NASAL AIR FLOW DURING NORMAL SPEECH PRODUCTION

by

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ABSTRACT

Nasal air flow was measured during the speech of 112 normal subjects (59 females and 53 males) ranging in age from 3 years to 37 years, 6 months. Flows were zero during nearly all oral consonant and vowel utterances, suggesting that velopharyngeal closure was air-tight. Nasal flow occurred during all nasal consonants and during vowels occurring adjacent to nasal consonants. Both age and sex effects were demonstrated for flow on vowels preceding nasal consonants. The data were interpreted to have implications for clinical speech procedures and suggestions for further research were offered.

INTRODUCTION

During the production of most speech sounds in the English language, the velopharyngeal mechanism is presumed to serve as an active mechanical valve which controls the amount of coupling between the oral and nasal portions of the upper airway. This control of oral-nasal coupling accomplishes two important things in the normal speech production process: one, it enables the development of oral air pressures and air flows sufficient to produce many of the consonant sounds of speech, and two, it enables the generation of voice that is perceived as free from hypernasal quality. Despite the recognized importance of normal velopharyngeal function to normal speech production, many of the details of such function remain to be specified. The present study is part of a larger series of studies being conducted in the Department of Speech and Hearing Sciences at The University of Arizona to provide needed information about velopharyngeal function in normal speech production.

Three questions are of central importance in the current investigation's part of this larger series of studies. The first concerns the extent to which air-tight velopharyngeal closure is characteristic of so-called phonetically oralized speech elements. The impetus for this question is the belief that is commonly held by many individuals that complete closure of the velopharyngeal port is not to be expected in normal speakers (Nusbaum, Foley, and Wells, 1935; Moll, 1962; Van den Berg, 1962).

The second question of the three concerns the possibility of the existence of a developmental schedule for gaining control over the velopharyngeal closure mechanism. The impetus for this question is the lack of information pertinent to this topic and the fact that several motor speech behaviors continue to be refined toward adult-like standards well after normal speech is acquired and sometimes as late as 11 to 12 years of age (Kent, 1976).

The third question of importance to the present investigation amounts to an inquiry into the possible existence of a sex difference with respect to control of the velopharyngeal closure mechanism. A paucity of information exists in this regard, although that which is available (McKerns and Bzoch, 1970) would lead one to believe that there could well be differences in function between the sexes based on differences in velopharyngeal structure.

The general design of the present investigation involved an attempt to address these three questions through the measurement of nasal air flow during the speech of a large group of males and females whose ages were distributed over a wide range. More specifically, subjects were selected to encompass a range that at the younger end extended downward to the youngest age at which standard tasks could easily be performed and at the older end extended upward into middle-aged adulthood. Flow was selected as the method for studying velopharyngeal function because of the simplicity of its measurement and because for the purposes of answering the questions mentioned above, it constituted a sufficient tool for the study of normal speakers (Warren, 1967).

METHOD

Subjects

One hundred twelve individuals served as subjects for this investigation. Ninety two of these subjects, 49 females and 43 males, ranged in age from three years to 18 years. The chronological ages of these subjects were distributed relatively evenly across this age range such that at least one subject, and usually more than one, fell within each four-month interval from age three to age eighteen. This distribution typically included subjects of both sexes within each four-month interval. The remaining persons studied were 20 adults, ten of each sex, ranging in age from 18 years, two months to 37 years, six months. The majority of these subjects were less than 25 years of age. All 112 subjects were selected to meet the following criteria: normal speech and voice commensurate with their age, hearing reported to be within normal limits, no known structural or neurological disorders and no known respiratory infections or allergies at the time of testing. All subjects were monolingual English speakers living in Tucson, Arizona.

Equipment

Two aspects of each subject's speech production were recorded: nasal air flow (herinafter referred to as flow) and the acoustic pressure wave (hereinafter referred to as the speech signal). Flow from each subject's external nares was channeled through an individually-custom-formed mask placed over the nose. Masks were made of Dux-seal, a relatively compliant, clay-like material that can be molded by hand. Flow from the mask was sensed by a double-coned, two-square inch, Silverman-type, pneumotachometer coupled to a differential air-pressure transducer. The analog output voltage of the latter was amplified and the resulting signal was low-pass filtered through a system with a sharp roll-off that markedly attenuated the signal above 20 Hz. Display of the conditioned-flow analog was made on one channel of a two-channel storage oscilloscope. The flow analog was calibrated through use of a continuously-variable flow pump whose output was directed through a rotameter and the pneumotachometer in series. The speech signal was sensed by a condenser microphone positioned approximately six inches below and to the front of the subject's lips. The output from the microphone was amplified and the resulting analog of the speech signal was displayed on the second channel of the storage oscilloscope. When it was deemed necessary to record data permanently, displays on the screen of the oscilloscope were photographed with a Polaroid camera. For certain activities, an electronic metronome was used to aid subjects in the pacing of their speech.

Speech Sample

Utterance tasks consisted of three groups of activities: sustained productions, syllable repetitions, and nonsense productions embedded in a carrier phrase. Sustained productions included individual utterances of /i/, /s/, /z/ and /n/ at normal conversational pitch, loudness, and quality. Each utterance was made following an inspiration of about twice normal depth and lasted for about 5 seconds. Syllable repetitions included productions of /ti/, /di/, /si/, /zi/ and /ni/, each in trains of seven utterances, made at normal conversational pitch, loudness, and quality, with equal stress on each syllable, and at an utterance rate of 3/second. Nonsense productions included the vowel-consonant-vowel (VCV) combinations /iti/, /idi/, /isi/, /izi/, and /ini/ in the carrier phrase "Say ________ again" produced at conversational pitch, loudness, and quality, with normal prosody and with stress placed on the second vowel on the VCV. Each of the VCV productions was performed in a separate carrier phrase three times in succession. The utterances included in the study sample were chosen to encompass a variety of phonetic contexts that could be easily executed by the younger subjects. Design of the sample was also guided by a desire to include a variety of manners of consonant production (plosive, fricative, and nasal), and to include voicing contrasts for cognate pairs. A single place of consonant and vowel production was chosen, namely, lingua-alveolar. This place had the advantage of avoiding lip gestures on consonants and vowels that would interfere with the seal formed by the nasal mask. The high vowel /i/ was selected for study within the front vowel series because of its presumed stringent velopharyngeal closure requirements (Moll, 1962), a factor we considered important a priori for insuring the strength of a criterion target were a developmental schedule to be manifested. The utterance rate of 3/sec was found in pilot study to be the maximum rate at which very young subjects could reliably perform.

Procedure

Each subject was seated upright and positioned so that the screen of the oscilloscope was out of his visual field. A dux-seal mask was molded for the nose and positioned on the subject. Each mask was made to form a small tube whose proximal end fitted air-tight against the upper lip and the mid-facial region surrounding the nose. Care was taken to insure that the walls of the mask did not block the external nares or contact the nasal alae. Next, the microphone was positioned and the subject was instructed to repeat each utterance produced by an investigator. The model utterances produced for the subject met the criteria discussed in the previous section. In the case of syllable repetitions, the investigator modelled utterance rate to the flashing and clicking of the metronome. Subject utterances judged to be appropriate copies of the model were not accepted and additional speech samples were elicited until an appropriate copy was obtained. Those utterances produced appropriately were stored on the screen of the oscilloscope for analysis. A second investigator recorded the flow magnitudes of interest directly from the stored display. In cases where the flow analog could not be instantly segmented with regard to phonetic events, the oscilloscopic display was photographed for later perusal.

RESULTS

We choose to divide the description of our results in accordance with the three group of activities performed by our subjects: sustained productions, syllable repetitions, and nonsense productions embedded in a carrier phrase.

Sustained Productions

The phonemes /i/, /s/, /z/, and /n/ comprised the group of sustained productions investigated. No nasal flow occurred for any of the utterances of the first three of these phonemes, that is, velopharyngeal closure presumably was air-tight for the 999 samples (3 phonemes x 3 repetitions x 111 subjects[1]) involving sustained oral consonant or vowel elements. By contrast, all 333 sustained productions of /n/ involved nasal flow. Criterion scores were computed for each subject as the mean peak flow on his three /n/-productions. The resulting scores for the subject group yielded a mean value of 98.9 cc/sec, with a range of 23.3 cc/sec to 246.7 cc/sec and a standard deviation of 38.1 cc/sec. Perusal of the

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1. Data for our subject group proved to be homogeneous. However, one of the 112 subjects presented data that usually were distinctly different from those of the other 111 participants. To prevent this subject's data from unduly distorting the descriptive statistics for the overall group, we deemed it reasonable to isolate these data for separate discussion. They are considered in a subsequent footnote at the end of the RESULTS section.

criterion score data for /n/ revealed no indication that nasal flow was related to either the age or sex of the subjects studied.

Syllable Repetitions

The syllables /ti/, /di/, /si/, /zi/, and /ni/, each performed in trains of seven, comprised the group of syllable repetitions. The middle three repetitions in each train were selected for analysis. No nasal flow occurred for any of the utterances of the syllables /ti/, /di/, /si/, and /zi/. That is, no flow occurred for 2664 sound elements (4 different syllables X 2 phonemes each X 3 repetitions X 111 subjects) involving oral consonant and vowel elements.[2] By contrast, of the 666 speech sounds -- 333 /n/s and 333 /i/s -- involved in the /ni/ syllable repetitions, all of the nasal consonants and all but nine of the vowels were accompanied by nasal flow. The nine speech sound utterances not accompanied by flow were performed by three subjects who uttered /i/ (three times each) without nasal flow.

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2. The statement "no nasal flow" should be qualified in the context of these first four syllable repetitions and in the context of the first four nonsense syllables studied to mean that no air passed from the mouth to the nose by way of the velopharynx. Very small magnitudes of nasal flow were observed for some subjects' productions of the utterances mentioned. These were typically less than $\pm$ 5 cc/sec, involved very gradual changes in flow, and often involved swings in flow from positive to negative and vice versa. Such observations are consistent with those of Lubker and Moll (1965) who demonstrated that their occurrence is related to minor displacements of the velum which alter the volume of the nasal cavity, change its internal pressure slightly, and cause small flows in and out of the nose in the presence of air-tight velopharyngeal closure. From the perspective of the measurements of importance to this investigation, these flows were viewed as artifacts and specified as zero.

Criterion scores were computed for both /n/ and /i/ for each subject on his three productions of each phoneme. These computations were derived from measurements of flow made at the midpoint of each phoneme as determined from the accompanying speech signal. Flows measured at these points in the utterances proved to correspond closely to the maximum flow during the /n/ and the minimum flow during the /i/. Resulting scores were characterized by an overall subject group mean nasal flow for /n/ of 88.8 cc/sec, with a range of 40.0 cc/sec to 273.0 cc/sec and a standard deviation of 34.1 cc/sec. For /i/ the overall subject group mean was 47.5 cc/sec, with a range of 0.0 cc/sec to 167.0 cc/sec and a standard deviation of 25.3 cc/sec. Perusal of the data for /n/ and /i/ for the /ni/ utterances revealed no indication that nasal flow was related to either the age or sex of the subjects studied.

Computation of the ratio of measured nasal flow on /n/ to that on /i/ resulted in a subject group mean quotient value (excluding the three subjects mentioned above) of 2.1, with a range of 1.1 to 8.0 and a standard deviation of 1.0. Thus, for the typical subject of our group, the flow measured from the nose during /n/ approached roughly twice the magnitude of the flow measured from the nose /i/. As with the separate flow data for /n/ and /i/ for the /ni/ syllable, perusal of the quotient data revealed no indication that there were any effects related to either age or sex of the subjects.

Nonsense Productions Embedded in a Carrier Phrase

The syllables /iti/, /idi/, /isi/, /izi/, and /ini/, embedded in a carrier phrase, comprised the group of nonsense productions investigated. Nasal flow was zero for all of the 3996 individual speech sounds produced for the first four of these VCV syllables (4 syllables X 3 speech sounds each X 3 repetitions X 111 subjects). The fifth of the nonsense syllables studied, /ini/, invariably was accompanied by nasal flow during the nasal consonant segment (/n/) of the utterances. At the midpoint of /n/, these flows (for 333 utterances) were of a mean magnitude for the subject group of 94.2 cc/sec, with a range of 30.0 cc/sec to 260.0 cc/sec and a standard deviation of 38.9 cc/sec. Inspection of the criterion score data for /n/ showed no indication that nasal flow was related to either the age or sex of the subjects.

Flows measured at the midpoint of the initial vowel in the /ini/ nonsense productions resulted in a subject group mean value of 12.2 cc/sec, with a range of 00.0 cc/sec to 80.0 cc/sec, and a standard deviation of 15.9 -c/sec. Flows were found to be zero at the midpoint of the initial vowel in /ini/ for 64 of the 111 subjects studied. Excluding these 64 subjects, recalculation of the mean, range, and standard deviation for the subject group resulted in values of 28.7 cc/sec, 3.3 cc/sec to 80.0 cc/sec, and 17.4 cc/sec, respectively. Inspection of the criterion scores on the initial /i/ for our 111 subjects revealed two clear performance effects, one related to subject age and the other related to subject sex. With regard to age, there existed a moderate trend for an increasing proportion of the subjects to demonstrate nasal flow with increasing age. For example, in considering the contiguous ages studied from three to 18 years, and subdividing this range into three year intervals, our data showed the following proportions of subjects to demonstrate nasal flow at the midpoint of the vowel in each interval, respectively, 13.6%, 20.0%, 42.9%, 78.6%, and 71.4%. For our adult group, which covered a wide range of ages without being evenly distributed, the proportion of subjects demonstrating nasal flow at the midpoint of the vowel was 50%.

With regard to sex, 32 of the 47 subjects demonstrating nasal flow at the midpoint of the initial /i/ were female. This proportioning (i.e., 68.1%0 was observed not only overall but also in approximately the same magnitude across the five contiguous age subdivisions just mentioned and in our adult subject group.

For the final vowel in /ini/, flows measured at the midpoint, yielded a subject group mean value of 43.3 cc/sec, with a range of 8.0 cc/sec to 120.0 cc/sec and a standard deviation of 23.1 cc/sec. Examination of the criterion score data failed to reveal nasal flow effects for either age or sex.

Computation of the ratio of measured nasal flow on /n/ to that on the initial /i/ in the syllable /ini/ resulted in a subject group mean quotient value (excluding the 64 subjects mentioned above) of 6.3, with a range of 1.5 to 35.0 and a standard deviation of 5.6.

Inspection of the quotient data revealed no effects with regard to either age or sex of the subjects. Finally, ratio computation of flow on /n/ to that on the final /i/ in the syllable /ini/ yielded a subject group mean quotient value (based on all 111 subjects) of 2.7, with a range of 1.2 to 8.0 and a standard deviation of 1.2. Again, neither age nor sex effects were apparent upon inspection of the quotient data.[3]

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3. As mentioned in Footnote 1, one of our subjects presented data that were single in kind for the majority of utterances sampled. This subject, a female, age 13 years seven months, performed in a manner typical of the overall subject group on sustained productions and the utterances of /ni/ and /ini/. However, she demonstrated flow on certain phonemes in non-nasal phonetic contexts for the syllable repetition and nonsense production activities. Nasal flow was found to be zero for all vowel utterances while a clear burst of flow occurred during the production of almost every /t/, /d/, /s/, and /z/. These bursts were of short duration and ranged in magnitude from 20 cc/sec to 80 cc/sec. Flow for the voiced element in each cognate pair was roughly twice that which occurred for the corresponding voiceless element.

DISCUSSION

We choose to discuss our investigation under three subheadings: fully oralized utterances, fully nasalized utterances and simultaneously oralized and nasalized utterances, and clinical implications and research needs.

Fully Oralized Utterances

The fully oralized utterances of this investigation turned out to be the isolated utterances of /i/, /s/, and /z/, the syllable repetitions of /ti/, /di/, /si/, and /zi/, and the carrier phrase embedded syllables /iti/, /idi/, /isi/, and /izi/. Nasal flow was zero and the velopharynx presumably was closed air-tight for all of these utterances as produced by 111 of our subjects. The phonemes included in our fully oralized category are routinely categorized by phoneticians as oral consonants and vowels. Our findings indicate that these speech sounds are fully oralized by both sexes as early as age three and that the use of air-tight velopharyngeal closure for their production is maintained into middle-aged adulthood (37 years, 6 months was the upper limit studied here).

Our findings on fully oralized utterances are in agreement with those of other researchers who have used pneumotachometers to study nasal flow during speech samples similar to those used in the present investigation (Warren and DuBois, 1964; Lubker and Moll, 1965; Machida, 1967; Lubker, Schweiger, and Morris, 1970; Lubker, 1973).

That is, oral consonants and vowels have been found by these other authors to be produced with no nasal flow or with very minimal flows. In those instances where such minimal flows occurred, they appeared not to be the result of a velopharyngeal leak but of velar elevations in the presence of an air-tight velopharyngeal seal (Lubker and Moll, 1965; Lubker, 1973). Recall from footnote 2 that in the present study we treated such occurrences of flow as artifacts and specified them as zero flows.

Researchers who have used warm-wire flowmeters to study nasal flow during speech samples similar to ours, have provided data that are both supporting and conflicting with regard to our findings. For example, Quigley et al. (1963) and Quigley (1967) found essentially no nasal flow on utterances that are routinely classified as oral consonants and vowels. By contrast, both Van Hattum and Worth (1967) and Emanuel and Counihan (1970) report nasal flows for certain oral consonant and vowel elements. Both pairs of authors acknowledge the fact that some of these flows are probably attributable to the occurrence of velar elevations in the presence of an air-tight velopharyngeal seal. In other cases, where the flows are seemingly of too large a magnitude to be accounted for solely by velar displacements, both pairs of authors express concern that these may reflect leaks between the oral and nasal sections of their flow-measuring apparatus. It is difficult to view the reports of either pair of these authors with much conviction because of the measurement problems they acknowledge. Hardy (1967) has severely criticized the instrumentation system used in the Van Hattum and Worth (1967) study on a number of significant accounts. Some of the same criticisms apply equally as well to the instrumentation of Emanuel and Counihan (1970).

Also relevant to the present discussion are available cinefluorgraphic data on velopharyngeal function during speech conditions of the nature studied in the present investigation. Moll (1962) presents data for velopharyngeal closure on vowels that reveal that although the velopharynx is usually closed for vowel productions, it is open for a small percentage of utterances; usually in the neighborhood of 15% for the /i/-vowel contexts studied here. Bzoch (1968), by contrast, found no velopharyngeal opening in a cinefluorgraphic study of upper airway function. Aside from his formal investigation, Bzoch also inspected some 200 cinefluorographic films of normal speakers and found only occasional occurrences of velopharyngeal opening on oral speech elements. He attributed these occasional occurrences of velopharyngeal opening to slow utterance rates. We are inclined to accept Bzoch's conclusion based on our own further observations of several adult subjects who performed our study protocol at slower utterance rates than we studied in our 112 subjects. Two of six such subjects, all of whom demonstrated air-tight velopharyngeal closure for syllable repetitions at our usual rate of 3 per second, occasionally showed small nasal flows when utterance rate was dropped below 1.5 syllables per second. Bzoch would appear to have made an important observation when he stated that "a slow rate of utterance of syllables is a factor related to the occasional occurrence of velopharyngeal opening on non-nasal speech elements." Clearly, this factor needs to be specified or controlled in subsequent investigations.

Recall that one of our 112 subjects violated the rule of air-tight velopharyngeal closure during some of the consonant elements in her productions of the syllable utterances of concern here. Her unique nasal flow patterns suggest that she briefly opened the velopharynx slightly during consonant elements but maintained the velopharynx closed air-tight for adjacent vowel elements. Despite this idiosyncratic adjustment pattern, this subject's speech was normal in all regards. Although air-tight velopharyngeal closure is clearly typical for the oral consonants and vowels mentioned here, the data of our single subject with a velopharyngeal leak and normal speech raise the question about the necessity for air-tight closure. Other authors, most notably Warren (1967), have documented relatively small nasal flows in subjects with velopharyngeal closure judged to be adequate for speech purposes. For example, taking a very conservative velopharyngeal orifice size of 10 mm^2 as representing an "adequate" degree of velopharyngeal closure, one might expect to find nasal flows during voiceless stop-plosive productions that would reach magnitudes in the neighborhood of 100 cc/sec. It is also important to keep in mind that the amount of velopharyngeal opening that the listener will tolerate before labeling speech as deviant may differ with regard to whether the deviancy pertains to hypernasal voice quality or misarticulations -- the first predominantly an acoustics problem and the second predominantly an aeromechanics problem. Much remains to be learned in these regards.

Fully Nasalized Utterances and Simultaneously Oralized and Nasalized Utterances

We did not measure oral airflow in this investigation. Presumably, it was zero during the sustained productions of /n/, and zero during the major part of the /n/s in the syllable repetitions in /ni/ and in the carrier phrase embedded syllable utterances of /ini/ (Lubker and Moll, 1965; Subtelny, Worth, and Sakuda, 1966; Gilbert, 1968). Here we shall categorize all /n/ productions as fully nasalized. Our flow data for such nasalized utterances proved to be comparable for the three different phonetic contexts in which /n/ was studied. Furthermore, they revealed no apparent age or sex effects for our subject group. It is tempting to generalize these findings as being indicative of a fully matured velopharyngeal behavior that is acquired by at least age three and is maintained through middle-aged adulthood. It must be remembered, however, that several factors influence the flow of air from the nose during speech, including nasal pathway resistance, velopharyngeal airway resistance, and oral air pressure (Warren, 1967). The last of these alone, that is, oral pressure, is reported to be influenced by factors such as phonetic context, age of the subject, and sex of the subject, although the nature of such influences are not necessarily congruent from one study to another (Arkebauer, Hixon, and Hardy, 1966; Subtelny et al., 1966; Diggs, 1972; Bernthal and Beukelman, 1978). Too little is currently known to make much of the fact that our data did not show effects for context, age, or sex.

Our findings on fully nasalized utterances are in agreement with those of some authors (Warren and DuBois, 1964; Subtelny et al., 1966) and in disagreement with other (Lubker and Moll, 1965; Lubker, Schweiger, and Morris, 1970). Specifically, we observed peak nasal flows of magnitudes approaching about 100 cc/sec on the average. Warren and DuBois (1964) and Subtelny et al., (1966) show data of these approximate magnitudes for utterances of /m/, /n/, and /ng/. By contrast, the studies of Lubker and Moll (1965) and Lubker et al. (1970), done in the same laboratory, present data that are typically twice the magnitude of those found here and presented by other investigators. Lubker and Moll (1965), for example, show flows of 200 cc/sec peak magnitude for /n/ in running speech phrases comparable to ours, while Lubker et al. (1970) show flows of over 210 cc/sec on the average for the /m/ in an /imi/ utterance context. It is difficult to reconcile flow magnitudes twice the magnitude of ours without invoking an explanation that embodies major laryngeal adjustments that would result in substantially higher flows being delivered to the oral cavity. We note that not only are the nasal flows reported from the Lubker and associates laboratory higher for the context mentioned above, but that they are also approximately double of what we observed under conditions where flows from the nose were believed to be the result of velar adjustments in the presence of air-tight velopharyngeal closure. Perhaps the nasal flow channel calibration for the Lubker and Moll (1965) and the Lubker et al. (1970) studies was off by a constant factor related to the misreading of the standard scale. We have no other explanation.

The simultaneously oralized and nasalized utterances of this investigation were the /i/ vowels paired adjacent to the nasal consonant /n/ (that is, /ni/ and /ini/). Oralization is assumed for these utterances on the basis of past studies of oral air flow (Lubker and Moll, 1965; Subtelny et al., 1966; Machida, 1967; Emanuel and Counihan, 1970; Van Hattum and Worth, 1967). Evidence for the nasalized component of these utterances is clear from our nasal flow data and from the data of others on nasal flow (Warren and DuBois, 1964; Lubker and Moll, 1965; Van Hattum and Worth, 1967).

Our findings for nasal flows on the three different contexts for the /i/ vowel revealed that the /i/s following the nasal consonant /n/ (that is, in /ni/ and in the second vowel in /ini/) were of closely comparable magnitudes while those measured on the /i/ preceding the nasal consonant were of only about one-fourth the magnitude of the other two. The occurrence of nasal flows on /i/, a phoneme classified as oralized in typical phonetic schemes, is clearly attributable to the co-articulation of the nasal consonant /n/ with the vowels immediately preceding and following. In the case of the two contexts in which vowels follow the nasal, the occurrence of nasal flow on the vowel appears to be related to carry-over coarticulation in which the velopharynx does not close air-tight for the vowel after being open for the nasal. This finding is not unexpected and is consistent with the observations of others who have studied velopharyngeal function (Warren and Dubois, 1964; Lubker and Moll, 1965; Moll and Daniloff, 1971) in similar contexts. Such carry-over coarticulation is basically a consequence of the biomechanical nature of the speech mechanism (Hixon and Abbs, in press).

For the utterance contexts in which /i/ preceeded the nasal consonant /n/ (that is, the first vowel in /ini/), the occurrence of nasal flow on the vowel is clearly a result of another form of coarticulation, namely anticipatory. That is, the speaker begins to open the velopharynx during the initial vowel in /ini/ in anticipation of the nasal consonant which follows. This form of nasalization of the vowel in a nasal context has been observed by researchers using different observational techniques (Warren and Dubois, 1964; Moll and Daniloff, 1971). The performance of our subjects in terms of anticipatory coarticulation by the velopharynx, is one of the most interesting findings of the present investigation.

With regard to age, our nasal flow data on the initial /i/ in /ini/ demonstrated a moderate trend for a greater proportion of the subjects to show nasal flow at the mid-point of the initial vowel with increasing age. We interpret these data as evidence that progressively older subjects were demonstrating earlier anticipatory coarticulation in preparation for the forthcoming nasal. This progressively earlier occurrence of flow for older subjects constitutes a sort of "spread of nasalization" across the /ini/ syllable that moves in the direction of the first vowel. Unfortunately, our measurements at the mid-point of the vowel do not precisely define the function of the age effect we have mentioned. To obtain the necessary information in this regard would require that we be able to specify the precise moment of velopharyngeal opening within each vowel utterance. We did not record our data permanently and so cannot make such determinations post-hoc. We are inclined to interpret our observations in terms of motor skills acquisition associated with the increased age of our subjects. That is, with increasing age, up to at least age 12 where the behaviors become adult-like, it appears that subjects take more and more advantage of preparatory gestures for following sounds. This may reflect an increased economy of biomechanics with increasing experience in using the speech mechanism. Kent (1976), for example, has shown that several aspects of speech motor control do not become fully adult-like ingrained until approximately this age. We believe the potential for understanding developmental schedule for speech motor control may be enhanced by more detailed studies of the spread of nasalization phenomenon we have mentioned.

Recall that a clear sex effect was apparent in our flow data on the initial vowel in /ini/. Specifically, approximately 70% of the subjects who demonstrated nasal flow at the mid-point of the vowel were females, both overall and in the different age sub-groupings in which we considered our data. We are uncertain as to the reasons for this sex effect. Possibilities include a potentially greater tolerance for the spread of nasalization in females without the perception of hypernasality and biomechanical differences between the sexes that might favor greater anticipatory coarticulation by females. We lean toward the latter as a possible explanation for our findings. McKerns and Bzoch (1970) have shown that velopharyngeal function differs considerably between males and females on a number of dimensions. Differences demonstrated included the orientation of the velum to the pharynx during velopharyngeal closure, the relationship of the inferior point of contact of the velum to the palatal plane, the degree of elevation of the velum, the amount of contact between the velum and the posterior pharyngeal wall, the distance from the uvula to the posterior pharyngeal wall, and the length of the velum in function for speech. It seems reasonable to suppose that other dynamic velopharyngeal function differences might exist between the sexes and that these might be manifested in measures such as the nasal flow recordings made in the present study. That is, there may be certain mechanical advantages that would permit females and not males to engage in an earlier anticipatory opening of the velopharyngeal mechanism in preparation for /n/. Far too little is yet known about velopharyngeal biomechanics and aeromechanics to speculate with any degree of certainty in this regard.

Clinical Implications and Research Needs

The results of this investigation appear to have implications for both clinical and research endeavors. It is our experience that many clinicians are of the opinion that some degree of velopharyngeal leakage may routinely accompany the production of what are phonetically classified as oralized speech sounds. The results of this investigation of a large number of normal subjects do not support this notion. Rather, it is apparent that for the types of utterances sampled air-tight velopharyngeal closure is nearly universal. This finding would appear to have implications with regard to the evaluation and the physical and behavioral management of persons with velopharyngeal incompetence. That is, the target for "normal" velopharyngeal closure is an air-tight seal. It remains to be determined what precisely the tolerable limits are for other than air-tight velopharyngeal closure. The fact that one of our subjects demonstrated normal speech in the presence of a small nasal flow suggests that air-tight closure may not be a necessary requisite for normal speech. More detailed studies of subjects of this nature may prove to be an informative undertaking toward understanding the closure demands for normal speech production. Thus, the anticipated clinical observation in normal velopharyngeal closure on oral sounds would be no flow. However, small flows should not be taken as evidence of velopharyngeal incompetence. Fortunately, for clinical concerns, our results provide the first extensive data to illustrate that, at least for the oralized speech samples studied here, the clinician need not be concerned about subject differences with respect to age (over a wide range), sex, or phonetic context.

Our data on flow for the nasal consonant /n/ constitute a substantial body of information relative to the flows associated with fully nasalized consonants. They may well represent a useful standard of comparison for those concerned with secondary surgical procedures and prosthetic management techniques that occasionally "over-correct" for velopharyngeal incompetence to the extent that nasal breathing is impaired and hyponasality occurs. The central tendency and dispersion measures we have provided for nasal flow should provide a useful starting point for those interested in determining "typical" values for normal subjects.

With respect to research, there are clear needs to be filled. Knowing that air-tight velopharyngeal closure must develop sometime between birth and age three, it is obviously important to proceed with studies to determine the age at which children gain adult-like control of the velopharynx for oralized speech sounds. It should prove profitable to study such children with regard to both age and sex effects. New technological advances in flow measurement instrumentation, such as miniature thermistors, now make it possible to pursue such study without encumberance to the speech mechanism. Studies using such procedures are now underway in The University of Arizona Laboratories.

We acknowledge that the speech utterances studied in this investigation were limited with regard to sampling the phonemes of American English. Additional informal study in our laboratory of a small group of adults suggests to us that our findings of air-tight velopharyngeal closure on vowel utterances should not be generalized to all vowels. For example, some subjects demonstrate air-tight velopharyngeal closure on high vowels but show small velopharyngeal leaks on low vowels. This being the case, subsequent research should also take into account vowels in addition to the /i/ we studied here.

Finally, a number of aspects of velopharyngeal function cannot be fully specified with nasal flow measurements alone. It would seem useful to undertake a comprehensive study of velopharyngeal function using other forms of innocouus aeromechanical procedures for quantifying such factors as velopharyngeal orifice area and the relationship between oral pressure and nasal flow. The technique of Warren and DuBois (1964) seems well suited to such pursuits.

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