consonant production is inversely related to the speaker's age in individuals with normal speech (Bernthal & Beukelman 1978; Stathopoulos & Weisner 1985; Stathopoulos 1986; Smith et al, 2004). Bernthal and Beukelman

(1978) studied oral pressure on /p/ and /b/ in thirty-six speakers ranging in age from 4;6 to 46;2 years. They reported a decreasing mean peak Po for children aged 4;6 to 6;9 years (6.7cmH2O) compared to youths aged 10;0 to 12;10 years (6.15cmH2O) and compared to adults aged 19;6 to 46;2 years (4.55cmH2O). Stathopoulos and Weismer (1985) measured Po in thirty subjects divided into three different age categories and found a similar decrease in Po across age groups. Mean Po for children (4-8 years), youths (10-12 years) and adults (18-30 years) was 6.2cmH20, 5.8cmH2O, and 4.6cmH20, respectively. Smith et al. (2004) compared Po of fifty-six normal speaking individuals 5-18 years old with data previously reported by Andreassen, Smith and Guyette (1992) for adults. Again, younger children were found to generate significantly greater Po than older speakers. Zajac (2000) reported results from 223 children, teens, and adults (6-37 years-old) with normal speech. Across stimulus constructions, mean Po on /p/ demonstrated a decreasing trend from ~7-8cmH2O to ~5-6cmH2O as age increased from 6-8 years old up to adulthood (18-37 years old).

The body of work on Po as a function of age consistently indicates that Po decreases as age increases from approximately six years old into early adulthood. At present, it is not possible to state definitively what the expected Po values are for children younger than six years of age. A few studies have included children as young as four-years-old. For example, Searl and Carpenter (1999) reported data from ten non-VPI subjects who ranged in age from 4;4 – 6;3 years old (mean: 5;2 years). Average Po on /p/ in various contexts ranged from ~9-11.5cmH2O for these young children. These values are higher than those reported by Bernthal and Beukelman

(1978) who had a group of subjects roughly within this same age range (~4.5 to 7 years). The age range in Stathopoulos and Weismer (1985) did go as low as four-years-old but ranged outside of the preschool age group with an upper limit of eight years (all data were pooled for the analysis). In the Smith et al. (2004) study, four children age five years old were included. However, the authors concluded that there were not enough subjects in this younger age range to draw meaningful conclusions about typical performances.

Explanations have been provided as to why Po is inversely related to age from childhood to adulthood. The smaller surface area of the child's speech mechanism compared to the adult's presents greater mechanical impedance to airflow and thus may result in greater Po (Stathopoulos & Weismer, 1985). A second explanation relates to the intensity of the speech that is sampled. Sound pressure level (SPL) is known to be positively correlated with the magnitude of Po in adults (Young, Zajac, Mayo & Hooper, 2001). Stathopoulos (1986) suggested that differences in SPL of the typical speech of children compared to that of adults might explain Po differences between younger and older speakers. In her study of twenty children age eight-ten years old and twenty adults aged 22-34 years old, she found that there were differences in Po when subjects were asked to speak in their typical loudness level. Using the instruction to speak at a "comfortable" level, the children produced the stimuli at a higher SPL than the adults. When the elicitation procedure was altered to obtain recordings of stimuli produced with comparable SPL, no significant differences in peak Po were found for children vs. adults.

In addition to age, gender also has been considered as a factor related to peak Po production during speech. Three studies have indicated that males generate higher Po than females. Dalston et al. (1988) studied 151 males and 116 females in six age categories producing the word ‘hamper.’ Oral pressure (cmH2O) on /p/ was as follows:

Age Range	Male	Female
<7	8.3	5.8
7-10	6.9	5.8
10-13	6.6	6.2
13-16	6.3	5.5
16-19	5.7	3.6
>19	4.9	4.0

Dalston et al. concluded that males tended to generate higher Po than females at each age level. The overall reduction in Po across the age range studied also was greater for the male group. Zajac & Mayo (1996) reported that young adult males generated significantly higher pressures on /p/ (5.9cmH2O) than adult females (4.7cmH2O). Results from a study of young and older adults by Zajac (1997) indicated that male speakers exhibit higher Po than female speakers during the production of /p/ in ‘hamper.’ Collapsing speakers in the young and old age groups, male subjects had a mean Po of 6.55cmH2O compared to 5.15cmH2O for females. In contrast, Stathopolous and Weismer (1985) did not find a gender difference for speakers that ranged in age from 4-30 years (data pooled across the full age range for the gender comparison). Bernthal and Beukelman (1978) offered mean Po values for males and females in three age ranges, but did not evaluate differences statistically. They reported data for ~4-7, 10-13 and 19-46 year olds: Males had values of 7.3cmH2O, 6.3cmH2O and 4.1cmH2O, respectively compared to females who had values of 6.1cmH2O, 6.0cmH2O and 5.0cmH2O. The Po for males in the youngest and the oldest age groups are notably greater than those for females in the same age group.

Nasal Air Flow

During production of nasal phonemes, the VP port is opened to allow nasal airflow. Conversely, during oral phoneme production, the expectation is that the VP port is closed so that air and acoustic energy is diverted primarily through the oral rather than the nasal cavity. The extent to which the VP port is closed during oral phoneme production is known to be dependent, in part, on the oral-nasal feature of the consonants that precede and follow a given phoneme. There is an ongoing need to specify the extent to which an airtight VP seal is maintained for a given speaker across trials and speech tasks. Data from Smith and Guyette (1996) and Searl and Carpenter (1999) suggest that individuals with perceptually normal speech may at times demonstrate substantial Vn during an oral consonant not bounded by a nasal phoneme.

Although Vn during speech has been the focus of many studies, only a small number have included a wide enough age range with sufficient subjects per age category to address the issue of age as a factor in the presence and magnitude of Vn.

Thompson and Hixon (1979) had 112 subjects ranging in age from 3 years to 37 years (92 falling within 3-18 years) produce sustained vowels, fricatives and nasals, as well as nonsense syllables in carrier phrases. The group produced sustained oral consonants and vowels, and oral consonants in vowel-consonant-vowel syllables (in isolation and carrier phrases) without Vn. Placing a nasal phoneme adjacent to a vowel did result in Vn on the vowel. Thompson and Hixon also made note of one 14 year old female who demonstrated occasional instances of rather large Vn (up to 80cc/sec) on some stimuli, despite having perceptually normal speech. Zajac (2000) reported Vn data for 223 children, teens and adults without cleft palate ranging in age from 6-37 years old. He analyzed the Vn data by age (6-8, 9-10, 11-12, 13-16 and 18-37 year olds) using /p/ as the measurement point in a syllable series (/pi/) and a word ("hamper") produced in isolation and in a short sentence. Mean flow values were low across age groups and stimuli (highest mean = 17cc/sec for 18-37 year olds on the sentence task). Post hoc analysis of the syllable production data indicated significant differences between six-eight year-olds and teenagers, six-eight year-olds and adults, and nine-ten year-olds and adults. Despite the statistically significant differences across age groups, the small group means for Vn led Zajac to conclude that an essentially airtight VP closure is exhibited during the production of /p/ at the syllable level by non-cleft speakers, regardless of age. He suggests that Vn rates of 20cc/s or less be considered complete/air-tight VP closure when producing /p/ at the syllable level, regardless of age. Smith et al. (2004) had fifty-six children divided into three age groups (5-8, 9-13 and 14-18 years old) produce oral syllables and the word “hamper” while Vn was measured. There were significant differences in Vn across the age groups with an overall trend for increased Vn with increased age. Vn demonstrated during oral sound segments were less than 10cc/s for children five-eight years, less than 20cc/s for youth 9-13 years and less than 30cc/s for teenagers 14-18 years, respectively.

A number of other studies have sampled Vn but only for a relatively restricted age range. For example, Searl and Carpenter (1999) recorded Vn (along with Po) on /p/ for non-VPI subjects ranging in age from approximately four to six years of age. Vn occurred infrequently at the peak Po of /p/ in various syllable constructions, suggesting fairly complete VP closure. However, eight of ten speakers had at least one Vn spike ≥45cc/sec indicating that young children may intermittently show evidence of nasal air escape on oral consonants. Others have reported occasional Vn on oral consonants in older children and adults that are of sufficient magnitude to exclude recording artifact and velar elevation as the cause (Warren, 1967; Thompson & Hixon, 1979; Andreassen et al, 1992).

Overall, Vn appears to occur infrequently on oral consonants regardless of speaker age. However, occasional bursts of Vn have been noted to occur. Additionally, although Vn of large magnitude does not occur often, the three studies best suited to evaluate the impact of speaker age on Vn magnitude during oral consonants have indicated a tendency for Vn to increase as age increases. (Thompson & Hixon, 1979; Smith et al., 2004; Zajac, 2000). Most investigators have downplayed the occurrence of Vn on oral consonants given the limited magnitude and frequency of occurrence. Whether or not even younger children (i.e., down to age three years) demonstrate similar patterns of Vn as do older children and adults is not known.

Differences in Vn as a function of gender have received limited attention. What data are available do not provide a clear picture about expected Vn as a function of gender. The Thompson and Hixon (1979) study revealed 32 of the 47 subjects who demonstrated Vn at the midpoint of the initial /i/ in nonsense productions were female. Zajac and Mayo (1996) reported gender specific data within their study. Male subjects produced values of 149ml/s on /m/ and 20ml/s on /p/ compared to values of 129ml/s and 10ml/s, respectively, for female speakers. The values for /p/ were statistically significantly different and suggested less Vn for males. Zajac (1997) did not find a significant main effect of gender on Vn for /p/ in the word hamper using young adults compared to older adults. Zajac (2000) also did not find any significant gender effect for Vn on either /m/ or /p/ for speakers ranging in age from 6-37 years of age. Additional studies are needed to clarify whether one should expect differing amounts of Vn for males compared to females. A conservative conclusion based on the available evidence to date is that if male-female differences are present for Vn on oral consonants, these differences are likely to be relatively small. Gender specific data on Vn in children younger than six years old have not been reported.

Velopharyngeal Orifice Area

As with Po and Vn, normative values for VP area estimates for nasal and oral consonants have been reported for elementary school aged children, teenagers and adults, but there is very little information available on preschool age children. As noted below, most researchers report that airtight closure of the VP port (i.e., VP area estimate of ~0mm^2) is expected most of the time on oral phonemes not bounded on either side by a nasal consonant, at least for school age children and adults. Normative values for VP area estimates on nasal consonants are available for children as young as five-years-old. Smith, Guyette, Patil and Brannan (2003) reported results for fifty-six children ranging in age from 5 years to 18 years. Subjects in the five-nine year old age group demonstrated a mean VP orifice area of 38.53mm^2 on /ma/ and 16.07mm^2 on the /m/ in ‘hamper.’ VP area estimates increased significantly for the 10-13 year olds (50.70mm^2 on /ma/; 21.29mm^2 on the /m/ in ‘hamper’) and for the 14-18 year olds (68.14mm^2 and 24.25mm^2, respectively). Zajac (2000) reported that teenagers (13-16 years old) and adults (18-37 years old) demonstrated significantly larger VP area estimates for /m/ in syllable, word and sentence level productions compared to six-eight and nine-ten year olds. VP area estimates on /m/ produced by adults in two other studies have reported values that are roughly consistent with those noted for the adults in the above studies (Andreassen et al., 1992; Zajac & Mayo, 1996).

Estimated VP orifice area data on oral consonants have been published on children as young as five-years-old. Smith et al. (2004) reported that VP area estimates on /p/ in oral syllables and the word “hamper” showed a small but consistent trend toward larger areas with increased age. Subjects were grouped as five-eight, 9-13 and 14-18 years old. Group means for the youngest age group ranged from $0.12mm^2$ to $0.44mm^2$ compared to $0.13mm^2$ to $0.97mm^2$ for the 9-13 year olds, and $0.22mm^2$ to $1.21mm^2$ for the 14-18 year olds. The data from Zajac (2000) also suggests a subtle trend for increased VP orifice area estimates with increased age in his study of 223 children, teens and adults without cleft palate ranging in age from 6-37 years old. However, Zajac did not statistically analyze the data because a large proportion of the productions had essentially no Vn and thus area calculations approaching 0 mm^2 (i.e., <0.1 mm^2). Based on tabled data from Zajac (2000), VP area estimates remained fairly constant across age groups (6-8, 9-10, 11-12, 13-16, and 18-37 years old) for the syllable stimuli (/pi/ and /p^/) with group mean values never exceeding $0.2mm^2$ for any age group. However, for the word "hamper" produced in isolation and in a sentence, area estimates increased gradually from $0.1mm^2$ for the youngest age group to ~0.7-$0.9mm^2$ for the oldest speakers. The study by Zajac and Mayo (1996) also reported VP area estimate data for young adults that were consistent with Zajac (2000) demonstrating a mean of $0.75mm^2$.

Across the studies of VP area estimates, an ongoing issue that has not been addressed is how general growth of the airway should be taken into consideration. Absolute VP orifice areas may increase from childhood to adulthood during consonant production. However, it is not known whether the VP opening relative to the maximal diameter of the VP airway remains constant as speaker's age.

There has been some limited investigation of differences in VP area as a function of gender. Zajac (2000) did not find a gender difference for either /m/ or /p/ for subjects between 6-37 years of age. In an earlier study of adults (18-37 years), Zajac and Mayo (1996) found no significant difference between males and females in terms of VP orifice area for /m/ (males = 17.5mm^2; females = 22.2mm^2) or /p/ (males = 0.9mm^2; females = 0.6mm^2). Smith et al. (2004) also did not find a significant difference between males and females (5-18 years old) in terms of VP area estimates on /p/ in syllables or the word “hamper.” Andreassen et al. (1992) studied twenty adults aged 20-36 years and found that women demonstrate statistically significantly smaller VP area estimates for /p/ in the word “hamper”. Area estimates for /p/ in other syllable series also were smaller for women but not statistically different. Area estimates for /m/ in “hamper” were also smaller for women but this was not statistically significant.

Overall, the literature supports the conclusion that young children produce oral and nasal consonants with smaller estimated VP area openings than teenagers and adults. The data are not particularly clear about whether a difference between males and females should be expected on this measure. Again, there has been very little reported on VP area estimates of children younger than six years. Subjects younger than six years of age have been included in at least one study of VP area estimates, but the data were combined with children ranging up in age to eight or nine years old.

Physical Correlates of Velopharyngeal Aerodynamics

Normative data for speech and language abilities have typically been established based on chronological age (CA), and, to a lesser extent, gender. Efforts to establish VP aerodynamic norms have followed suit. The data on VP aerodynamics as a function of gender have not clearly indicated differences for males compared to females. Data for children (school-age and up) and adults have supported the conclusion that VP aerodynamics do differ across the age ranges studied to date. One of the appeals of using age (and also gender) as the primary parameter for establishing VP aerodynamic norms is the simplicity in determining chronological age (and gender), facilitating the collection of the normative data and making application of the norms to clinical populations a straightforward proposition. However, the differences in VP aerodynamics across age categories are not due to chronological age itself, but rather to some other inherent physical characteristic(s) of the speaker. Features such as neurological maturity, body size, respiratory capacity, typical speaking intensity level and so forth, are likely the more direct influences on the aerodynamic measures. However, research efforts on VP aerodynamic norms to date have focused almost exclusively on chronological age as the parameter around which such norms are constructed, and other potentially more direct correlates have not been investigated to the authors knowledge.

STATEMENT OF PURPOSE

At present there are limited data regarding VP aerodynamics for children younger than six years of age. Normative studies of VP aerodynamics have focused heavily on school-age children, teenagers and young adults. However, SLPs often attempt to make decisions about the adequacy of VP function in children as young as three or four years of age. Aerodynamic data can serve as one piece of evidence in this decision making process. However, the values of these measures are limited given that appropriate norms are not available to help interpret results.

Ultimately, the goal of the proposed line of research is to establish appropriate VP aerodynamic norms that could be used for clinical purposes with very young children. Before initiating large-scale normative data collection, however, it is prudent to more carefully consider those characteristics of the speaker that might influence the aerodynamic measures of interest. The primary purpose of this study was to describe VP aerodynamics for children age 3;0 to 4;11 years and to investigate the relationship between various speaker characteristics (e.g., gender, body size) and the aerodynamic measures. Specific research questions were as follows:

1. What is the mean Po, Vn, and VP area estimate for oral and nasal consonants for children age 3;0-4;11 years? An equal number of boys and girls will be studied to allow description of aerodynamic values by gender.
2. Do Po, Vn, and VP area estimate during oral and nasal consonants vary with the following speaker characteristics in 3;0 to 4;11 year old children?
    a. Height
    b. Weight
    c. Head circumference
    d. Chest Circumference
    e. Cross-sectional area of the open VP port during nasal breathing

This question was intended to help guide decisions about the design of future normative studies of VP aerodynamics. A measure of lung function also would be logical to include; however, at present, quick, reliable, and non-invasive measures of respiratory function in preschool age children are difficult to make (Sly & Lombardi, 2003). Nevertheless, standing height has been shown to be a relatively strong predictor of forced vital capacity and other respiratory measures (Nystad, Samuelsen, Nafstad, Edvardsen, Stensrud & Jaakkola, 2002). An individual's typical intensity level during speech also can be considered a parameter that is inherent to the speaker and which also is expected to influence at least Po. Sound pressure level (SPL) during production of the experimental stimuli was measured, but not specifically manipulated in the study, so that it could be included in the correlational analysis.

3. Are the aerodynamic measures from young children stable over two data collection sessions? Stability of VP aerodynamic measures has not been considered in prior studies of normal speaking children, although greater variability within a single data collection session has been reported for children compared to adults.

A secondary purpose of this study was to compare Po, Vn, and VP area estimates from the preschool-age children (age 3;0-4;11) to school-age children (age 7;0-8;11). This purpose was in line with the more traditional approach to establishing aerodynamic norms based on CA. If the two age groups turn out not to differ, it may allay some concern that clinicians might have in using VP aerodynamic data from older children when evaluating younger children. If the two age groups do differ, the case becomes stronger for pursuing large scale data collection on children down to 3 years of age.

Specific research questions for this secondary purpose were as follows:

1. What is the mean Po, Vn and VP area estimate for oral and nasal consonants produced by children age 7;0 to 8;11?
2. Is there a difference in Po, Vn, and VP area estimate between the two age groups? When doing the comparison between age groups, an additional calculated value was computed that is the ratio of the calculated VP area to the VP cross-sectional area during nasal breathing that is referred to here as the percent VP area (%VP area). VP area estimates during consonant production reportedly increase in size with speaker age. Some investigators have hypothesized that this is evidence of greater coarticulation (if a nasal context is being considered) or simply less discrete articulatory production with increasing CA. However, the larger VP area estimates from childhood to adulthood may simply reflect larger absolute size of the VP port. The relative opening of the VP port during oral and nasal consonant production may remain unchanged as speakers get older, but no data have been reported to either confirm or refute this.

Future studies that help establish VP aerodynamic norms also must consider the influence from variables related to the speech sample (e.g., vowel and consonant context, position of the consonant within the stimulus, syllable stress, etc.) and aspects of how the speech is produced (e.g., rate, intensity, etc.). In the proposed study, these latter variables related to production parameters are not systematically manipulated, but they are roughly constrained by the modeling and elicitation procedures to screen out productions that vary notably in terms of rate, loudness, pitch, and inflection. Evaluating the influence of speech sample variables on Po, Vn and VP area was not a focus of this study. However, the speech protocol that subjects were asked to complete included stimuli not analyzed here that can be analyzed in the future. The additional stimuli could be used to evaluate issues such as the influence of vowel context (high vs. low tongue position), consonant context (nasal vs. oral) and stimulus construction (syllable train vs. short phrase) on Po, Vn and VP area.

METHOD

Subjects

Twenty-two children with normally developing speech between the ages of 3;0 and 4;11 were included to address the first purpose of this study. This age range was chosen because it is a critical time frame in which children with suspected velopharyngeal insufficiency (VPI) are being evaluated to help determine the need for intervention related to VP function, but information on VP aerodynamics for this age range are lacking. A smaller group of children (n=10) with normal speech between the ages of 7;0 and 8;11 were also included in this study to evaluate whether preschool age children perform differently than older children (purpose #2). All children within the study were Caucasian. Power analysis for a subset of the planned comparisons helped guide the decision on the number of subjects in each group. Consider the question of gender differences in Po within the preschool age group. A *t*-test could be used to compare the mean Po for males vs. females. Using Po means and standard deviation values from Searl & Carpenter, (1999) and Smith et al., (2003) as estimates for young speakers, using groups of eleven males and eleven females achieves 91% power when a *t*-test is utilized to test gender differences at a 5% significance level (calculated using PASS 2002-Power Analysis and Sample Size software). As a second example, means and standard deviations from published literature for children (Searl & Carpenter, 1999 and Smith et al., 2003) were used to estimate power for the planned comparison of younger and older children. With one group of twenty-two and another of ten, and a significance level of 5%, 84% power would be achieved using a *t*-test for Po.

Participation of the children was solicited using email flyers to the University of Kansas Medical Center faculty, staff and students, postings within KUMC and the community, and direct solicitation by the investigator and other clinical faculty during interactions with co-workers, friends and families that are in contact with the Hearing and Speech Department. Inclusion criteria for these 32 children were as follows:

1. Speech, language, hearing, and communication skills developing normally up to the time of data collection. Parents completed a questionnaire that asked about speech, language, hearing and other issues that might impact speech or velopharyngeal aerodynamics (Appendix A). Modified administration of the Goldman-Fristoe Test of Articulation (2^{nd} Edition; Goldman & Fristoe, 2000)(GFTA) was used to screen speech sound production. The screening required the child to repeat the single word stimuli from the GFTA rather than using pictures to elicit words; the repetition task was used to be more expedient with the screening given the young age of the subjects. A SLP who is licensed in KS and certified by ASHA (primary advisor) judged all productions, making note of errors on the form. The test was scored following the guidelines in the GFTA manual. Ratings of hypernasality, hyponasality and nasal emission were also made as the child repeated syllable series and phrases (Appendix B). These ratings were done live by the primary advisor. Productions were

also tape recorded for rater agreement purposes. A five-point rating scale was used (0 = none, 4 = severe). Ratings equal to or less than one for all hypernasality, nasal emission, and hyponasality stimuli in the protocol were required for inclusion. Appendix C includes GFTA scores and other descriptive information from the subject screening protocol for individual subjects.

2. American English as their primary spoken language. This was based on parent report.
3. Absence of medical conditions that are likely to have an impact on speech (e.g., cleft lip/palate, neuromotor disease, etc.). Parents were asked to identify any medical conditions affecting motor movement, respiration, head and neck structures or function, allergies or other conditions that may affect nasal patency, and brain function and cognition (Appendix A).
4. Normal velar structure and movement during vowel production. A licensed and certified SLP (primary advisor) completed an oral mechanism examination of the palate and oropharynx to rule out cleft palate, bifid uvula, or other anomalies. This oral mechanism exam also included observations and ratings of velar and lateral pharyngeal wall movement during sustained vowel production (Appendix B).
5. Absence of upper respiratory infection, sinus congestion or other nasally obstructive conditions on the day of data collection. Parents were asked to report whether the child was experiencing any nasal congestion or

difficulty passing air through the nose. In addition, as part of the experimental protocol, nasal breathing measures that allow calculation of nasal resistance were obtained. Normative nasal resistance (Rn) data for the younger age range are sparse. Vig and Zajac, (1993) reported data for children grouped from 5-12 years of age for males and females. Subjects in the current study who had measured Rn that fell within the 95% confidence interval for each gender remained in the study. For males the confidence interval was1.1-11.0cmH2O/L/s (mean = 6.0) and for females the interval was 3.0-8.0cmH2O/L/s (mean 5.5).

Instrumentation

PERCI-SARS (v3.43) hardware and software was utilized to obtain the aerodynamic measures of interest. To measure Po, a ~15cm length of polyethylene tube (2.42mm outer diameter, 1.67mm inner diameter) was placed between the lips in midline extending approximately 1cm behind the upper central incisors. The tube was on top of the tongue with the tip angled toward the roof of the mouth to reduce the likelihood that the tongue obstructed the catheter opening. This tubing was connected to one port of a differential pressure transducer (Setra Model 239) with the other port open to the atmosphere to detect Po. The output from the pressure transducer was routed to a signal conditioning unit where it was amplified and filtered (50Hz low pass filter). The amplified and filtered signal was then routed via a USB connection to a personal computer. PERCI-SARS software was utilized for display, measurement, labeling and archiving of the Po signal. The pressure transducer was calibrated each day before data collection following standard procedures (i.e., introduction of known pressures using a water manometer).

In order to measure Vn, a soft latex nasal mask was attached to a pneumotachometer (Hans Rudolph Model 3719) and the mask was placed over the child's nose. The pneumotachometer screen was heated to 37^0 C with a pneumotachometer heating unit (Hans Rudolph Inc. Pneumotachometer Heater Control). The pneumotachometer was attached to a second differential pressure transducer (Setra Model 239) with the output routed to the signal-conditioning unit where it was amplified and filtered. The pneumotachometer and pressure transducer arrangement were calibrated each day before data collection following standard procedures by using a compressed air source and a rotometer to introduce known rates of air flow into the system.

The SPL of the voice was measured using the calibrated condenser microphone that is part of the PERCI-SARS system. This microphone was mounted in a 2" inch long PVC tube that was attached to the outflow port of the pneumotachometer. The condenser microphone was mounted in the PVC tube so that it was oriented 90^0 from the direction of the airflow exiting the pneumotachometer. The microphone signal was routed to the high-speed data input port of the PERCI-SARS signal-conditioning unit where it was amplified. The amplified SPL signal was routed to the personal computer and displayed simultaneously with the air pressure and flow data. The condenser microphone that comes with the PERCI-SARS system was calibrated prior to being shipped to the user.

Speech Sample

The full speech sample was constructed to include assessment of Po and Vn during oral and nasal consonant production in high and low vowel contexts and also in syllable series and short phrases. For the phoneme /p/, the adjacent consonant was also varied (/m/ and /b/). The full stimulus set includes 33 items and is shown in Table 1.

Table 2 presents the stimuli in prioritized blocks that were solicited in a preset order so that there was a common set of data for addressing the research questions even for those who completed only a small portion of the stimulus set. Given the young age of the speakers in this study, it was anticipated that some would not tolerate the aerodynamic recordings for this full set of stimuli.

Blocks #1 and #2 served as the data set analyzed in this study. The oral consonant /p/ and the nasal consonant /m/ were heavily emphasized within the protocol because use of the centrally placed catheter for Po measurement can interfere with lingual consonants. For the target consonants /p/ and /m/, it was possible to acquire Po, Vn and SPL measures. Additional lingua-alveolar and lingua-palatal consonants were included in the protocol but Po was not sensed during these productions. Recordings of Blocks #3-6 are archived for future analysis. All of the older subjects completed blocks #3-6. Fourteen of the younger subjects completed all of the stimulus blocks. Seven of the younger subjects completed only blocks #1-2. One younger subject completed blocks #1-5. It was of interest to include both high and low tongue position vowels throughout the protocol because clinically it has been noted that

Table 1

Stimulus set

Experimental Consonant	Consonant Context	Vowel Context	Syllable Series	Phrase
/p/	--	/i/	/pipipi/	Pay Peewee
	--	/a/	/papapa/	Pay Papa
	/m/ (preceding)	/i/	/pimpimpim/	Mom peeked out
		/a/	/pampampam/	Mom popped out
	/b/ (preceding)	/i/		Bob peeked out
		/a/		Bob popped out
/m/	--	/i/	/mimimi/	Pay Mimi
		/a/	/mamama/	Pay Mama
/t/	--	/i/	/tititi/	Pay Tiesha
		/a/	/tatata/	
/f/	--	/i/	/fififi/	Pay Felix
		/a/	/fafafa/	
/ʃ/	--	/i/	/ʃiʃiʃi/	Pay Sheila
		/a/	/ʃaʃaʃa/	
/k/	--	/i/	/kikiki/	Pay Keysha
		/a/	/kakaka/	
/s/	--	/i/	/sisisi/	Pay Cici
		/a/	/sasasa/	
/p/	/m/	/ae/	Hamper Pamper	Hamper Us Pamper Us

Table 2

Block order of stimuli

Block #1	Block #2	Block #3	Block #4	Block #5	Block #6
/pipipi/	/tititi/	Pay Peewee	Pay Tiesha	/kikiki/	Pay Keysha
/papapa/	/tatata/	Pay Papa	Pay Felix	/kakaka/	Pay Cici
/mimimi/	/fififi/	Pay Mimi	Pay Sheila	/sisisi/	
/mamama/	/fafafa/	Pay Mama		/sasasa/	
/pimpimpim/	/ʃiʃiʃi/	Mom peeked out			
/pampampam/	/ʃaʃaʃa/	Mom popped out			
Hamper		Bob peeked out			
Pamper		Bob popped out			
		Hamper us			
		Pamper us			

vowel height may be associated with higher/lower Vn and Po on an adjacent consonant when VP opening is present. A nasal context was included because it is believed to be a more demanding speech situation for the VP mechanism (Warren 1979; Warren, Dalston, Trier & Holder, 1985; Dalston et al., 1988; Mayo, Warren & Zajac, 1998; Zajac & Hackett, 2002). The speaker must allow the VP port to open during production of the /m/ but then transition relatively quickly to a closed port for the /p/ so that Po can build and nasal emission of air on the oral consonant can be avoided. In the literature, the nasal context has focused exclusively on stimuli where the /m/ precedes the /p/ (i.e., a situation where perhaps carryover nasalization might occur). The stimulus "hamper" was included in the protocol because it has been used extensively in the literature. Use of that context here may allow more direct comparison of data from the current study to data reported previously for older children and adults.

For all of the experimental consonants there was a three-syllable train and a corresponding three-syllable phrase for each vowel and consonant context other than the /b/ consonant context. The syllable trains were analyzed in this study. Syllable series were chosen for analysis here because there was relatively high assurance that even the youngest children in the study would be able to produce this phonetically and linguistically simple set of stimuli. There was concern that not all of the young speakers would tolerate the length of the data recording session required for completing the full set of stimuli even if they were capable of producing the phrases. The data from phrase productions are available for analysis in the future.[1]

The bilabial voiced stop /b/ could also be produced without distortion from the centrally placed oral catheter and, as such, could serve as a target consonant. Initially a syllable series for the /bp/ context was included in the protocol. However, the first several children included in the study had varied significantly in the manner in which they produced the stimuli (releasing /b/ vs. not releasing /b/) even with modeling, instruction, and feedback from the investigator. Therefore, the stimulus was removed from the recording protocol. Additionally, clinical protocols used currently often focus on the voiceless /p/ rather than the voiced /b/ when assessing adequacy of VP function because voiceless stops are normally produced with greater Po. The higher-pressure demand for /p/ makes it more likely to show evidence of VP dysfunction (reduced Po and/or increased Vn) compared to /b/. Prior data from a group of children with normally developing speech aged approximately four to eight years of age (Searl & Carpenter, 1999) did not identify any differences in frequency of occurrence or magnitude of Vn as a function of stimulus voicing feature. Finally, given the age of the subjects in the current study it seemed prudent to limit the overall length of the protocol to those consonants that most likely will be used in a clinical aerodynamic assessment.

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[1] While the phrase stimuli may not carry significant linguistic meaningfulness for the youngest speakers, they do place the target consonants in real words within grammatically correct phrases. In this way, the phrase stimuli are perhaps a closer approximation to more typical speech production than are the syllable trains.

Procedures

Children over the age of 7;0 signed an Assent form; parents of all participants signed a Parental Permission form. After obtaining signatures, the parent or guardian completed a questionnaire that asked about the child’s medical, speech, language and hearing history (Appendix A). A licensed and certified SLP with 15 years experience (eight years involvement with assessing VP function; JS) completed the GFTA administration and ratings of hypernasality, hyponasality and nasal emission (Appendix B). This speech screening was audiotape recorded with a headset microphone and portable CD recorder so that it could be played back at a later time for assessment of intra- and inter-rater reliability.

The investigator measured the child’s height using a wall-mounted ruler. The child stood with shoes off, heals against the wall and the back straight. Height was recorded to the nearest centimeter. The child was weighed using a high quality scale without shoes on and coat/sweater/sweatshirt removed (weight recorded to the nearest kilogram). Head circumference was measured using a ribbon measuring tape placed at the widest diameter above the ears and the eyebrows (recorded to the nearest centimeter). Chest circumference was measured using the ribbon measuring tape around the chest, roughly at the nipple line (recorded to the nearest centimeter). The child’s shirt was left on for this measure, which was recorded to the nearest centimeter.

The child was seated in front of the aerodynamic equipment. The instrumentation and procedures were described for the child using language appropriate for their age. They were allowed to feel the nasal mask and to try it on prior to data collection. They also had the Po catheter placed in the mouth and practiced saying /p/ syllable series and words to become accustomed to the instrumentation.

When the child was familiar with the placement of the mask and oral catheter, instructions were given to elicit a nasal breathing curve. To obtain the nasal breathing curve, the Po catheter was placed in the mouth and the nasal mask was placed over the nose. The child was instructed to inhale (nose or mouth), close the lips on the oral tube and exhale slowly and steadily out the nose. The investigator modeled the task and had the child practice prior to recording the nasal breathing. The goal was to have children produce three nasal flow curves. All of the older children were able to do so; 14 of the 22 younger children (63%) were able to do the task. Eight of the younger children could not produce a useable nasal breathing curve for various reasons (intermittent obstruction of the Po tube; highly variable flow rate from moment to moment; pressure and flow curves that did not align, etc.)

The nasal breathing curve was used for three purposes: calculation of Rn, calculation of the nasal cross-sectional area (an estimate of the diameter of the VP port), and estimation of nasal pressure (Pn). The Rn value was used for exclusionary purposes as described previously, although no subjects for whom a breathing curve was obtained had to be excluded. An estimate of the nasal cross-sectional area was used as an indication of the absolute size of the VP port during a task that should induce an open VP port (i.e., nasal breathing). Use of this cross-sectional area is described further in the Analysis section. Pn was needed to calculate VP area estimates during speech. It could be measured directly by placing a catheter in one nostril while Vn is measured with a tube inserted in the other nostril. However, young children are less likely to be cooperative with this approach compared to the Pn estimation procedure proposed here. The method of estimating Pn is described in the following Measures section.

If a child was unable to generate an acceptable nasal breathing curve they were not automatically excluded from the study. The investigator also verified nasal patency by alternately occluding a child's nostril as they breathed through the nose. Subjective ratings of patency on a three-point scale (0=no obstruction, 2=significant obstruction to air passage) were made for each nostril. Subjects had to have bilateral ratings of 1 or less to remain in the study.

After completing the nasal breathing task, the instructor asked the child to repeat the speech stimuli. Specific instructions were as follows: "Take a breath and say, '(experimental stimulus)' in your talking voice". The software was engaged to record the child's production of the stimulus. Software settings were adjusted to allow for 30 seconds worth of recording at a time. When the child completed one experimental stimulus, the investigator immediately asked them to say the next stimulus. This sequence of the investigator providing a model and the child repeating the stimulus was repeated until the 30 second recording time was exhausted. That screen was then digitally labeled and saved and the recording system was re-engaged for another 30 seconds of recording.

During the speech recording, the investigator and thesis advisor monitored the child's productions in terms of the rate, loudness, stress patterning and intonation. The intent was to have them produce each experimental stimulus at a rate of three to five syllables per second on one breath using pitch, loudness and voice quality that were consistent with what was heard in their conversational speech. Unusual or exceptional stress placement or intonation also were to be avoided. If the child deviated from their typical speech pattern, that sample was subsequently marked for exclusion for data analysis and a repetition of the stimulus was solicited.

Each item in the stimulus list was produced three times. The order of the stimulus productions was recorded in blocks that remained constant across speakers as indicated in Table 2. While it may be preferable to fully randomize the stimuli, this could significantly slow down the data collection session with these young children. Shifting from one stimulus to a completely different stimulus may confuse the child or at least require a full model from the investigator prior to each stimulus (as opposed to giving an initial model and then after a successful imitation from the child, instructing them, "Say it again"). Additionally, if a full randomization of the stimuli were used, there was a risk of having widely disparate data sets from one child to the next if children did not complete the full stimulus set. By recording the stimuli in a preset order there was greater assurance of a common, minimum data set that could be analyzed.

Each child’s parent or guardian was asked if they were willing to return for a second data recording session. Data from a second session was used to address the issue of within speaker stability of VP aerodynamic measures. For those that agreed, a second meeting was arranged and the child repeated the protocol as described above. There were a total of twelve younger children who completed a second set of recordings. Nine of these were completed within three days of the original recording; the remaining three were gathered on the same day as the original recording with a one hour break between recording sessions.

Measures

Peak Po served as the point of measurement for Po (cmH2O), Vn (cc/s) and SPL for the experimental consonants /p/ and /m/. These measures were taken from the experimental consonant in the second syllable of the syllable train. For “hamper,” the /p/ was the experimental consonant of interest and it was within the second syllable of the word. Po and the corresponding Vn and SPL were measured for the experimental consonant from the three repetitions of each syllable train or word and averaged for each speaker. The investigator used the ‘manual’ cursor control (left/right arrows of the keyboard) to place a cursor at the peak of the Po curve for the experimental consonant in a given production. This value, along with the corresponding Vn and SPL, were logged for later analysis. For /t, f, ʃ/, only Vn and SPL are obtained. Measures were taken from the second syllable of the series.

To obtain VP area estimates (mm^2), the Vn and Po tracings from the nasal breathing task were used to construct a graph allowing estimates of Pn. From a speaker's three nasal breathing attempts, one was selected that most closely met the following criteria:

- simultaneous rise in Po and Vn tracing from baseline
- sharp upward slope of the Po and Vn curve
- relatively steady, and gradual decline of both the Po and Vn curves
- simultaneous return of the Po and Vn tracing to baseline
- sufficiently high maximum Vn that exceeded a speaker's Vn during any of the speech stimuli productions

Using the PERCI-SARS software, cursors were placed at 75cc/sec intervals on the Vn curve and the corresponding Po was logged. Using the Vn-Po measures at 0cc/sec and at each 75cc/sec interval up to the speakers maximum Vn, a graph was constructed using a custom program in MATLAB. The curve was used to estimate Pn at any given Vn for that speaker. In this manner, Pn, Po and Vn values were available for use in the modified hydraulic equation to estimate VP port area. In order to minimize human error in the mathematical calculations, the Po, Vn and estimated Pn values were entered into an Excel spreadsheet and a function was created that automatically calculated the VP area estimate. Percent VP area was calculated by dividing a given VP area estimate by that speaker's cross-sectional area during nasal breathing with the resulting value multiplied by 100. This calculation was also set up as a formula in Excel to limit calculation errors.

Intra-measurer error for the aerodynamic parameters was checked by having the investigator re-measure 20% of the stimuli. This was essentially a check on the investigator's reliability in placing the cursor at the peak of the Po curve for the correct syllable (Vn was simply recorded as the value at the site of the cursor placement for peak Po measurement). For intra-measurement agreement, the mean Po value on the first measurement differed, on average, from the value at the second measurement by 0.2cmH2O. A *t*-test for paired data resulted in a *t* value of 0.104 and a probability value of 0.879 indicating that the two sets of measures did not differ significantly (using .05 as the criterion). A second investigator trained to the task also measured 20% of the stimuli to allow an assessment of inter-measurer agreement. The mean difference between the two measurers was 0.3cmH20 and the *t*-test was not statistically significant using an alpha level of .05 (t=0.176, p=0.844).

Inter- and intra-rater agreement were assessed for the perceptual ratings of hypernasality, hyponasality, and nasal emission that were completed as part of the subject screening. Ratings for 25% of the subjects were repeated for the intra-rater agreement (8 subjects x 13 productions rated = 104 samples in the agreement analysis). The same SLP who completed the initial screening listened to the audio tape recordings at least two weeks after the first screen. The ratings from the two measurement times were in exact agreement for 97% of the samples (101 of 104); there was never more than one scale point difference. At no time was there a rating that exceeded minimal on any of the parameters rated and, in fact, all disagreements involved ratings of hyponasality. For inter-rater agreement, a second licensed SLP with a minimum of two years clinical experience evaluating individuals with VP incompetency completed ratings for 25% of the subjects. Exact agreement occurred

94% of the time (98 of 104). Again, all disagreements were within one scale point of each other and no ratings ever exceeded minimum. Of the six disagreements, four occurred on hyponasality samples and two on nasal emission samples.

Analysis

Mean Po, Vn, and VP area for each stimulus were calculated for each speaker. To address the first research objective (description of VP aerodynamics for young children), group means, standard deviations, and ranges were calculated with subdivision based on stimulus and gender. Descriptive statistics were reported for the 7;0-8;11 year old group as well.

Various statistical inference procedures were utilized to answer the research questions. As part of the description of VP aerodynamics in the young group, differences in each measure were evaluated as a function of stimulus. The data for /p/ and for /m/ were analyzed separately because of expected differences in all of the measures. For /p/ stimuli (/pi/, /pa/, /pim/, /pam/, hamper, pamper), a series of one-way analyses of variance (ANOVA) were computed to look for differences in each aerodynamic measure/calculation. A *t*-test for independent measures was calculated to assess gender differences for the four dependent variables for the /p/ stimuli (data collapsed across the six stimuli). For /m/, a series of four *t*-tests for paired data were used to evaluate differences in the four dependent variables for /mi/ compared to /ma/. Gender differences for the /m/ data were also evaluated with four separate *t*-tests (one each for Po, Vn, VP area and %VP area; data collapsed for /mi/ and /ma/). For the /t/, /f/ and /ʃ/ productions, a two (vowel) x three (consonant) ANOVA was calculated with Vn as the dependent measures (recall that Po was not measured for these stimuli).

The second research question focused on whether Po, Vn and VP area vary within the young group as a function of height, weight, head circumference, chest circumference and cross-sectional area of the VP port. Two approaches were used to address this question. First, multiple correlation analysis (*Pearson product moment correlation coefficients*) was completed using the body size measures and the four VP measures (Po, Vn, VP area, %VP area). Probability values for each correlation were computed. Second, the young children were divided into two groups on each of the respective body measures. That is, for a given measure, such as height, the group was roughly split in half into taller and shorter children based on the percentile value for that child (groups were divided at the 50th percentile mark). A *t*-test was then used to evaluate differences for each aerodynamic measure with the group divided along a chosen body size parameter.

The third research question asked whether aerodynamic measures from the preschool speakers are stable over two recording sessions. For each speaker, grand means for Po and Vn were calculated for /p/ and for /m/, respectively, from the first recording session. Grand means also were calculated from the productions in the second recording session. *T*-tests for repeated measures were calculated for Po and Vn, for /p/ and for /m/. The VP area estimate and %VP area data were not tested for stability over the two recording sessions. Both of these are computed values that come from the Po and Vn measures.

Comparison of Po, Vn, VP area, and %VP area of the older and the younger children was done using an ANOVA approach. For /p/, a two (group) x six (p-stimuli) ANOVA was calculated for each of the four aerodynamic measures. For /m/, a two (Group) x two (m-stimuli) ANOVA was calculated for each measure.

Although a large number of statistical tests were run in this analysis, the criterion level for determining statistical significance was held at 0.05 for each test. This was done in part because this study could be viewed as a pilot investigation of VP aerodynamics in 3;0 to 4;11 year old children, a group for whom aerodynamic data have not previously been reported. Using an adjusted alpha level following usual statistical procedures would have resulted in an extremely conservative alpha level (depending on how it was calculated, the adjusted criterion could have been ~0.001 or lower) which may have obscured potentially relevant trends that should be followed up in subsequent larger scale investigations.

RESULTS

Description of VP Measures in Young Children

Oral Consonants

Means, standard deviations, and ranges for Po, Vn, VP area, and %VP area for the /p/ stimuli are presented in Table 3 and Appendix D. A one-way ANOVA was computed for each of the four dependent variables to evaluate differences as a function of the six /p/-stimuli. The one-way ANOVA results are presented in Table 4.

Mean Po on /p/ across all stimuli for the young group was 8.25cmH20 (sd = 1.92). The ANOVA for Po was not statistically significant (F=2.073, p=0.073) indicating that Po did not differ across the six /p/-stimuli. Mean Vn on /p/ across the six stimuli was small (5.76cc/s; sd=10.88) and measures of 0cc/s were quite common. Although Vn occurred infrequently and was limited in magnitude across the six consonants, the one-way ANOVA was statistically significant (F=4.777, p=0.000). Post hoc testing identified significantly greater Vn on /p/ in /pim/ compared to /pa/ (p=0.048). Vn on /p/ in /pam/ was significantly greater than that in /pi/ (p=0.009), /pa/ (p=0.006), and pamper (p=0.038). None of the other paired comparisons were significantly different at the 0.05 alpha level.

Fourteen of the 22 young speakers (64%) had nasal breathing curves that could be used to estimate Pn, allowing calculation of VP area. Mean VP area for /p/ from these 14 subjects was 0.09mm^2 (sd=0.56mm$^{2)}$.

Table 3

Descriptive statistics of aerodynamic measures for /p/ in the young group (SD = standard deviation; Po=oral pressure (cmH20); Vn=nasal flow (cc/sec); VP area=velopharyngeal area (mm$^{2)}$)

	/pi/	/pa/	/pim/	/pam/	hamper	pamper	combined
Po							
Mean	8.97	9.13	8.70	7.53	7.77	7.38	8.25
SD	1.79	2.51	3.52	2.76	1.76	2.36	2.57
Range	5.22-12.61	4.99-14.71	5.07-19.98	4.12-16.81	5.27-12.86	2.02-12.08	2.02-19.98
Vn							
Mean	1.75	1.41	10.64	12.56	5.08	3.11	5.76
SD	1.68	1.53	14.59	16.33	10.86	4.36	10.89
Range	0.00 - 5.07	0.00 - 6.26	0.00 - 51.64	0.00 - 64.26	0.00 - 50.51	0.00 - 14.64	0.00 - 64.26
VP Area							
Mean	0.00	0.00	0.08	0.07	0.37	0.03	0.09
SD	0.00	0.00	0.15	0.11	1.37	0.10	0.56
Range	0.00 – 0.00	0.00 – 0.00	0.00 - 0.50	0.00 - 0.39	0.00 - 5.13	0.00 - 0.38	0.00 - 5.13
% VP Area							
Mean	0.00	0.00	0.37	0.30	1.26	0.16	0.35
SD	0.00	0.00	0.66	0.49	4.66	0.48	0.77
Range	0.00 - 0.00	0.00 - 0.00	0.00 - 2.10	0.00 - 1.83	0.00 - 17.45	0.00 - 1.78	0.00 - 17.45

Table 4

Analysis of variance results for aerodynamic measures on the /p/ stimuli in the young group

	Df	*F*	*P*
Po			
between groups	5	2.073	0.073
Within groups	126		
Total	131		
Vn			
between groups	5	4.777	0.000
Within groups	126		
Total	131		
VP Area			
between groups	5	0.854	0.516
Within groups	78		
Total	83		
% VP Area			
between groups	5	0.823	0.537
Within groups	78		
Total	83		

Rounding to two decimal places, mean area values for /pi/ and /pa/ were 0.00. Mean VP area for the stimuli with /p/ in a nasal context also approached zero, although rare instances of larger VP gaps did occur. VP area did not differ significantly across the six /p/-stimuli as indicated by the one-way ANOVA (*F*=0.854, *p*=0.516). Mean %VP area on /p/ for the group was 0.35% (sd=1.9%). Again, there was no significant difference in the %VP area across the six stimuli as indicated by the non-significant one-way ANOVA (*F*=0.823; *p*=0.537).

One purpose of this study was to evaluate whether young male and female children differed in terms of VP aerodynamic measures. Table 5 provides descriptive statistics for Po, Vn, VP area, and %VP area for the /p/ stimuli for males and females, respectively. In this table, data have been collapsed across all six stimuli because the above analysis indicated no significant differences for Po, VP area and %VP area and, although statistically significant, only a small actual difference in Vn was present across the stimulus set. A *t*-test for independent measures was performed for each of the four dependent variables to evaluate gender differences. None of the four *t*-tests were statistically significant (see Table 5) indicating that Po, Vn, VP area and %VP area were statistically similar for the young male and female speakers.

The oral consonant /p/ served as the primary focus of this study. However, Vn also was recorded as subjects produced the oral consonants /t/, /f/ and /ʃ/ in consonant-vowel syllable series. Means, standard deviations and ranges of Vn for these productions are presented in Table 6. Overall, Vn was quite limited across all of these production with a mean flow of less than 2cc/sec.

Table 5

Descriptive statistics and *t*-test results for the aerodynamic measures on /p/ as a function of speaker gender in the young group (Po=oral pressure (cmH20); Vn=nasal flow (cc/sec); VP area=velopharyngeal area (mm$^{2)}$)

	Mean	**SD**	**Range**	***t*-value**	***p***
Po					
Male	8.41	2.86	4.47 - 19.98	0.529	0.468
Female	8.08	2.26	2.02 - 13.93		
Vn					
Male	6.46	10.92	0.00 - 51.64	0.549	0.460
Female	5.06	10.90	0.00 - 64.26		
VP Area					
Male	0.03	0.09	0.00 - 0.50	0.877	0.352
Female	0.15	0.79	0.00 - 5.13		
% VP Area					
Male	0.16	0.41	0.00 - 2.10	0.826	0.366
Female	0.54	2.70	0.00 - 17.45		

Table 6

Descriptive statistics for nasal airflow (cc/sec) on /t/, /f/ and /ʃ/ in young children

Stimulus	Mean	SD	Range
/ti/	0.88	1.30	0.00 - 3.84
/ta/	4.66	15.22	0.00 - 70.67
/fi/	0.82	1.25	0.00 - 4.64
/fa/	1.58	3.27	0.00 - 14.97
/ʃi/	0.85	1.26	0.00 - 4.37
/ʃa/	1.39	1.29	0.00 - 4.24
Combined	1.69	2.25	0.00 - 70.67

Out of nearly 370 syllable series produced (21 subjects x 6 stimuli involving /t/, /f/ and /ʃ/ x 3 repetitions), there were only four instances in which Vn was greater than 50cc/s (maximum of 70.67cc/s). A frequency count of instances of Vn within specified ranges is given in Appendix E (frequency counts for all stimuli are included). A two (vowel) x three (consonant) ANOVA with Vn as the dependent variable was not statistically significant for either main effect (Vowel: *F*=0.073, *p*=0.842; Consonant: *F*=0.825, *p*=0.746) or the interaction effect (*F*=0.586, *p*=0.378).

Nasal Consonant

Means, standard deviations, and ranges for Po, Vn, VP area, and %VP area for /m/ are presented in Table 7 along with results from a series of *t*-tests for paired data to evaluate differences between /mi/ and /ma/. Appendix D provides descriptive data on each individual subject. Mean Po for /mi/ and /ma/ combined was 0.82cmH2O (sd=0.57). The *t*-test for Po was statistically significant using an alpha level of 0.05. However, the actual difference between the group mean Po for /m/ in /ma/ compared to /mi/ was small (0.35cmH2O).

Combining data for /mi/ and /ma/, Vn mean on /m/ was 53.05cc/s (sd=29.07cc/s), VP area was 12.25mm^2 (sd=5.93mm^2), and %VP area was ~51% (sd=23%). None of the three *t*-tests for paired data resulted in a statistically significant value (see Table 7) indicating no difference in Vn, VP area, and %VP area for /m/ in the /ma/ versus the /mi/ productions.

The male and female speaker means, standard deviations, and ranges for Po, Vn, VP area, and %VP area for the /m/ stimuli are presented in Table 8. A *t*-test for independent measures was calculated for each of these four dependent variables. None of the four *t*-tests were statistically significant (Table 8) indicating no difference between young males and females in terms of Po, Vn, VP area and %VP area.

Relationship Between Body Size and VP Aerodynamic Measures in Young Children

Two statistical approaches were utilized to evaluate the relationship between body size and aerodynamic measurements. The first focused on the strength of the correlation between body measurements (height, weight, head circumference, chest circumference and cross-sectional area of the VP port during nasal breathing) and the four VP measures (Po, Vn, VP area and %VP area). The second approach was a statistical comparison for each VP measure with the young participant group divided approximately in half for each body size measure (i.e., those with values above the 50th percentile compared to those with values below the 50th percentile for a given body parameter). Separate correlation matrices and statistical comparisons were completed for the /p/ and the /m/ data.

For the correlation matrix involving the /p/ stimuli (Table 9), the overall mean Po, Vn, VP area and %VP area, respectively, were calculated for each speaker for the full set of six /p/ stimuli. These grand means from each speaker were then correlated to each of the body measurements for that speaker. Vn was not significantly correlated with any of the body size measures, most likely because Vn was typically 0cc/sec (i.e., the distribution of Vn values was fairly restricted). Oral air pressure was significantly positively correlated with head circumference (i.e., as head circumference increased, Po increased), although the correlation coefficient of 0.182

Table 7

Descriptive statistics of aerodynamic measures for /m/ in the young group (SD = standard deviation; Po = oral pressure (cmH20); Vn = nasal flow (cc/sec); VP area = velopharyngeal area (mm$^{2)}$)

	/mi/	**/ma/**	**Combined**	***t* - value**	***p***
Po					
Mean	0.64	0.99	0.81	4.195	0.047
SD	0.41	0.67	0.57		
Range	0.10 - 1.51	0.31 - 3.19	0.10 – 3.19		
Vn					
Mean	46.64	59.78	53.05	2.264	0.140
SD	22.02	34.24	29.07		
Range	7.78 - 79.25	12.19 - 124.05	7.78 - 124.05		
VP Area					
Mean	12.32	12.19	12.25	0.003	0.957
SD	6.01	6.09	5.93		
Range	2.14 - 21.26	4.31 - 24.65	2.14 - 24.65		
% VP Area					
Mean	52.15	48.29	51.46	0.163	0.690
SD	26.93	22.31	23.11		
Range	7.16 - 83.10	14.41 - 82.29	7.16 - 83.10		

Table 8

Descriptive statistics and *t*-test results for the aerodynamic measures on /m/ as a function of speaker gender in the young group (Po=oral pressure (cmH20); Vn=nasal flow (cc/sec); VP area=velopharyngeal area (mm$^{2)}$)

	Mean	**SD**	**Range**	***t*-value**	***p***
Po					
Male	0.85	0.72	0.22 - 3.19	0.246	0.622
Female	0.76	0.38	0.00 - 1.62		
Vn					
Male	53.34	28.96	7.78 - 115.37	0.004	0.949
Female	52.76	29.89	12.19 - 124.05		
VP Area					
Male	12.91	6.66	2.14 - 24.65	0.344	0.563
Female	11.55	5.21	3.69 - 19.01		
% VP Area					
Male	53.48	24.76	7.16 - 82.59	0.487	0.492
Female	46.85	24.55	11.83 - 83.10		

Table 9

Correlation coefficients (*r*) and probability values (*p*) for body size and aerodynamic measures on /p/ stimuli in the young group (Po=oral pressure (cmH20); Vn=nasal flow (cc/sec); VP area=velopharyngeal area (mm$^{2)}$)

	Po	**Vn**	**VP Area**	**% VP Area**
Height				
r-value	0.164	-0.045	0.273	0.265
P	0.060	0.611	**0.012**	**0.015**
Weight				
r-value	-0.010	0.014	0.293	0.284
P	0.906	0.874	**0.007**	**0.009**
Head Circumference				
r-value	0.182	-0.144	0.059	0.048
P	**0.036**	0.100	0.591	0.666
Chest Circumference				
r-value	0.114	-0.052	0.239	0.225
P	0.191	0.552	**0.028**	**0.040**
Cross Sectional Area of the VP Port				
r-value	0.168	-0.153	0.066	0.047
P	**0.006**	0.075	0.553	0.670

was considered small according to guidelines suggested by Cohen (1988). The resulting r^2 value for the Po-head circumference correlation indicated that head circumference accounted for approximately three percent of the variance in Po. VP area and %VP area were both significantly positively correlated with height, weight and chest circumference, but not head circumference or cross sectional area of the VP port during nasal breathing. The statistically significant *r*-values ranged from 0.225 - 0.293 (small per Cohen's guideline) with the percent variance accounted for ranging from ~5% to 8.5%.

A correlation matrix using the aerodynamic measures for /m/ is presented in Table 10. Two of the twenty correlations were statistically significant. Nasal airflow was significantly positively correlated with weight; an *r*-value of 0.410 is interpreted as a medium strength correlation (Cohen, 1988) and roughly 17% of the variance is accounted for by the weight measure. Percent VP area was significantly correlated with cross-sectional area of the VP port. This was a negative correlation that was classified as a medium strength relationship. This negative correlation is not surprising given that the cross-sectional area itself is part of the calculation of %VP area. As cross-sectional area increases, %VP area decreases because cross-sectional area is the denominator in the %VP area calculation.

As indicated above, a series of *t*-tests for independent measures was calculated to evaluate differences in Po, Vn, VP area, and %VP area, as a function of height, weight, head circumference, and chest circumference (total of 16 *t*-tests for the /p/ stimuli and 16 for the /m/ stimuli). *T*-tests for differences as a function of cross-

Table 10

Correlation coefficients (*r*) and probability values for body size and aerodynamic measures on /m/ stimuli in the young group (Po=oral pressure (cmH20); Vn=nasal flow (cc/sec); VP area=velopharyngeal area (mm$^{2)}$)

	Po	**Vn**	**VP Area**	**% VP Area**
Height				
r-value	0.040	0.300	-0.020	-0.100
P	0.801	0.051	0.921	0.621
Weight				
r-value	0.078	0.410	0.155	0.071
P	0.621	**0.006**	0.441	0.727
Head Circumference				
r-value	0.133	-0.168	-0.159	-0.309
P	0.394	0.281	0.427	0.116
Chest Circumference				
r-value	0.145	0.210	-0.096	-0.196
P	0.354	0.176	0.632	0.328
Cross Sectional Area of the VP Port				
r-value	-0.079	-0.274	-0.037	-0.397
P	0.694	0.167	0.855	**0.040**

sectional area of the VP port were not completed because information on percentile divisions for this measure is not available. For a given body parameter, the speakers were divided into two groups: those with measures placing them above the 50th percentile and those below it. The separation into two groups did not always result in an equal number of subjects in each group, but in no instance did the groups differ by more than two subjects. None of the 16 *t*-tests for /p/ were statistically significant (see Table 11). For the /m/ stimuli, there were no significant differences in any aerodynamic measure based on body parameters, with one exception (Table 11). Vn was significantly greater for the "tall" group compared to the "short" group (means of 61cc/s and 43cc/sec, respectively).

Sound Pressure Level and VP Aerodynamic Measures in Young Children

Sound pressure level was measured simultaneously with Po and Vn allowing an assessment of the strength of the relationship between SPL and the primary dependent variables. Pearson product moment correlation coefficients were calculated to assess the relationship between SPL and Po and Vn for /p/ and for /m/, respectively. None of the four correlations were statistically significant (Table 12), indicating that there was not a strong relationship between SPL and the aerodynamic measures in young children who were asked to talk in their "regular" voice (i.e., SPL was not specifically manipulated in this study).

Stability in Po and Vn Across Two Recording Sessions

Twelve of the 22 young speakers completed the protocol a second time within one hour to one week after the original data collection. Differences in Po and Vn

Table 11

Statistical results of *t*-test comparisons of tall/short (Height), heavy/light (Weight), and large/small (Head and Chest Circumference, respectively) for each of the aerodynamic measures. Results are reported separately for /p/ and /m/ (*t*= *t*-value; *p*=probability; Po=oral pressure; Vn=nasal flow; VP area=velopharyngeal area)

Stimulus	Aerodynamic Measure	Height		Weight		Head Circumference		Chest Circumference	
		t	*p*	*t*	*p*	*t*	*p*	*t*	*p*
/p/									
	Po	0.001	0.994	0.085	0.771	0.398	0.529	2.566	0.112
	Vn	0.158	0.692	0.162	0.688	0.801	0.372	2.110	0.149
	VP Area	0.609	0.437	0.170	0.681	0.181	0.672	0.061	0.805
	%VP Area	0.530	0.469	0.100	0.753	0.069	0.794	0.004	0.951
/m/									
	Po	0.309	0.581	1.916	0.174	0.028	0.869	1.853	0.181
	Vn	4.581	**0.038**	3.798	0.058	1.559	0.219	1.369	0.249
	VP Area	2.153	0.155	0.255	0.618	0.551	0.465	0.558	0.462
	%VP Area	1.039	0.318	0.015	0.903	3.278	0.082	3.173	0.087

Table 12

Correlation coefficients (r) and associated probability values (*p*) for the relationships between SPL and Po and Vn, respectively, for /p/ and /m/ in the young group

		r	***p***
/p/			
	Po	-0.050	0.552
	Vn	0.011	0.688
/m/			
	Po	-0.185	0.213
	Vn	0.043	0.451

between the first and second stimulus recording sessions were evaluated using *t*-tests for paired data. For /p/, there was a statistically significant difference in Po (*t*=3.129, *p*=0.002), but not Vn (*t*=0.271, *p*=0.785). Oral pressure was greater for the second data recording session (Table 13). Although statistically significant, the actual difference was small (0.74cmH20). One possibility explored here was that SPL might have differed from Time 1 to Time 2, potentially contributing to the Po difference that was found. However, SPL during /p/ from Time 1 recordings compared to Time 2 recordings did not differ (*t*= -0.833, *p*=0.380). For /m/, Po and Vn did not differ when comparing values from the first and second recording sessions.

VP Measures in Older Versus Younger Children

A secondary purpose of this study was to compare Po, Vn, VP area, and %VP area of the younger and older children. Descriptive statistics for the four dependent variables from the productions by the older children are offered in Tables 14 (for the /p/ stimuli) and 15 (for the /m/ stimuli).

In order to compare the older to the younger children, a two (group) x six (/p/ stimuli) ANOVA was calculated for each of the four variables (Po, Vn, VP area, and %VP area). For the /p/ data, none of the four ANOVAs resulted in statistically significant main effects of Group (Table 16). This indicated that the aerodynamic measures on /p/ did not differ significantly between the younger and the older children. The main effect of Stimuli was statistically significant for Vn on /p/. Post-hoc testing indicated that /pim/ and /pam/ had higher Vn than each of the remaining four /p/ stimuli. Probability values for these post hoc tests for /pim/ were as follows:

Table 13

Descriptive statistics (mean and standard deviation [SD]) of oral Pressure (Po) and nasal flow (Vn) on /p/ and /m/ at each recording session. Paired *t*-test results (t) and associated probability values (*p*) are included

		Time1		**Time 2**		**Statistical Results**	
/p/		mean	SD	mean	SD	*t*	*p*
	Po	8.21	2.45	8.95	2.58	-3.129	**0.002**
	Vn	6.70	11.76	7.17	13.29	-0.273	0.785
/m/							
	Po	0.846	0.641	0.928	0.691	-0.422	0.676
	Vn	53.77	33.53	58.34	29.35	-0.518	0.609

Table 14

Descriptive statistics of aerodynamic measures for /p/ stimuli in the older group (SD = standard deviation; Po = oral pressure (cmH20); Vn = nasal flow (cc/sec); VP area = velopharyngeal area (mm$^{2)}$)

	/pi/	**/pa/**	**/pim/**	**/pam/**	**hamper**	**pamper**	**combined**
Po							
Mean	8.41	7.85	7.96	7.01	7.68	7.72	7.77
SD	2.43	1.58	2.04	1.89	1.68	2.06	1.95
Range	4.48 - 11.95	5.37 - 10.93	4.52 - 11.89	3.44 - 9.66	4.87 - 9.72	4.54 - 11.20	3.44 – 11.95
Vn							
Mean	0.64	1.36	12.50	9.07	1.18	1.12	4.31
SD	0.75	1.81	15.76	8.00	1.33	1.08	4.79
Range	0.00 - 2.05	0.00 - 5.46	0.00 - 49.09	0.23 - 22.92	0.00 - 4.18	0.00 - 2.65	0.00 – 49.09
VP Area							
Mean	0.00	0.00	0.15	0.21	0.00	0.00	0.06
SD	0.00	0.00	0.19	0.52	0.00	0.00	0.12
Range	--	--	0 - 0.50	0 - 1.67	--	--	0.00 – 1.67
% VP Area							
Mean	0.00	0.00	0.40	0.75	0.00	0.00	0.19
SD	0.00	0.00	0.47	2.03	0.00	0.00	0.42
Range	--	--	0.00 – 1.39	0.00 – 6.50	--	--	0.00 – 6.50

Table 15

Descriptive statistics of aerodynamic measures for /m/ in the older group (SD = standard deviation; Po = oral pressure (cmH20); Vn = nasal flow (cc/sec); VP area = velopharyngeal area (mm$^{2)}$)

	/mi/	**/ma/**	**Combined**
Po			
Mean	0.79	0.97	0.88
SD	0.54	0.57	0.56
Range	0.32 - 2.01	0.33 - 2.07	0.32 – 2.07
Vn			
Mean	62.83	74.99	68.91
SD	34.73	47.25	40.99
Range	19.58 - 115.73	16.70 - 147.04	16.70 – 147.04
VP Area			
Mean	14.14	16.62	15.38
SD	6.00	8.82	7.41
Range	5.29 - 21.65	4.12 - 29.52	4.12 – 29.52
% VP Area			
Mean	41.28	47.87	44.58
SD	14.09	22.12	18.11
Range	17.18-59.64	13.38-80.88	13.38-80.88

/pi/ - 0.001, /pa/ - 0.001, hamper - 0.031, and pamper - 0.004. For /pam/, the post-hoc probabilities were as follows: /pi/ - 0.000, /pa/ - 0.000, hamper - 0.022, and pamper - 0.003. No other post hoc comparisons of Vn on /p/ were significantly different at the 0.05 level. The Stimulus main effect was not statistically significant in the other three ANOVAs for Po, VP area or %VP area. None of the interaction effects of Group x Stimuli were statistically significant for any of the four measures taken on /p/.

Four additional two (group) x two (/m/ stimuli) ANOVAs were calculated to evaluate differences on Po, Vn, VP area and %VP area for /m/. There were no significant main or interaction effects for any of the four ANOVAs (Table 16) indicating that the younger and older children had statistically similar aerodynamic values for the /m/ stimuli.

Table 16

Analysis of variance results comparing the older and younger groups on each aerodynamic measures for /p/ and /m/, respectively (Po = oral pressure (cmH20); Vn = nasal flow (cc/sec); VP area = velopharyngeal area (mm$^{2)}$)

	/p/ stimuli		**/m/ stimuli**	
	F	*p*	*F*	*P*
Po				
Group	1.654	0.200	0.200	0.657
Stimuli	1.596	0.163	3.116	0.083
Group x Stimuli	0.381	0.862	0.294	0.590
Vn				
Group	0.976	0.324	3.074	0.085
Stimuli	7.232	**0.000**	1.997	0.163
Group x Stimuli	0.365	0.872	0.003	0.957
VP Area				
Group	0.165	0.685	2.487	0.122
Stimuli	0.711	0.616	0.353	0.556
Group x Stimuli	0.865	0.506	0.432	0.514
% VP Area				
Group	0.345	0.558	0.728	0.398
Stimuli	0.717	0.611	0.043	0.837
Group x Stimuli	0.764	0.577	0.625	0.434

DISCUSSION

The purpose of this study was to describe Po, Vn, VP area and %VP area in children age 3;0 to 4;11. In addition to basic descriptions of central tendency and dispersion on each measure, gender differences were evaluated and relationships of body size measurements and SPL with the four VP measures were explored in an effort to determine whether these variables should be considered in future normative data collection studies. Stability of the VP measures over two recording sessions also was evaluated for the young speakers with the intent, again, to guide procedures in future normative data collection efforts, and also to provide insight into appropriate clinical practice when using aerodynamic measures in this young age group. A secondary purpose of this study was to compare VP measures in young children (3;0-4;11 years) to older children (7;0-8;11 years). This younger vs. older child comparison served as a preliminary test of the need to aggressively pursue normative values for the younger group for whom published values are sparse.

VP Measures in Young Children

Oral Air Pressure

Mean Po on /p/ for the young children in the current study was just over 8cmH2O, a value that falls within the range of means reported for the youngest children in other studies. Previously published studies have not included a group of subjects as young as in the current study. The closest age group matches are from Searl and Carpenter (1999) and Bernthal and Beukelman (1978). Searl and Carpenter reported higher mean pressures (~9-11cmH2O) on a similar set of stimuli for children who were slightly older than those in the current study (age 4;6-6;3 years). Bernthal and Beukelman reported a lower mean (6.7cmH20) for a group of children age 4;6-6.9 years. Others who have averaged data from children ranging from approximately four years up to eight years of age have found mean Po values that are also lower than those in the present study (Smith et al., 2004; Stathopolous and Weismer, 1985; Zajac, 2000).

Differences in pressure values reported across studies are difficult to interpret given differences in stimuli and procedures. However, even when selecting only the stimuli that are common between two studies, it appears that there are differences (typically, 1-3cmH2O differences for /p/). The set of Po means in the current study are the only ones that are derived solely from a group of very young children (i.e., without averaging in with older children). As such, they can be taken as a preliminary set of expected values for young children. Future studies that include children along the age continuum from 3;0 up to late-childhood or adulthood will be needed to carefully define whether the inverse relationship between age and Po found for children $\geq$6 years up into adulthood is maintained for children younger than six years of age.

Peak Po on /m/ in the current study was 0.8cmH2O, a value very close to that reported by Zajac (2000) for 6-8 year old children. For adults, somewhat higher Po on /m/ has been reported with mean values of approximately 1.0 to 1.5cmH2O. It may be that the relationship between speaker age and Po on /m/ is different than that for Po on /p/. Again, however, a differently designed study that specifically looks at this relationship is needed to draw any firm conclusions. The current results stand as preliminary norms for Po on /m/ in very young children.

Males and females in the young age group did not differ in terms of Po on /p/ or on /m/. Although Stathopolous and Weismer (1985) also did not find a gender difference in Po for subjects ranging in age from 4-30 years, three other studies have reported significantly higher values on /p/ produced by males. Two of the three studies that reported a gender difference included only adult speakers (Zajac & Mayo, 1996; Zajac, 1997) while the other had the youngest age category simply labeled as being less than 7 years of age (Dalston et al., 1988). It may be that a gender difference in Po generation does not emerge until later in childhood as physical differences (and perhaps respiratory capacities and functions) are greater.

Nasal Air flow

Young speakers in this study had very limited Vn during /p/ production, averaging less than 6cc/s across all /p/ stimuli and ~2cc/s on the other oral consonants (/t, f, ʃ/). Mean Vn values never exceeded 15cc/s for any of the oral consonant stimuli (although individual values occasionally exceeded 50cc/s). The limited flow values suggest that these very young speakers routinely maintained complete or nearly complete VP closure during oral consonant production. The limited Vn values in the current study are similar to those reported for older children and adults (Hoit et al., 1994; Smith et al., 2004; Thompson & Hixon, 1979; Zajac, 2000). Summarizing across all of the studies, a reasonable expectation is that average Vn for children producing oral consonants should be ~20cc/s or less, even when producing /p/ in a nasal context (such as the word “hamper”). Occasional Vn values exceeding 20cc/s occur in children, but do not seem to occur repeatedly in a given speaker who is asked to say the same stimulus three or more times in a row.

Searl and Carpenter (1999), Thompson and Hixon (1979) and Andreassen et al. (1992) have all reported that some speakers (children and adults) will occasionally have a large Vn spike on /p/ that cannot be attributed to recording artifact or velar elevation (>40 or 50cc/s). Such spikes did occur in the current study on the /p/ stimuli as well as the other oral consonant productions, but infrequently. There were seventeen instances during /p/ stimuli productions where Vn exceeded 40cc/s, representing 4.2% of the productions (maximum Vn was ~64cc/s); for the other three oral consonants, four instances of Vn greater than 40cc/s occurred, representing 1.0% of the productions (maximum Vn was ~71cc/s). Other investigators have not specifically detailed the frequency with which these somewhat larger Vn spikes occur making it difficult to offer a more detailed comparison with the current results. However, overall, it seems that Vn spikes greater than 40 or 50cc/s occur infrequently in children, even those as young as 3 years of age.

Normative Vn data for nasal consonant productions by children younger than age five or six have not been reported. The data for the twenty-two young children in this study suggest that a mean Vn of ~50cc/s should be expected for three-five year olds with typically developing speech, although the standard deviation is large (~55% of the mean). The Vn on /m/ in the current study is less than what has been found for older children and adults (Andreassen et al., 1991; Zajac & Mayo, 1996; Zajac, 2000). The youngest age category in the Zajac (2000) study was six-eight year-olds with a mean Vn of 76cc/s (sd=27). Zajac reported that Vn on /m/ increased as a function of age from 76cc/s in the youngest speakers up to 120cc/s in young adults. Zajac and Mayo (1996) and Andreassen et al. (1991) reported Vn on /m/ by adult speakers ranging from ~130-180cc/s. Vn data on /m/ in the current study not only extend the data set further down the age range, it is also consistent with the notion that Vn is less in younger speakers compared to older speakers. Changes in vocal tract dimension and respiratory/laryngeal aerodynamics as a function of age have been offered as reasons for greater Vn on /m/ as speakers get older. For example, the cross-sectional area of the nasal airway is known to increase throughout childhood (Warren, Hairfield & Dalston, 1990; Vig and Zajac, 1993) and nasal resistance to airflow decreases (Hoshino, Togawa and Nishihira, 1988; Laine-Alava and Minkkinen, 1997; Principato and Wolf, 1985). Respiratory-laryngeal airflow during speech is also known to increase from preschool age to young adulthood (Netsell, Lotz, Peters & Schulte, 1994). Increases in nasal airflow during speech would be expected as children get older based on greater airflow and reduced impedance to airflow by the nasal passageway.

Velopharyngeal Orifice Area

The VP area data for /p/ and for /m/ are in general agreement with prior reports looking at older children. For /p/, the estimated VP area in the current study (mean of 0.09mm^2) was comparable to the mean VP area reported by Smith et al. (2004) for five-eight year-old children. Zajac (2000) reported that mean VP area estimates for /p/ never exceed 0.2mm^2. The small VP areas reported in all studies are not surprising considering that Vn is limited in both magnitude and frequency of occurrence during /p/ production in children. Smith et al. (2004), Zajac (2000) and Andreassen et al. (1991) have reported that VP area is larger on /p/ when there is a preceding nasal consonant (as in the word “hamper”). In the current study, the VP area for /p/ was the largest for the word “hamper” followed by /pim/, /pam/, “pamper,” /pi/ and /pa/. There may simply have been a lack of statistical power to identify a difference. Regardless, children age 3;0 to 4;11 years appear to have a VP gap during /p/ production that approaches zero nearly all of the time across different stimulus constructions.

The VP area estimates for /m/ produced by 3;0-4;11 year olds in the present study are smaller than area estimates reported in older children. Zajac (2000) reported the most comprehensive data set on VP area estimates in non-cleft palate children across a wide age range. The overall mean VP area estimate on /m/ in the current study was 12.25mm^2 compared to 19.6mm^2 for the 6-8 year-olds in the Zajac study (2000). Zajac’s data indicated that VP area estimates on /m/ increased as speaker age increased, and the smaller area values from the younger subjects in the current study fit this trend. This is a predictable relationship given the expectation of an overall increase in the size of the VP port as children grow. Presuming that the degree of VP opening during /m/ remains constant relative to the size of the VP port as a person grows, then the absolute size of the VP area on /m/ will increase with general growth.

This is the first study, of which the author is aware, that reported VP area as a percentage of a speaker's cross-sectional area during rest breathing. Not all of the young speakers were able to generate nasal breathing curves to allow calculation of cross-sectional area. However, ~64% of the group was able to do so. From this subset of young participants, the %VP area calculation suggested that the VP port opens during /m/ approximately 50%, on average, of the overall cross-sectional area measured at rest. Standard deviations and ranges on the %VP area measure were large with some speakers occasionally opening the VP port more than 80% of the cross-sectional area measured at rest. For /p/, the young speakers opened the VP port anywhere from 0% (/pi/ and /pa/) up to 1.3% ("hamper") on average. The standard deviations were still relatively large (in fact, larger than the mean %VP area for four of the six /p/ stimuli), but the maximum %VP area measured never exceeded 20%.

The %VP area is a measure to consider in future studies of normative VP aerodynamics as a function of age because it can help determine whether the increase in VP area estimates seen with increased age of the speaker are due strictly to changes in the dimensions of the VP port or changes in the relative amount of VP opening utilized by speakers of varying ages. Although the older and younger children did not differ in terms of %VP area, it is interesting to note that the younger children generally had larger %VP areas. For /m/, the older children opened the VP port on /m/ 44% compared to 51% for the younger children; for /p/, the older children opened the port 0.35% compared to 0.19% for the younger children. Perhaps with maturation, the relative extent of movement of the VP structures toward or away from closure (soft palate elevation and pharyngeal wall motion) changes.

Relationship Between Body Size and VP Aerodynamic Measures in Young Children

Body size measurements of height, weight, head circumference, chest circumference, and cross-sectional area of the VP port were taken for each participant in the study. The intent was to determine whether one of these, or a subset, were strongly related to any of the aerodynamic measures in young children, or if differences in the magnitude of aerodynamic measurements occur as a function of the various body size measures. Although each of these body size measures are expected to be positively correlated to chronological age in children, age itself is not the direct factor that might induce differences in the aerodynamic measures. This analysis sought to identify the more direct influences on VP aerodynamic measures with the possibility that future normative data collection efforts might need to utilize a variable(s) other than chronological age as the independent variable.

Overall, there were no strong relationships identified between Po and Vn with any of the five body size measures. There were some statistically significant relationships, but the strength of the correlations was generally small and the percent variance accounted for in the aerodynamic measures was limited. The analysis of the aerodynamic measures as a function of each body size measure (i.e., comparing taller vs. shorter, heavier vs. lighter, etc.) also suggested that none of the body size measures selected for study have significant explanatory power relative to the aerodynamic measures. The lack of statistical differences in this set of comparisons might be due to the fact that the most salient physical characteristics were simply not chosen for study. Perhaps a measure that is more reflective of respiratory capacity or neurological maturity would have resulted in a larger difference or stronger correlation for some or all of the aerodynamic measures. Additionally, the division along each body size measurement was done by dividing the group at the 50th percentile mark. It may be that if a group of children were identified who fell closer to each extreme of the distribution for a measure (e.g., 75th percentile or higher vs. 25th percentile or lower), differences in aerodynamic measures could emerge. This study utilized a convenience sample of young children and did not specifically target inclusion of children who diverge on the various body size measures. Future studies should consider the alternative approach of selecting subjects based on body size measures, considering that even with a rather homogenous group of speakers, there were some statistically significant correlations (albeit weak) that emerged. In any future work, chronological age should be considered as an additional variable for subject selection. Chronological age is easy to determine as well as likely to be relatively strongly associated with nearly any body size (or neurological maturity marker) that is selected.[2]

Although not a body size measurement, SPL also was measured for each production so that correlations with the aerodynamic measures could be completed. Stathopolous (1986) reported Po data suggesting that the inverse relationship between

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[2] Post-hoc, chronological age was run in correlational analyses with the aerodynamic measures. Age was not significantly associated with any of the four measures for the /p/ or the /m/ stimuli. Chronological age was significantly correlated ($p<0.000$) with each of the body size measures with r values ranging from 0.41 to 0.60 (moderate to strong correlations).

age and Po was due to the fact that children are more likely to produce speech at a higher SPL than adults when asked to speak at their “typical” or “comfortable” level (as is often done most studies of Po in children and adults). Sound pressure level was not manipulated in the current study. However, utilizing the natural variation in SPL that occurred when children produced the stimuli in their “speaking” voice, there were no significant correlations between Po or Vn for the /p/ or the /m/ stimuli. Sampling SPL across a wider age range of subjects (with the expectation of SPL decreasing as age increases) would be expected to elicit greater spread of the SPL, making identification of a relationship with Po or other measures more likely. Alternatively, direct manipulation of SPL within the same speaker could get more directly at the issue of whether SPL impacts aerodynamic measures in 3-5 year old children.

Stability of Po and Vn in Young Children

Variability in aerodynamic measures across repeated productions of a stimulus within one data collection session has been reported (i.e., standard deviations of Po, Vn or other measures in the prior literature are reflective of this variability). However, it is not known whether children generate mean Po and Vn that is consistent from one recording session to another when there is more than just a few minutes separation in recorded trials. This is an important issue when considering collection of normative data. If non-disordered children are found to generate Po, for example, on one day that is substantially different than what they do on another day, that would dictate how one goes about gathering normative data (averaging values across some number of recording sessions or defining confidence intervals for particular measures as a function of age, gender or other grouping variables being used). Clinicians most often gather aerodynamic data in one session, not multiple sessions, when estimating values of Po and Vn. However, if the measures vary substantially in typically developing children, then it begs the question: what does a clinician need to do to have confidence that a true picture of expected aerodynamic values have been obtained from a given speaker.

Nasal airflow on /p/ and /m/, respectively, did not differ significantly between the first and the second recording sessions in this study. Oral air pressure also did not vary significantly for /m/, but it did for /p/. This will require replication to make sure it is not a spurious finding. Inspection of the data for individual speakers did not help in determining why this occurred. It did not appear to be just an isolated speaker or small subset of speakers that contributed to the increase in Po at the second recording. Post-hoc, a comparison was completed for SPL to see if the children were simply increasing intensity in the second session, with a subsequent increase in Po. However, this was not the case (SPL was statistically similar between Time 1 and Time 2). Clinically, it maybe of less importance to explain the Po difference noted here between Time 1 and Time 2. The magnitude of the difference was small (~0.7cmH2O) relative to the mean Po, falling well within the 1 standard deviation range of the mean of the Po at either the first or the second recording. A similar size difference from Time 1 to Time 2 might be of importance if the mean Po was notably lower, as might occur in some clinical populations. However, adding to the current data set with additional three-five year olds, and analyzing data for older children will be important to more carefully detail what the expectation should be for Po stability over recording sessions. From a clinical perspective, the lack of difference in Vn is reassuring. For /p/, the constancy in the Vn measure across sessions reflects the fact that there is little if any nasal air escape during /p/ production even in very young children.

VP Measures in Older versus Younger Children

Oral Air Pressure

Children in the older age group in the current study (7;0 – 8;11 years), had Po means comparable to those reported for similarly aged children in studies by Andreassen et al. (1992) and Zajac (2000). Po on /p/ and /m/ did not differ between the 3;0-4;11 year olds and the 7;0-8;11 year olds in the current study. This was surprising in light of earlier studies in which investigators reported that Po is inversely related to speaker age. As suggested above, it may be that the inverse relationship is only present within a specific age range (in this case roughly six years old to young adulthood); below this age range, the relationship between Po and age has yet to be defined. A study that includes a continuum of age categories starting as young as 3;0 years and continuing into adulthood (perhaps the whole lifespan) is needed to speak to this issue with confidence. Stathopolous and Weismer (1985) reported that differences in SPL between younger children and older speakers might have accounted for Po differences in their own, and other, studies. That is, younger children tend to speak with greater SPL which might lead to increased Po. In the current study, post hoc testing indicated that there was no difference in SPL between the younger and older children for either the /p/ or the /m/ stimuli[3].

Nasal Air Flow

Nasal air flow on /p/ and /m/ did not differ between the younger and older children in the current study. Both groups had low mean Vn on /p/ with values well below the 20cc/s suggested by Zajac (2000). Studies that have included teenagers and adults as well as children have noted an increase in Vn on /p/ for the oldest speakers (Smith et al., 2004; Zajac, 2000), but the overall magnitude of the Vn remains limited (<20cc/s) and the frequency of occurrence of Vn on /p/ is low (although not formally quantified by past researchers). In the current study, the frequency of occurrence of Vn greater than 40cc/s for the older group was 6 out of 180 measurement points (i.e., 3.3% of the measures; recall that the young group had 4.6% of measures greater than 40cc/s). There are not enough instances of significant Vn (arbitrarily defined here as >40cc/s) in the current study to analyze the data statistically or to draw strong conclusions about whether frequency of occurrence of Vn differs between preschool and early school age children other than to note that these larger Vn spikes happened more frequently for the younger group. Neurological maturity resulting in less precise VP control is tempting to consider, but no specific indices of neurological maturity were included in the current study. Clinically, again, it is reassuring to have some

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[3] For /p/ stimuli, the mean SPL values for young and old children were 67.8dB and 66.2dB (t=1.002, p=0.118). For /m/ stimuli, the mean SPL values for young and old children were 96.1dB and 96.6dB (t=0.769, p=0.776). Recall that the microphone for dB measurement was at the end of a tube connected to the pneumotachometer, which explains the higher dB values for /m/ relative to /p/ (i.e., greater Vn flowing through the pneumotachometer and attached tubing for the nasal consonant).

rough guidelines indicating that no more than 5% of a very young child's oral consonant productions (more specifically, /p/) should have exceptional Vn.

Although the group mean Vn on /m/ was higher for the older compared to the younger children in this study (~69cc/s vs. 53cc/s), this difference was not statistically significant. This is somewhat surprising considering that others have reported an increase in Vn (and VP area) with speaker age that is attributed to increased dimensions of the nasal passage, reduced nasal resistance, and increased respiratory-laryngeal airflow. It may be that the age categories utilized in this study were simply not far enough apart to have resulted in distinct differences in the important body size/physiology features. However, measures of nasal cross-sectional area and nasal resistance were gathered in this study for both groups. Although not part of the planned analysis, subsequent statistical comparisons did indicate a significant reduction in nasal resistance and an increase in cross-sectional area of the VP port for the older compared to the younger children[4]. In this case, then, it seems that there were the expected differences between age groups in at least some of the variables thought to contribute to increased Vn on /m/ in older children (no indices of respiratory-laryngeal airflow were gathered). Increasing the subject pool, particularly the older age group, may help draw out the difference by increasing statistical power.

VP Area and % VP Area

Po and Vn form the basis of the VP area estimate. Therefore, given the lack of statistically significant differences between older and younger children on Po and Vn

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[4] For nasal resistance, the *t*-value of 6.781 had an associated probability of 0.003. For cross-sectional area of the VP port, the *t*-value of 9.032 had an associated probability that was less than 0.000.

for /p/ and /m/, it is not surprising that there was no difference in VP area estimates between the age groups for either consonant. In contrast, one might predict that the %VP area should differ between age groups given comparable VP area estimates between groups, but significantly greater VP cross-sectional area estimates for the older children. The VP cross-sectional area is the denominator in the %VP area calculation. Therefore, a larger VP cross-sectional area relative to comparable VP area estimate would result in a reduced %VP area. Percent VP areas were, in fact, lower on /p/ and /m/ for the older children, but not to a degree that reached statistical significance.

CONCLUSIONS & LIMITATIONS

This study is the first to describe VP aerodynamic measures in children limited to age 3;0 to 4;11 years of age; other studies included children as young, but their data were averaged with children up to 8 years of age. These data provide at least preliminary values for both males and females that can be utilized clinically until a database derived from a larger number of young children is available. The results of this study do beg the question whether large scale normative data collection on children as young as three years are needed. The lack of statistically significant differences between the younger and older children on any of the aerodynamic measures suggests that clinicians may be justified in applying normative values from older children (~7-9 years of age) to younger children. However, the number of young children included for study was small in terms of normative data collection, and the older child group was even smaller. It seems prudent to increase the size of both age categories, increasing statistical power and also increasing the ability to generalize the results to the population. Additionally, including a continuum of age categories (i.e., 5;0-6;11 years; and ranges above 8;11 years) similar to the design used by Zajac (2000) would allow for a more complete data set capable of more precisely addressing questions about the relationship of age to the various aerodynamic measures.

The body size measures included in this study generally were not strongly correlated with any of the aerodynamic measures. Future studies will need to consider whether these are the most appropriate variables to consider, or if others should be included. At a minimum, it may be worthwhile to design a study that specifically seeks out children who fall towards the ends of the body size measures being investigated. The fact that some body size measures were significantly (although not strongly) correlated to aerodynamic measures should serve as incentive to consider the body size measures again, but perhaps using a different study design. The current study used a convenience sample that, not unexpectedly, had many children who fell within the second and third quartiles for any given measure. Forcing greater body size differences in the subject selection process will add significantly to the subject identification and recruitment process, but may yield valuable information that helps in the constructions of aerodynamic norms. Future normative data collection efforts will need to consider whether gender is an important grouping variable to include. The current study did not find any differences as a function of gender in the young speakers, arguing against the need. However, there have been enough reports in the literature suggesting possible gender differences in Po, in particular, that continuing to include gender as a relevant variable is reasonable until a larger data set is gathered from preschool age children.

The choice of stimuli to include in normative data collection must also be carefully considered. For the /p/ stimuli, there were some significant differences in Vn with the /mp/ context eliciting greater flow than /pi/ and /pa/. Such differences have been reported for older children and the /mp/ context appears to have clinical utility in identifying VP issues in speakers with VP dysfunction. While it seems clear that normative data collection should include /p/ in a nasal context as well as a non-nasal context, it is not clear if a particular /mp/ context is preferable over another. There were some differences in Vn on /p/ among the four /mp/ stimuli included in the data set. Continued inclusion of more than one /mp/ context in the normative data collection may be necessary to ultimately determine if significant differences (statistically and clinically) among the various /mp/ choices are present.

Some limitations to this study have been alluded to in the discussion above and relate to an inability to address certain questions (such as the relationship between Po and age) because of the nature of the research questions asked and the subsequent design of the study (primarily geared towards describing aerodynamics, accounting for a set of predefined variables such as gender and particular stimuli). Additional limitations are principally related to the ability to generalize the findings. The subject groups were small and certainly cannot be considered sufficient for normative data gathering. The stimulus set was also restricted in various ways, similar to what has been reported in other studies. The primary data set was based on a single oral consonant /p/ and the stimuli reported here were non-word productions with the exception of “hamper” and “pamper” (neither of which may have a high level of linguistic significance for the youngest children in the study). Many of the children in this study did complete additional recordings that incorporate real words and short sentences (although /p/ remains the primary target). That data should prove helpful in allowing greater generalization of the data, or at a minimum, allowing greater confidence in what is known about aerodynamics on /p/. Gathering both Po and Vn measures on other stop consonants and fricatives poses significant difficulty in terms of Po measurement, particularly with young children. Finally, not all of the children were able to generate an acceptable nasal breathing curve for nasal resistance, cross-sectional area, and VP area calculations. Therefore, these data sets are derived from an even smaller number of speakers than the Po and Vn data. Expanding the number of subjects for whom such measures are obtained is needed to truly consider the values normative.

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Appendix A

QUESTIONNAIRE

CHILD’S NAME:________________ PARENT/GUARDIAN:________________

GENDER:_______________________ ADDRESS:___________________________

DATE OF BIRTH:______________ _____________________________________

PHONE #:____________________________

	YES	NO	NOT SURE
1. Has your child’s pediatrician, teacher, or anyone else actively involved in your child’s life indicated that your child has a speech or language problem or needs to see a speech therapist?	___	___	___
2. Do you have any concerns regarding the development of your child’s speech or language?	___	___	___
3. Have you or anyone else actively involved your child’s life noticed any recent changes in his/her voice (e.g. roughness, hoarseness, breathy)?	___	___	___
4. Has your child’s pediatrician, teacher, or anyone else actively involved in the child’s life suggested that your child has a hearing problem?	___	___	___
5. Do you have any concerns regarding your child’s hearing?	___	___	___
6. Does your child currently have tubes placed in his/her ears?	___	___	___

7. Has your child's pediatrician, teacher, or anyone else actively involved in the child's life raised concern of a potential learning problems? ___ ___ ___

8. Is your child currently seeking medical attention for any respiratory (breathing) problems? ___ ___ ___

9. Has your child's pediatrician, teacher, or anyone else actively involved in the child's life suggested your child has a problem with muscle strength or coordination? ___ ___ ___

10. During regular check-ups with the pediatrician does your child fall within normal limits on the growth curve? ___ ___ ___

11. Is your child currently experiencing any nasal drainage or obstruction problems? ___ ___ ___

12. Is your child currently seeking medical attention for any oral (mouth) or dental problems (e.g. cleft palate, jaw infection)? ___ ___ ___

If you answered YES or NOT SURE to any of the above, please briefly describe the problem in the space provided below each question.

Appendix B*
Perceptual Rating Form

NASAL EMISSION

		Trial 1	Trial 2	Trial 3
		0------------4	0------------4	0------------4
1. Paula paid Perry.	/pa/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
2. Terry told Teddy.	/ta/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
3. Kelly called Carla.	/ka/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
4. Father fed Fido.	/fa/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
5. Sally saved Sarah.	/sa/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
6. Sherry shoved Shelly.	/ □a/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
7. Charlie chewed chili.	/t□a/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
8. Sarah slid slowly.	/sla/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
9. Sally smelled smoky.	/sma/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
10. Riley road railroads. (control)	/ra/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.

HYPERNASALITY (nasal flutter)

1. He will read to Lee.	/li/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
2. You were rude to Lou.	/lu/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
3. Bob had our dollar. (control)	/la/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.

HYPONASILITY (nose open)

1. Buy mama a mop.	/ma/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
2. Ted knew ninety songs.	/na/	.__.__.__.__.	.__.__.__.__.	.__.__.__.__.
3. Nan made more money.		.__.__.__.__.	.__.__.__.__.	.__.__.__.__.

VP MOVEMENT (sustained/repeated /a/; head level; relaxed jaw)

Range	Soft Palate			Lat. Phar.		
	x1	x2	x3	x1	x2	x3
Not observable	___	___	___	___	___	___
No movement	___	___	___	___	___	___
Minimal/Slight	___	___	___	___	___	___
Mod./Marked (>pal. plane)	___	___	___	___	___	___

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*taken from the University of Kansas Medical Center: Cleft Palate and Craniofacial Center evaluation protocol

APPENDIX C

YOUNG SPEAKERS

	Gender	Age*	Height	Weight	Head	Chest	Nasal Patency Rating		Rn	X-Area	Goldman-Fristoe Test of Articulation		SP Move.	Lat.Wall Move.
							Right	Left			Stand.Score	Percentile		
1	M	57	108.0	20.0	50.8	57.0	0	0	4.2	18.9	101	46	2	2
2	M	43	102.9	18.6	51.0	55.0	0	1	4.0	20.8	125	98	2	0
3	M	41	96.5	13.9	49.0	51.0	1	0	--	--	117	85	2	2
4	M	45	104.1	17.7	52.5	54.0	0	0	--	--	119	96	2	2
5	M	43	105.5	16.8	48.3	52.0	1	1	1.4	--	120	97	2	0
6	M	51	104.1	20.0	53.3	55.0	0	1	3.2	32.9	121	98	2	2
7	M	37	92.1	13.2	48.0	49.0	0	0	6.2	23.8	120	91	2	2
8	M	58	114.3	16.8	54.6	57.2	1	1	--	29.9	99	43	2	2
9	M	49	94.0	14.8	53.3	55.9	0	0	3.9	--	117	92	2	2
10	M	48	101.6	18.4	49.5	57.2	1	1	7.1	23.4	113	84	2	2
11	M	45	105.4	18.1	54.0	57.2	0	0	5.8	22.5	106	55	2	1
12	F	51	100.3	15.5	49.0	48.0	0	0	6.1	21.3	107	56	2	1
13	F	58	114.3	22.7	51.5	57.0	1	0	4.1	23.1	114	78	2	2
14	F	39	90.2	12.3	47.5	48.0	0	0	5.8	25.2	120	93	2	2
15	F	38	100.3	16.3	50.8	55.9	0	0	3.3	31.2	118	88	1	0
16	F	43	99.7	16.5	50.8	53.3	1	1	4.6	29.1	104	54	2	0
17	F	55	91.0	15.6	47.0	48.0	0	0	3.6	19.5	112	39	2	1
18	F	59	134.0	31.4	52.7	67.9	0	0	--	29.4	109	55	2	1
19	F	41	106.7	16.9	50.8	53.3	0	0	--	--	115	80	2	0
20	F	36	102.0	16.8	49.5	55.6	0	0	--	--	91	37	2	1
21	F	38	99.1	15.6	49.5	48.0	1	1	--	--	105	58	2	2
22	F	53	109.2	17.1	50.8	51.0	0	1	--	--	104	44	2	2
Mean		**46.7**	**103.4**	**17.5**	**50.6**	**53.9**	**0.3**	**0.4**	**4.5**	**25.1**	**112**	**73**	**2.0**	**1.0**
SD		**7.5**	**9.5**	**3.9**	**2.1**	**4.6**	**0.5**	**0.5**	**1.5**	**4.6**	**9**	**22**	**0.2**	**1.2**
Minimun		**36.0**	**90.2**	**12.3**	**47.0**	**48.0**	**0.0**	**0.0**	**1.4**	**18.9**	**91**	**37**	**1.0**	**0.0**
Maximum		**59.0**	**134.0**	**31.4**	**54.6**	**67.9**	**1.0**	**1.0**	**7.1**	**32.9**	**125**	**98**	**2.0**	**2.0**

*See Key on next page.

APPENDIX C

OLDER SPEAKERS							Nasal Patency Rating				Goldman-Fristoe Test of Articulation			
Subject	Gender	Age	Height	Weight	Head	Chest	Right	Left	Rn	X-Area	Stand.Score	Percentile	SP Move.	Lat.Wall Move.
1	M	95	114.3	21.3	53.3	62.2	0	0	4.1	37.9	108	>52	2	1
2	M	89	137.2	25.9	52.1	59.7	1	1	3.8	25.7	109	>58	2	2
3	M	105	125.1	21.5	52.1	57.8	0	1	6.1	36.5	106	>42	2	2
4	M	101	154.9	40.4	55.9	71.1	0	0	3.2	35.9	107	>46	2	2
5	M	99	134.0	27.7	54.0	64.8	0	1	1.9	24.6	107	>46	2	2
6	F	102	127.0	33.8	54.0	72.4	0	0	2.6	48.0	103	>46	2	2
7	F	105	122.0	26.2	53.0	61.1	0	0	3.2	30.8	103	>44	2	2
8	F	88	121.9	26.3	52.1	66.0	0	0	3.3	32.7	106	>58	2	1
9	F	90	128.9	32.0	55.2	72.4	0	0	4.2	34.7	105	>56	2	0
10	F	89	120.7	24.6	50.8	63.5	1	1	5.0	31.3	106	>58	2	2
Mean		**96.3**	**128.6**	**28.0**	**53.3**	**65.1**	**0.2**	**0.4**	**3.7**	**33.8**	**106**		**2.0**	**1.5**
SD		**7.0**	**7.7**	**5.3**	**1.6**	**6.3**	**0.5**	**0.5**	**1.2**	**7.4**	**2.1**		**0.0**	**1.2**
Minimun		**88**	**114.3**	**21.3**	**50.8**	**57.8**	**0.0**	**0.0**	**1.9**	**24.6**	**103**		**2.0**	**0.0**
Maximum		**105**	**154.9**	**40.4**	**55.9**	**72.4**	**1.0**	**1.0**	**6.1**	**48.0**	**109**		**2.0**	**2.0**

Key: Age = months; Height = cm; Weight = kg; Head = head circumference in cm; Chest = chest circumference in cm; Right = nasal patency rating for the right nostril where 0=no obstruction, 4=severe obstruction; Left = nasal patency for the left nostril where 0=no obstruction, 4=severe obstruction; Rn = nasal resistance in cmH2O/cc/s; Stand.Score = Goldman-Fristoe Standard Score; Percentile= Goldman-Fristoe Percentile Score; SP Move. = Soft palate movement rated from 0=no movement to 2= moderate movement; Lat.Wall Move. = lateral wall movement rated from 0=no movement to 2= moderate movement.

APPENDIX D

ORAL AIR PRESSURE (cmH20)

YOUNG MALES

	1	2	3	4	5	6	7	8	9	10	11
/pi/	7.75	6.9	7.71	10.86	9.23	8.65	9.03	8.49	9.63	12.46	9.41
/pa/	8.19	6.88	7.52	7.28	4.99	9.27	7.67	14.71	9.68	14.22	8.83
/pim/	6.63	5.57	6.34	6.39	9.1	6.79	5.07	14.13	9.2	19.98	8.86
/pam/	6.54	6.03	6.01	7.82	7.87	7.6	4.55	16.81	6.72	8.32	7.45
hamper	5.98	6.71	9.8	7.91	8.1	7.09	5.6	8.89	6.81	12.86	7.21
pamper	6.19	5.88	10.01	4.47	10.44	7.38	6.09	8.48	6.53	12.08	7.32
Mean	6.88	6.33	7.90	7.46	8.29	7.80	6.34	11.92	8.10	13.32	8.18
SD	0.89	0.57	1.69	2.10	1.86	0.96	1.70	3.72	1.55	3.81	0.96
Min	5.98	5.57	6.01	4.47	4.99	6.79	4.55	8.48	6.53	8.32	7.21
Max	8.19	6.9	10.01	10.86	10.44	9.27	9.03	16.81	9.68	19.98	9.41
/mi/	0.44	0.36	0.9	1.51	0.22	0.26	0.29	0.44	0.45	0.7	1.49
/ma/	0.59	0.53	1.06	2.17	0.41	0.66	0.31	0.65	0.77	3.19	1.33
Mean	0.52	0.45	0.98	1.84	0.32	0.46	0.30	0.55	0.61	1.95	1.41
SD	0.11	0.12	0.11	0.47	0.13	0.28	0.01	0.15	0.23	1.76	0.11

APPENDIX D

ORAL AIR PRESSURE (cmH20)

YOUNG FEMALE

	12	13	14	15	16	17	18	19	20	21	22
/pi/	9.04	10.44	8.17	7.13	6.72	5.22	9.10	12.61	10.92	8.19	9.57
/pa/	8.41	10.46	8.57	7.28	9.25	5.18	8.18	10.31	9.9	11.23	12.93
/pim/	9.16	8.97	8.25	10.8	5.88	5.98	8.21	5.46	9.50	7.11	13.93
/pam/	8.09	8.32	6.88	9.68	4.12	4.78	7.22	5.94	6.72	5.60	12.60
hamper	8.51	8.86	6.02	8.75	7.44	5.27	5.73	9.41	6.96	7.43	9.50
pamper	8.11	7.31	6.31	10.34	4.42	5.36	2.02	7.67	7.37	8.13	10.50
Mean	8.55	9.06	7.37	9.00	6.31	5.30	6.74	8.57	8.56	7.95	11.51
SD	0.46	1.23	1.10	1.55	1.93	0.39	2.58	2.74	1.77	1.86	1.89
Min	8.09	7.31	6.02	7.13	4.12	4.78	2.02	5.46	6.72	5.6	9.5
Max	9.16	10.46	8.57	10.8	9.25	5.98	9.1	12.61	10.92	11.23	13.93
/mi/	1.31	0.87	0.6	0.36	0.86	0	0.43	0.62	0.69	0.31	0.97
/ma/	--	0.63	0.76	0.72	1.62	1.23	1.27	0.7	0.91	0.71	0.47
Mean	1.31	0.75	0.68	0.54	1.24	0.62	0.85	0.66	0.80	0.51	0.72
SD	--	0.17	0.11	0.25	0.54	0.87	0.59	0.06	0.16	0.28	0.35

APPENDIX D

ORAL AIR PRESSURE (cmH2O)

	OLD MALE					OLD FEMALE				
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
/pi/	7.02	7.82	6.79	6.41	11.95	10.77	8.49	8.66	4.48	11.66
/pa/	6.59	8.56	8.55	6.09	7.41	8.3	8.03	8.66	5.37	10.93
/pim/	7.3	7.53	7.02	5.94	9.7	9.04	8.09	8.57	4.52	11.89
/pam/	6.07	7.95	7.47	5.23	9.66	8.23	5.58	7.62	3.44	8.82
hamper	6.79	8.41	9.72	5.19	8.58	8.05	7.13	8.36	4.87	9.72
pamper	5.51	9.43	9.77	5.89	7.82	7.83	7.07	8.18	4.54	11.2
Mean	6.55	8.28	8.22	5.79	9.19	8.70	7.40	8.34	4.54	10.70
SD	0.66	0.68	1.33	0.49	1.64	1.09	1.05	0.40	0.63	1.19
Min	5.51	7.53	6.79	5.19	7.41	7.83	5.58	7.62	3.44	8.82
Max	7.30	9.43	9.77	6.41	11.95	10.77	8.49	8.66	5.37	11.89
/mi/	2.01	1.07	0.32	0.52	0.27	0.51	1.26	0.62	0.42	0.88
/ma/	2.07	1.21	0.64	0.43	0.33	0.82	1.6	1.24	0.39	0.98
Mean	2.04	1.14	0.48	0.475	0.3	0.67	1.43	0.93	0.405	0.93
SD	0.04	0.10	0.23	0.06	0.04	0.22	0.24	0.44	0.02	0.07

APPENDIX D

NASAL AIRFLOW (cc/sec) - Young Males

	1	2	3	4	5	6	7	8	9	10	11
/pi/	0.00	1.16	0	0	2.35	3.21	2.68	0.2	3.51	3.05	1.46
/pa/	0	1.19	0	0	2.95	2.82	1.16	0.63	0.63	3.44	1.76
/pim/	28.82	37.96	11.92	30.14	4.1	1.36	51.64	0.26	1.42	1.19	0.37
/pam/	18.09	20.3	3.64	4.08	3.28	3.36	47.6	4.67	1.09	22.32	0.93
hamper	7.09	3.15	17.06	2.62	2.65	7.29	4.57	0	0.20	3.05	0.73
pamper	14.14	5.04	0.63	4.44	1.49	7.82	7.75	0.73	0.13	3.83	1.36
Mean	11.36	11.47	5.54	6.88	2.80	4.31	19.23	1.08	1.16	6.15	1.10
SD	11.26	14.85	7.25	11.56	0.88	2.62	23.67	1.78	1.25	7.98	0.52
Min	0.00	1.16	0	0	1.49	1.36	1.16	0	0.13	1.19	0.37
Max	28.82	37.96	17.06	30.14	4.1	7.82	51.64	4.67	3.51	22.32	1.76
/ti/	0	0.00	0	3.78	3.84	0.66	0.27	--	0.00	0.63	3.31
/ta/	0.13	0	0.00	0	3.78	2.02	1.62	--	0	0.07	1.49
/fi/	0	0	0.00	0.2	4.64	0.86	2.32	--	0	0.40	0.9
/fa/	0.00	0.46	0	0.00	3.58	1.09	2.65	--	0.07	1.49	14.97
she	0.00	0	0.00	0.20	4.37	1.39	0.99	--	0.13	1.99	1.09
sha	0.86	0.23	0	0.86	4.24	1.85	2.29	--	0.66	1.79	2.82
Mean	0.17	0.12	0.00	0.84	4.08	1.31	1.69	--	0.14	1.06	4.10
SD	0.34	0.19	0.00	1.47	0.41	0.54	0.92	--	0.26	0.80	5.41
Min	0	0.00	0.00	0	3.58	0.66	0.27	--	0.00	0.07	0.9
Max	0.86	0.46	0	3.78	4.64	2.02	2.65	--	0.66	1.99	14.97
/mi/	54.12	75.72	21.60	48.96	65.49	51.51	75.23	9.7	7.78	43.66	48.13
/ma/	70.72	89.96	29.44	115.37	100.76	46.66	72.18	44.75	20.3	64.79	16.6
Mean	62.42	82.84	25.52	82.17	83.13	49.09	73.71	27.23	14.04	54.23	32.37
SD	11.74	10.07	5.54	46.96	24.94	3.43	2.16	24.78	8.85	14.94	22.30

APPENDIX D

NASAL AIRFLOW (cc/sec) - YOUNG FEMALE

	12	13	14	15	16	17	18	19	20	21	22
/pi/	2.85	4.77	3.18	1.62	0	2.92	0	0.43	5.07	0	0
/pa/	1.59	0.76	2.88	1.06	0.5	2.25	0.43	0.77	6.26	0	0
/pim/	8.01	1.16	1.16	1.42	3.88	6.23	0.10	7.12	9.67	26.07	0.00
/pam/	17.29	0.00	0.23	10.2	13.58	10.4	4.44	1.12	25.47	64.26	0.00
hamper	4.54	0.99	0	4.57	0.47	2.05	50.51	0.03	0.27	0.00	0.00
pamper	14.64	0.00	0.26	1.82	0.56	2.88	0.17	0.00	0.73	0.00	0.00
Mean	8.15	1.28	1.29	3.45	3.17	4.46	9.28	1.58	7.91	15.06	0.00
SD	6.48	1.78	1.41	3.54	5.29	3.29	20.27	2.75	9.30	26.26	0.00
Min	1.59	0	0	1.06	0	2.05	0	0	0.27	0	0
Max	17.29	4.77	3.18	10.2	13.58	10.4	50.51	7.12	25.47	64.26	0
/ti/	0.00	--	2.15	0	0.86	0.79	0.17	0.86	0.20	0.00	0.00
/ta/	0.00	0	3.28	4.64	0.23	1.29	5.56	2.35	0.69	0.00	0.00
/fi/	0.00	0.00	3.28	0.1	0.23	1.19	0.76	1.92	0.33	0.00	0.00
/fa/	0.00	0.20	3.21	0.63	2.12	1.39	0	1.23	0.0	0.00	0.00
she	0.00	0.00	3.75	0.03	1.29	0.26	0.36	2.02	0.07	0.00	0.00
sha	0	2.15	3.58	3.21	0.7	0.99	0.00	1.96	0.96	0.00	0.00
Mean	0.00	0.47	3.21	1.44	0.91	0.99	1.14	1.72	0.38	0.00	0.00
SD	0.00	0.94	0.56	1.99	0.72	0.42	2.18	0.56	0.38	0.00	0.00
Min	0.00	0.00	2.15	0	0.23	0.26	0	0.86	0.00	0.00	0.00
Max	0	2.15	3.75	4.64	2.12	1.39	5.56	2.35	0.96	0.00	0.00
/mi/	52.96	56.62	42.37	27.13	15.97	54.92	66.48	12.79	79.25	48.67	31.40
/ma/	--	80.06	17.12	57.27	23.62	67.71	124.05	12.19	107.39	55.62	34.83
Mean	52.96	68.34	29.75	42.20	19.80	61.32	95.27	12.49	93.32	52.15	33.12
SD	--	16.57	17.85	21.31	5.41	9.04	40.71	0.42	19.90	4.91	2.43

APPENDIX D

NASAL AIRFLOW (CC/SEC)

	OLD MALE			OLD FEMALE						
	1	2	3	4	5	6	7	8	9	10
/pi/	0	0	2.05	1.03	0.4	1.82	0	0.5	0.27	0.3
/pa/	0.63	0	3.78	0.86	0.93	5.46	0	1.06	0.83	0.03
/pim/	12.92	7.32	15.63	49.09	0.07	0.63	7.98	29.25	2.12	0
/pam/	9.9	4.44	3.31	11.46	0.56	0.23	21.73	22.92	5.86	10.33
hamper	1.16	0	0	0.03	1.39	4.18	2.15	2.05	0.5	0.36
pamper	0	0	0.4	2.52	2.65	0.1	2.52	0.86	1.12	0.99
Mean	4.10	1.96	4.20	10.83	1.00	2.07	5.73	9.44	1.78	2.00
SD	5.76	3.17	5.80	19.21	0.93	2.25	8.36	13.06	2.10	4.10
Min	0	0	0	0.03	0.07	0.1	0	0.5	0.27	0
Max	12.92	7.32	15.63	49.09	2.65	5.46	21.73	29.25	5.86	10.33
/ti/	0	0.7	0.83	2.42	0	1.59	0.1	0.07	0.1	1.66
/ta/	0.03	0.76	2.02	0.73	0	0.53	0.46	2.52	0.76	1.89
/fi/	0	0.89	2.19	1.16	0	0.07	0	0.8	0.66	1.66
/fa/	0.07	1.55	1.16	1.36	0	2.06	0.43	0	0	1.62
/ʃi/	0	0.3	2.02	0.83	0.03	0	0	0	0.1	1.46
/ʃa/	0	0.5	0.99	1.72	0	1.99	1.46	1.69	1	1.56
Mean	0.02	0.78	1.54	1.37	0.01	1.04	0.41	0.85	0.44	1.64
SD	0.03	0.43	0.61	0.63	0.01	0.95	0.55	1.05	0.42	0.14
Min	0	0.3	0.83	0.73	0	0	0	0	0	1.46
Max	0.07	1.55	2.19	2.42	0.03	2.06	1.46	2.52	1	1.89
/mi/	30.31	115.73	67.37	99.4	42.13	80.79	28.72	101.16	19.58	43.09
/ma/	21.09	116	136.87	92.08	44.85	147.04	44.72	85.13	16.7	45.45
Mean	25.70	115.87	102.12	95.74	43.49	113.92	36.72	93.15	18.14	44.27
SD	6.52	0.19	49.14	5.18	1.92	46.85	11.31	11.33	2.04	1.67

APPENDIX D

VELOPHARYNGEAL AREA ESTIMATES (mm^2)

YOUNG MALE

	1	2	3	4	5	6	7	8	9	10	11
/pi/	0.00	0.00	--	--	--	0.82	0.00	0.00	--	0.00	0.00
/pa/	0.00	0.00	--	--	--	0.00	0.00	0.00	--	0.00	0.00
/pim/	0.20	0.23	--	--	--	0.00	0.50	0.00	--	0.00	0.00
/pam/	0.10	0.05	--	--	--	0.00	0.15	0.00	--	0.07	0.00
hamper	0.00	0.00	--	--	--	0.00	0.00	0.00	--	0.00	0.00
pamper	0.00	0.00	--	--	--	0.00	0.00	0.00	--	0.00	0.00
Mean	0.05	0.05	--	--	--	0.14	0.11	0	--	0.01	0.00
SD	0.08	0.09	--	--	--	0.33	0.20	0.00	--	0.03	0.00
Min	0.00	0.00	--	--	--	0.00	0.00	0.00	--	0.00	0.00
Max	0.2	0.23	--	--	--	0.82	0.5	0	--	0.07	0
/mi/	15.61	14.29	--	--	--	18.26	18.48	2.14	--	9.40	10.37
/ma/	9.23	11.13	--	--	--	24.65	18.90	4.31	--	15.51	5.06
Mean	12.42	12.71	--	--	--	21.46	18.69	3.23	--	12.46	7.72
SD	4.51	2.23	--	--	--	4.52	0.30	1.53	--	4.32	3.75

APPENDIX D

VELOPHARYNGEAL AREA ESTIMATE (mm^2)

YOUNG FEMALE

	12	13	14	15	16	17	18	19	20	21	22
/pi/	0.03	0	0	0	0	0	0	--	--	--	--
/pa/	0.03	0	0	0	0	0	0	--	--	--	--
/pim/	0.19	0	0	0	0	0	0	--	--	--	--
/pam/	0.4	0	0	0.03	0.06	0.01	0	--	--	--	--
hamper	0.01	0	0	0	0	0	5.13	--	--	--	--
pamper	0.38	0	0	0	0	0	0	--	--	--	--
Mean	0.17	0.00	0.00	0.01	0.01	0.00	0.86	--	--	--	--
SD	0.18	0.00	0.00	0.01	0.02	0.00	2.09	--	--	--	--
Min	0.01	0	0	0	0	0	0	--	--	--	--
Max	0.4	0.00	0	0.03	0.06	0.01	5.13	--	--	--	--
/mi/	17.70	13.8	13.99	3.69	4.05	11.89	11.36	--	--	--	--
/ma/	--	17.21	10.64	10.52	6.50	4.83	13.77	--	--	--	--
Mean	17.70	15.51	12.32	7.11	5.28	8.36	12.57	--	--	--	--
SD	--	2.41	2.37	3.87	2.01	3.95	2.12	--	--	--	--

APPENDIX D

VELOPHARYNGEAL AREA ESTIMATE (mm^2)

	OLD MALE					OLD FEMALE				
	1	2	3	4	5	6	7	8	9	10
/pi/	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
/pa/	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
/pim/	0.10	0.07	0.20	0.50	0.00	0.00	0.07	0.50	0.00	0.00
/pam/	0.17	0.00	0.00	0.17	0.00	0.00	0.00	0.23	0.00	0.06
hamper	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
pamper	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean	0.05	0.01	0.03	0.11	0.00	0.00	0.01	0.12	0.00	0.01
SD	0.07	0.03	0.08	0.20	0.00	0.00	0.03	0.21	0.00	0.02
Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max	0.17	0.07	0.20	0.50	0.00	0.00	0.07	0.50	0.00	0.06
/mi/	8.57	21.65	15.86	21.41	11.32	15.52	7.56	21.08	5.29	13.13
/ma/	5.53	29.52	26.25	22.13	13.66	19.78	11.48	23.45	4.12	10.27
Mean	7.05	25.59	21.06	21.77	12.49	17.65	9.52	22.27	4.71	11.70
SD	2.15	5.56	7.35	0.51	1.65	3.01	2.77	1.68	0.83	2.02

Appendix E

Frequency of nasal air flow (cc/sec) in younger subjects

Stimuli		**40-49**	**50-59**	**60-69**	**70-79**	**80-89**	**90-99**	**≥100**	**Sum**
/pi/		0	0	0	0	0	0	0	**0**
/pa/		0	0	0	0	0	0	0	**0**
/pim/		1	5	1	1	0	1	1	**10**
/pam/		0	1	0	1	0	2	1	**5**
hamper		1	0	0	0	0	0	1	**2**
pamper		0	0	0	0	0	0	0	**0**
	Sum	**2**	**6**	**1**	**2**	**0**	**3**	**3**	**17**
/ta/		0	1	2	0	1	0	0	**4**
/ti/		0	0	0	0	0	0	0	**0**
/fi/		0	0	0	0	0	0	0	**0**
/fa/		0	0	0	0	0	0	0	**0**
/shi/		0	0	0	0	0	0	0	**0**
/sha/		0	0	0	0	0	0	0	**0**
	Sum	**0**	**1**	**2**	**0**	**1**	**0**	**0**	**4**
/mi/		7	16	14	7	9	6	1	**60**
/ma/		4	8	6	11	9	6	17	**61**
	Sum	**11**	**24**	**20**	**18**	**18**	**12**	**18**	**121**

Appendix E continued

Frequency of nasal air flow (cc/sec) in older subjects

Stimuli		**40-49**	**50-59**	**60-69**	**70-79**	**80-89**	**90-99**	**≥100**	**Sum**
/pi/		0	0	0	0	0	0	0	**0**
/pa/		0	0	0	0	0	0	0	**0**
/pim/		0	3	0	0	0	1	0	**4**
/pam/		1	0	0	0	0	1	0	**2**
hamper		0	0	0	0	0	0	0	**0**
pamper		0	0	0	0	0	0	0	**0**
	Sum	**1**	**3**	**0**	**0**	**0**	**2**	**0**	**6**
/ta/		0	0	0	0	0	0	0	**0**
/ti/		0	0	0	0	0	0	0	**0**
/fi/		0	0	0	0	0	0	0	**0**
/fa/		0	0	0	0	0	0	0	**0**
/shi/		0	0	0	0	0	0	0	**0**
/sha/		0	0	0	0	0	0	0	**0**
	Sum	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
/mi/		1	3	0	3	2	4	6	**19**
/ma/		2	1	4	1	1	1	12	**22**
	Sum	**3**	**4**	**4**	**4**	**3**	**5**	**18**	**41**