Effects of Vowel Height and Vocal Intensity on Anticipatory Nasal Airflow in Individuals With Normal Speech

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The purpose of this study was to determine the effects of vowel height and vocal intensity on the magnitude of anticipatory nasal airflow in normal speakers when producing vowel-nasal-vowel (VNV) sequences. Measurements of nasal and oral airflow were obtained from 15 men and 12 women with normal speech during production of the VNV sequences /ini/ and /ɑnɑ/ at low, medium, and high intensity levels. Ratios of nasal to oral-plus-nasal airflow were calculated for the initial vowel of both utterances at each of the intensity levels. Analysis of variance (ANOVA) procedures indicated a significant main effect of intensity level and a significant vowel-by-sex interaction effect ($p < .05$) on the airflow ratios. Overall, the airflow ratio was reduced at high as compared to low intensity levels, regardless of sex of the speaker or vowel type. Female speakers exhibited greater airflow ratios during production of /ini/ than during productions of /ɑnɑ/. Their airflow ratios were also greater during production of /ini/ than were those of male speakers. The results suggest that vocal intensity may affect velopharyngeal (VP) function in an assimilative nasal phonetic context. The results further suggest that anticipatory nasal airflow may be determined by the configuration of the oral cavity to a greater extent in women than in men. Theoretical and clinical implications are discussed.

KEY WORDS: vowel height, vocal intensity, anticipatory nasal airflow, oral airflow, velopharyngeal function

The relationship between velopharyngeal (VP) function and vowel height has been studied extensively using various physiologic techniques (e.g., Bell-Berti, 1976; Bell-Berti & Krakow, 1990; Fritzell, 1969; Kuehn & Moon, 1998; Lubker, 1968; Moll, 1962; Moll & Shriner, 1967). Moll (1962) reported that high vowels were produced with greater velar height than low vowels in a cinefluorographic study of normal speakers. Moll further reported that (a) VP closure was not achieved during vowels adjacent to a nasal segment, and (b) greater VP gaps were associated with low as compared to high vowels in a nasal context. Bell-Berti (1976) reported that electromyographic (EMG) activity of levator veli palatini was greater during production of high versus low vowels. Bell-Berti and Krakow (1990) further reported that high vowels were produced with greater velar height than low vowels in a kinematic study using the "velotrace" device. Kuehn and Moon (1998) evaluated VP closure force associated with various vowels using a custom-made force sensing bulb. A significant increase in force was reported when normal speakers produced high versus low vowels.

Aerodynamic studies have also suggested a systematic relationship between vowel height and anticipatory nasal airflow in normal speakers. In a review of research findings, Hajek (1997) noted that nasal airflow was greater in high versus low vowels in a VN context (e.g., Al-Bamerni, 1983). Hajek explained this relationship as resulting from increased oral impedance of high vowels that directs more airflow into the nasal cavity. Lubker and Moll (1965) measured oral and nasal airflow while simultaneously recording the articulatory positions of the tongue and velum in a single normal speaker. They reported that anticipatory nasal airflow increased whereas the size of the VP orifice remained constant during production of a vowel-nasal (VN) sequence. Lubker and Moll attributed this finding to an increase in oral cavity constriction. During production of the phrase "say nip," for example, velar height and VP distance were relatively constant during the vowel /e/, whereas nasal airflow increased, oral airflow decreased, and tongue-to-palate distance decreased (Figure 6, p. 266). In essence, the increase in nasal airflow during /e/ resulted from increased oral cavity constriction in anticipation of oral stopping for the nasal segment. Indeed, Lubker and Moll (1965) stated that "nasal pressure and flows undoubtedly are related to various oral phenomena as well as to the activities of the velopharyngeal mechanism" (p. 257).

Moll and Shriner (1967) and Moll and Daniloff (1971) suggested a "binary" theory of velar timing and control to account for vowel nasalization in VN contexts. According to this theory, the speech motor control program specifies nonnasal consonants as closed, nasal consonants (and utterance endings) as open, and vowels as neutral (or unspecified). Given a "look ahead" model, vowels preceding a nasal consonant assume an open velar specification. Although Kent, Carney, and Severeid (1974) acknowledged the attractiveness of this theory, they noted that it made predictions that did not occur in English (e.g., isolated vowels are not nasalized). In addition, Kent et al. reported velar movement and timing patterns of speakers that were not predicted by the theory. Specifically, they used cinefluorographic procedures to show that velar elevation actually started during certain vowels that were specified as open according to the model (e.g., vowels within a CVNC sequence). On the basis of these and other findings, Kent et al. suggested that "a fairly rigid time program" must exist for velar articulation (p. 488).[1]

The effects of vocal loudness and/or intensity level on VP function have also been of interest to clinicians and researchers. Watterson, York, and McFarlane (1994) used the Nasometer to measure nasalance of normal speakers at three perceptually determined loudness levels (soft, medium, and loud). Watterson et al. reported a trend for each subject's highest nasalance score during production of nasal sentences to occur in the soft condition. Conversely, the lowest nasalance score tended to occur in the loud condition. McHenry (1997) investigated the effect of increased vocal loudness on estimated VP orifice area in speakers with dysarthria. McHenry indicated that 89% of the speakers exhibited a decrease in VP orifice area when perceived vocal loudness was increased. For male and female speakers, orifice area calculations decreased by an average of approximately 4 mm^2 and 2 mm^2, respectively. In our clinical work, we have also observed that some individuals with repaired cleft palate demonstrate reduced VP orifice areas during aerodynamic testing when instructed to increase vocal loudness. These clinical observations are consistent with the results reported by McHenry (1997) for speakers with dysarthria. Zajac, Mayo, and Kataoka (1998) investigated the effects of sex and syllable stress on anticipatory and carryover nasal airflow in the nonsense sequence /ini/ produced by normal speakers. Results indicated that when /ini/ was produced with contrastive stress on the second syllable, the associated vowel was produced with increased sound pressure level (SPL) and reduced carryover nasal airflow. Zajac et al. suggested that VP closure during /i/ was enhanced as a function of stress and increased vocal intensity.

In contrast to the above studies, Sussman (1995) reported that voice intensity variations did not affect HONC (Horii's Oral Nasal Coupling Index) measures in normal adult speakers. The HONC procedure simultaneously obtains nasal and voice accelerometer signals to calculate a nasal-oral ratio as an index of perceived nasality. It must be emphasized, however, that HONC measures are normalized using a correction factor that equates the nasal and voice signal amplitudes during production of a sustained nasal segment. Because of this normalization process, it is not surprising that HONC measures are unaffected by intensity variations of speakers. In addition, it should be noted that Sussman (1995) investigated normal intensity variations over time and did not experimentally manipulate vocal intensity.

Finally, various investigators have noted sex differences relative to certain aspects of VP function (Kuehn, 1976; McKerns & Bzoch, 1970; Seaver, Dalston, Leeper, & Adams, 1991; Sussman, 1995; Thompson & Hixon, 1979; Zajac & Mayo, 1996). Relative to nasal airflow, Thompson and Hixon (1979) noted that more women than men exhibited anticipatory nasal airflow during production of /ini/. They attributed this finding to possible sex differences in the closure configuration of the VP sphincter as suggested by McKerns and Bzoch (1970). Zajac et al. (1998), however, did not report a sex

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[1] We do not intend to test a specific model of vowel nasalization in this study. The "binary" theory is presented for background purpose only. The interested reader is referred to Bell-Berti and Krakow (1990) for a description of an alternative coproduction account of vowel nasalization.

difference relative to anticipatory nasal airflow in speakers from North Carolina. Sussman (1995) reported that men required a larger HONC correction factor than women during sustained /m/ production. Sussman attributed this finding to a combination of sex differences in vocal and nasal intensity levels. Seaver, Dalston, Leeper, and Adams (1991) reported small but consistent differences in acoustic nasalance between male and female speakers from four different geographic regions. Women were reported to exhibit higher nasalance than men by 2%–3% during reading of passages loaded with nasal sounds. It should be noted, however, that several investigators have cautioned that sex differences in nasalance may be due, in part, to a mismatch in the sensitivity of the microphones used with the Nasometer (e.g., Putnam Rochet, Rochet, Sovis, & Mielke, 1998; Zajac, Lutz, & Mayo, 1996).

The above studies have provided important information on VP function relative to vowel height, loudness, or intensity levels. They have also suggested that sex differences may exist relative to certain aspects of VP function. None of the studies, however, has experimentally manipulated both vowel height and intensity simultaneously. Because we believe that the diagnosis and treatment of speakers with VP inadequacy (especially marginal dysfunction) are demanding challenges for most clinicians, studies that evaluate the effects of vowel type and vocal intensity may help to refine diagnostic procedures and/or provide support for specific management strategies. As noted above, our clinical observations have suggested that manipulation of vocal loudness may result in changes in estimated VP orifice area of individuals with repaired cleft palate. Boone and McFarlane (1994) have also suggested that increased loudness may decrease the perceptual consequences of hypernasality. If experimental evidence shows that VP function of speakers without cleft palate and with normal speech is affected by changes in intensity levels, then the use of increased vocal intensity as a behavioral strategy for speakers with repaired cleft palate may be justified. The purpose of the current study, therefore, was to determine the effects of vowel height and vocal intensity on the magnitude of anticipatory nasal airflow in male and female individuals without cleft palate and with normal speech when producing vowel-nasal-vowel (VNV) sequences.

Method

Participants

Fifteen men and 12 women participated in the study.[2] Participants were recruited from the campus of the University of North Carolina at Chapel Hill and the surrounding community. All of the participants were between 8 and 45 years old and spoke standard American English as their first language. The mean age for the men was 28 years, 1 month; mean age for the women was 24 years, 3 months. The upper age limit selected for the participants was deemed acceptable because previous studies have reported no evidence that VP function deteriorates with age (Hoit, Watson, Hixon, McMahon, & Johnson, 1994; Zajac, 1997).

All participants reported the absence of (a) speech, language, voice or hearing problems; (b) cleft lip and/or palate; and (c) allergies, sinus problems, or upper respiratory infections at the time of testing. Each participant was screened for normal nasal air emission by means of a mirror placed under the nostrils. All participants exhibited nasal air emission during production of nasal consonants and did not exhibit nasal air emission during production of oral consonants. Finally, the oral cavity of each participant was visually examined to rule out the presence of either a bifid uvula and/or midline palatal translucence that may be indicative of an undetected submucous cleft palate.

Speech Samples

Participants were instructed to repeat the phrases “say ini ini ini again” and “say ɑnɑ ɑnɑ ɑnɑ again” three times each at low, medium, and high intensity levels. The VNV sequences were produced with equal stress on both syllables. The medium intensity level was based on normal loudness of the speakers and was determined separately for the men and women. This was done because Zajac et al. (1998) reported differences in SPLs of men and women when producing /ini/ at self-determined loudness levels. For the male speakers, the SPL ranges were 74–78 dB for low intensity, 81–85 dB for medium intensity, and 88–92 dB for high intensity. For the female speakers, the SPL ranges were 70–74 dB for low intensity, 77–81 dB for medium intensity, and 84–88 dB for high intensity.

The above SPL ranges ensured that at least a 3-dB increase occurred between the adjacent intensity levels (i.e., between low-medium and medium-high levels). It must be noted, however, that because of the 5-dB range of the intensity levels, increases greater than 3 dB were possible. Indeed, speakers typically exhibited increases greater than 3 dB. The actual increases in SPL between the adjacent intensity levels for all subjects are reported below.

Instrumentation

A partitioned, circumferentially vented pneumotachograph face mask (Glottal Enterprises) and two air

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[2] Fifteen men and 15 women were recruited for the study. Results are reported for only 12 women because of investigator error that resulted in incomplete data collection for 3 subjects.

pressure transducers (Setra, Model 239) were used to detect oral and nasal airflow. The mask and transducers were calibrated using a flow rate of 250 ml/s delivered by a compressed air supply and rotameter. The mask and transducers were shown to be linear over the range of interest from 0 to 500 ml/s. A calibrated microphone was positioned 5 inches from the oral portion of the mask. The microphone was calibrated using a sound level meter and a 200-Hz tone referenced to 70-dB SPL(C). Airflow data were low-pass filtered at 50 Hz and digitized to a computer at a rate of 500 samples per s with 12-bit resolution. Acoustic data were low-pass filtered at 10 kHz and digitized at a sampling rate of 20 kHz with 12-bit resolution. PERCI-SARS (Microtronics, Inc.) hardware and software were used to acquire all data.

Procedures

Two adult mask sizes (medium and large) were available for the speakers. Self-adhesive foam tape was applied to the perimeter and nasal partition of the masks to help eliminate air escape and ensure a comfortable fit to the speaker's face. The speakers were seated before the computer monitor, and the SPL targets were displayed as two horizontal lines. The speakers were given three practice trials to familiarize themselves with the task. They were instructed to hold the mask by its handle and to gently but firmly press the mask against their face. They were told to say the speech samples so that the first vowel of each VNV sequence peaked within the displayed target range for SPL. Following practice, three additional trials were collected as data. If a speaker failed to achieve the SPL targets, then the trial was repeated. The order of the /ini/ and /ɑnɑ/ speech samples was counterbalanced for both the male and female speakers. All speakers produced the samples first at medium intensity. The low and high intensity conditions were then counterbalanced for both the male and female speakers.

Data Analysis

Oral and nasal airflow (ml/s) were measured at the midpoints of the first vowels in the /ini/ and /ɑnɑ/ sequences for each speaker and intensity condition. Although the speech stimuli consisted of VNV sequences, the second vowels were not analyzed for this report. As indicated above, the speakers were instructed to achieve the intensity targets only for the first vowels of the sequences. Not all of the second vowels, therefore, were produced within the intensity target range. Ratios of nasal to oral-plus-nasal airflow were calculated at the midpoints of the first vowels. Peak SPLs associated with the vowels were also determined to verify the intensity levels. The ratios were selected as the primary measure of interest because they control for variations in total vocal tract airflow that may occur with changes in intensity levels. Stathopoulos and Sapienza (1997), for example, reported a significant difference in average translaryngeal airflow for low versus medium intensity levels of normal speakers.

Mean values of oral airflow, nasal airflow, airflow ratios, and SPL were calculated based upon 9 measurements for each speaker, vowel, and intensity condition (i.e., 3 repetitions of the VNV sequence × 3 trials). Onset of the first vowel was identified when oral airflow exceeded zero flow level; offset was identified at peak oral airflow which preceded peak nasal airflow for /n/. PERCI-SARS software, Version 2.0 (Microtronics, Inc.), was used to analyze all data. This software automatically determined the vowel onset, offset, duration, and midpoint. The accuracy of the aerodynamic procedures in defining vowel duration was previously determined by Zajac et al. (1998). They reported no significant difference and a high correlation between vowel durations that were determined by aerodynamic and acoustic procedures.

Statistical Analysis

Group mean and standard deviation (*SD*) values for oral airflow, nasal airflow, and nasal to oral-plus-nasal airflow ratios associated with the first vowels of /ini/ and /ɑnɑ/ were calculated as a function of sex and intensity level. Analysis of variance (ANOVA) procedures with repeated measures were used to analyze each of the above data sets. The factors of the ANOVA included vowel type (2 levels), intensity (3 levels), and sex (2 levels)—with vowel type and intensity as repeated measures. Post hoc comparisons among groups were determined using Tukey Honestly Significant Difference (HSD) tests. Alpha levels were set at .05 for all statistical tests.

Group means and *SD*s were also calculated for the difference in SPL that occurred between adjacent intensity target levels. This was done to determine the actual increase in SPL that occurred from low to medium and from medium to high intensity levels.

Results

Group mean and standard deviation (*SD*) values for the increase in SPL that occurred between the adjacent intensity target levels associated with the first vowels in /ini/ and /ɑnɑ/ as a function of sex are presented in Table 1. As indicated above, the ranges of the intensity targets ensured a minimum increase of 3 dB between adjacent levels. As revealed in Table 1, however, the actual SPL increases averaged approximately 6–7 dB for all speakers as a group. Furthermore, inspection

Table 1. Means (*M*) and standard deviations (*SD*) of the increase in sound pressure level (SPL) that occurred between adjacent intensity levels for the first vowels in /ini/ and /ɑnɑ/ as a function of sex.

Sex / Adjacent Intensity Levels	SPL Increase (dB) /i/$_1$ *M*	/i/$_1$ *SD*	/ɑ/$_1$ *M*	/ɑ/$_1$ *SD*
Men (*N* = 15)				
Low to medium	6.0	1.3	6.3	1.4
Medium to high	6.7	1.5	6.7	1.4
Women (*N* = 12)				
Low to medium	5.9	1.6	6.7	1.6
Medium to high	5.8	1.5	7.4	1.6

Note. Intensity levels for men were 74–78 dB SPL (Low), 81–85 dB SPL (Medium), and 88–92 dB SPL (High). Intensity levels for women were 70–74 dB SPL (Low), 77–81 dB SPL (Medium), and 84–88 dB SPL (High).

Table 2. Means (*M*) and standard deviations (*SD*) of oral airflow associated with the first vowels in /ini/ and /ɑnɑ/ as a function of sex and vocal intensity level.

Sex / Intensity Level	Oral Airflow (ml / s) /i/$_1$ *M*	/i/$_1$ *SD*	/ɑ/$_1$ *M*	/ɑ/$_1$ *SD*
Men (*N* = 15)				
Low	74	48	70	37
Medium	69	31	73	26
High	85	33	89	35
Women (*N* = 12)				
Low	37	22	69	36
Medium	40	15	66	32
High	38	17	54	24

Note. Intensity levels for men were 74–78 dB SPL (Low), 81–85 dB SPL (Medium), and 88–92 dB SPL (High). Intensity levels for women were 70–74 dB SPL (Low), 77–81 dB SPL (Medium), and 84–88 dB SPL (High).

of individual values revealed that all speakers except two exhibited SPL increases greater than 3 dB. Although the data in Table 1 indicate overall similar increases among the speakers, women tended to have slightly larger SPL increases during /ɑ/ than /i/. We do not believe, however, that differences of the small magnitudes shown in Table 1 (e.g., 0.8 and 1.6 dB) for the female speakers confounded the intensity effects reported below.

Group means and *SD*s for oral airflow, nasal airflow, and airflow ratios associated with the first vowels of /ini/ and /ɑnɑ/ as a function of sex and intensity level are presented in Tables 2–4. Table 2 reveals that women appeared to exhibit reduced oral airflow (a) during production of /i/ as compared to /ɑ/, and (b) during production of /i/ as compared to men. Results of a 2 × 3 × 2 ANOVA revealed a significant main effect of sex [$F(1, 25) = 9.46$, $p = .005$], a significant main effect of vowel type [$F(1, 2 5) = 12.40$, $p = .002$], and a significant interaction between sex and vowel type [$F(1, 25) = 9.99$, $p = .004$]. Analysis of the simple effects of vowel type by sex revealed no significant difference between /i/ and /ɑ/ for men but a significant difference for women [paired $t(11) = 5.11$, $p = .001$]. Analysis of the simple effects of sex by vowel type revealed no significant difference between men and women for /ɑ/ but a significant difference for /i/ [independent $t(25) = 4.50$, $p = .001$]. These results confirm that women exhibited reduced oral airflow during production of /i/ as compared to /ɑ/ and during production of /i/ as compared to men. Although the data in Table 2 further suggests that men tended to exhibit greater oral airflow from low to high intensity levels, this trend was not statistically significant.

Table 3 reveals that (a) women appeared to exhibit greater nasal airflow during /i/ than /ɑ/, (b) women appeared to exhibit decreased nasal airflow from low to high intensity levels for both vowels, and (c) that men appeared to exhibit greater nasal airflow during /ɑ/ than women. Results of a 2 × 3 × 2 ANOVA revealed a significant interaction between sex and vowel type [$F(1, 25) = 7.91$, $p = .009$]. No main effects or other interactions were significant. Analysis of the simple effects of vowel type by sex revealed no significant difference between /i/ and /ɑ/ for men but a significant difference for women

Table 3. Means (*M*) and standard deviations (*SD*) of nasal airflow associated with the first vowels in /ini/ and /ɑnɑ/ as a function of sex and vocal intensity level.

Sex / Intensity Level	Nasal Airflow (ml / s) /i/$_1$ *M*	/i/$_1$ *SD*	/ɑ/$_1$ *M*	/ɑ/$_1$ *SD*
Men (*N* = 15)				
Low	54	32	60	34
Medium	49	27	56	26
High	52	10	57	24
Women (*N* = 12)				
Low	64	35	48	30
Medium	57	34	42	27
High	35	12	32	25

Note. Intensity levels for men were 74–78 dB SPL (Low), 81–85 dB SPL (Medium), and 88–92 dB SPL (High). Intensity levels for women were 70–74 dB SPL (Low), 77–81 dB SPL (Medium), and 84–88 dB SPL (High).

Table 4. Means (*M*) and standard deviations (*SD*) of nasal to oral-plus-nasal airflow ratios associated with the first vowels in /ini/ and /ɑnɑ/ as a function of sex and vocal intensity level.

Sex / Intensity Level	Nasal / Oral+Nasal Airflow Ratios			
	/i/$_1$		/ɑ/$_1$	
	M	*SD*	*M*	*SD*
Men (*N* = 15)				
Low	.44	.15	.43	.11
Medium	.40	.13	.41	.13
High	.36	.14	.38	.12
Women (*N* = 12)				
Low	.63	.13	.38	.10
Medium	.55	.12	.37	.10
High	.49	.19	.35	.13

Note. Intensity levels for men were 74–78 dB SPL (Low), 81–85 dB SPL (Medium), and 88–92 dB SPL (High). Intensity levels for women were 70–74 dB SPL (Low), 77–81 dB SPL (Medium), and 84–88 dB SPL (High).

[paired *t*(11) = –2.92, *p* = .014]. Analysis of the simple effects of sex by vowel type revealed no significant differences between men and women for either /i/ or /ɑ/. These results confirm that women exhibited greater nasal airflow during /i/ than /ɑ/. The statistical results do not confirm, however, either an intensity effect for the women or that the men exhibited greater nasal airflow than the women for /ɑ/.

Table 4 reveals that (a) women appeared to exhibit higher nasal to oral-plus-nasal airflow ratios for /i/ than /ɑ/, (b) women appeared to exhibit higher ratios for /i/ than men, and (c) both men and women appeared to exhibit reduced ratios from low to high intensity levels. Results of a 2 × 3 × 2 ANOVA indicated a significant main effect of intensity [$F(2, 50) = 12.37$, $p = .001$], a significant main effect of vowel type [$F(1, 25) = 17.43$, $p = .001$], and a significant interaction between sex and vowel type [$F(1, 25) = 20.42$, $p = .001$].[3] Relative to the main effect of intensity, the airflow ratios decreased as a function of increasing intensity regardless of vowel type or sex. Means and standard deviations for low, medium, and high intensity levels collapsed across vowels and sex were .47 (.11), .43 (.11), and .39 (.12), respectively. Post hoc Tukey HSD tests revealed a significant difference in the airflow ratios between the low and high intensity levels ($p < .05$). Relative to the interaction effect, analysis of the simple effects of vowel type by sex revealed no significant difference between /i/ and /ɑ/ for men but a significant difference for women [paired $t(11) = –6.19$, $p = .001$]. Analysis of the simple effects of sex by vowel type revealed no significant difference between men and women for /ɑ/ but a significant difference between men and women for /i/ [independent $t(25) = –3.21$, $p = .007$]. These results confirm an intensity effect regardless of sex or vowel type. The statistical results also confirm that women exhibited greater airflow ratios during /i/ than /ɑ/ and greater airflow ratios during /i/ than men.

Summary of Findings

A primary finding of the above analyses was that increased vocal intensity appeared to reduce nasal to oral-plus-nasal airflow ratios independent of sex of the speaker or type of vowel produced. A secondary finding was that independent of intensity, a sex-by-vowel interaction appeared to affect oral airflow, nasal airflow, and the airflow ratios. Specific to women, they exhibited (a) reduced oral airflow during /i/ as compared to /ɑ/, (b) increased nasal airflow during /i/ as compared to /ɑ/, and (c) increased nasal to oral-plus-nasal airflow ratios during /i/ as compared to /ɑ/. As compared to men, women also exhibited reduced oral airflow and increased nasal to oral-plus-nasal airflow ratios during /i/.

Discussion

Vocal Intensity Effects

The purpose of this study was to determine the effects of vowel height and vocal intensity on the magnitude of anticipatory nasal airflow in normal speakers when producing VNV sequences. A primary finding suggests that increased vocal intensity may facilitate VP closure in a VN context as reflected by decreased ratios of nasal to oral-plus-nasal airflow regardless of sex of the speaker or vowel type. In support of this interpretation, we must emphasize that there were no significant interactions involving either sex or vowel type with intensity for any of the dependent measures. In addition, the intensity findings are consistent with previous research. Zajac et al. (1998), for example, reported a decrease in both anticipatory and carryover nasal airflow as a function of increased SPL during stressed productions of /ini/ by normal speakers. McHenry (1997) reported that estimates of VP orifice size were reduced as a function of increased loudness by dysarthric speakers.[4]

Several phenomena may explain the effects of increased vocal intensity on anticipatory nasal airflow and VP function. As suggested by Öhman (1967), stress may

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[3] Descriptive statistics, including measures of kurtosis and skewness, revealed that the nasal to oral-plus-nasal airflow ratios were normally distributed. The data in Table 4, therefore, were not transformed before statistical analysis.

[4] Because we did not obtain differential oral-nasal air pressure measures during consonant production, we cannot report estimates of velopharyngeal orifice size for the present study.

function to provide a "transient increase in neural signal strength to the entire speech musculature" (cited in Netsell, 1971, p. 226). Netsell (1971) further reported that syllable stress increased both the velocity and displacement of vocal tract structures. Greater VP closure as a function of increased vocal intensity, therefore, may occur because of the activation of physiologic mechanisms underlying stress production. Because syllable stress is achieved by activation of the respiratory muscles that increase subglottal air pressure (Barlow, 1999), the respiratory system may be the impetus for the "transient increase" to other muscles of the vocal tract, including the velopharyngeal structures.

Indeed, McHenry (1997) suggested that increased vocal effort may change respiratory patterns and activate "coordinative structures" (Folkins, 1985) that in turn facilitate VP closure. McHenry cited the work of Gracco and Abbs (1988), who suggested that modification of one speech structure may modify the function of related structures. McHenry also cited the findings of Finkelstein et al. (1993) to suggest that a coordinative structure might involve respiratory effort and VP function. Finkelstein et al. suggested that as greater VP closure was required, a progressive hierarchy of muscles was recruited to achieve closure. Finkelstein et al. speculated that the initial recruitment involved levator and palatoglossus, then palatopharyngeus and the superior constrictor, respectively.

It should be noted that the idea of a coordinative structure that involves both the respiratory and VP structures may have some empirical support, at least in the animal physiology literature. Kogo et al. (1997), for example, recently reported coordinated activity between forced expiratory airflow and EMG activity of the VP muscles in dogs. When respiratory drive was experimentally increased via forced rebreathing, VP constrictor activity also increased. Kogo et al. interpreted these findings to suggest that the canine velum is constrained to elevate during increased respiratory drive in order to facilitate efficient gas exchange via an oral route.

The intensity findings of the present study may have diagnostic and/or clinical management implications. The estimation of VP orifice size at different intensity levels during pressure-flow testing may provide important prognostic information. If a speaker with repaired cleft palate and marginal VP function, for example, exhibits reduced VP areas with increased vocal intensity, then this may be a positive indicator that behavioral management strategies should be implemented, at least on a trial basis. Such strategies may include the use of increased vocal loudness (Boone & McFarlane, 1994), continuous positive airway pressure (CPAP) applied to the nasal cavity (Kuehn, 1991), or biofeedback of acoustic nasalance and/or nasal airflow. Obviously, the effectiveness of such procedures needs to be demonstrated. If VP orifice areas are not reduced with an increase in intensity, then this may indicate that the speaker is already using physiologic mechanisms to the maximum to achieve closure. In such cases, a recommendation for early secondary surgical management may be appropriate. Our experience at the Craniofacial Center at the University of North Carolina at Chapel Hill suggests that approximately 80% of speakers with repaired cleft palate and marginal VP function will require secondary surgical procedures after trial speech therapy. If a relatively simple addition to the pressure-flow procedure can successfully identify those individuals who will not benefit from speech therapy, then substantial savings in both time and resources may be gained.

The present findings may also support the use of increased vocal intensity as a behavioral strategy for individuals with marginal VP function and/or perceived hypernasality. As noted above, Boone and McFarlane (1994) cite increased vocal loudness as a method to modify hypernasal resonance. The effect of increased loudness on perceived hypernasality, however, may be explained at least in part by a relative increase in the opening of the oral cavity that tends to mask nasal resonance. Indeed, increasing the opening of the oral cavity is another behavioral strategy suggested by Boone and McFarlane (1994) to reduce hypernasality. The relatively large difference in acoustic nasalance between the vowels /i/ and /ɑ/ (McKay & Kummer, 1994) highlights this acoustic-perceptual effect. The results of the present study, however, suggest that increased vocal intensity may also directly facilitate VP closure. As noted by McHenry (1997), the Lee Silverman Voice Treatment program (Ramig, Pawlas, & Countryman, 1995) uses a key component of increased effort to facilitate VP function in patients with neurogenic involvement. For individuals with marginal VP function as a result of repaired cleft palate, we believe that a similar approach may also improve VP function. We suggest, for example, that structured approaches that incorporate the use of multiple levels of voice intensity targets combined with speaking tasks that employ contrastive syllable stress may be successful in improving VP function. We hope that the results of the current and future investigations will encourage the development and evaluation of such approaches.[5]

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[5] We need to caution the reader that previous evidence has suggested that some individuals with VP dysfunction may already raise their vocal intensity in an attempt to improve overall intelligibility. Indeed, such individuals may be at risk for the development of vocal pathology (e.g., D'Antonio, Muntz, Providence, & Marsh, 1988; McWilliams, Bluestone, & Musgrave, 1969). As indicated in the text, appropriate diagnostic testing is required to identify individuals who may benefit from a behavioral approach. In addition, the use of small incremental increases in intensity levels (e.g., 3 dB increases) may further reduce the risk of vocal symptoms/pathology.

Vowel Height Effects

A secondary finding of the study suggests that measures of oral airflow, anticipatory nasal airflow, and anticipatory nasal to oral-plus-nasal airflow ratios may be dependent upon both sex of the speaker and vowel type. Women, for example, exhibited reduced oral airflow and increased nasal to oral-plus-nasal airflow ratios as compared to men during /ini/. These findings suggest, in part, that women may have produced /i/ with relatively greater oral cavity impedance than men, thus shunting more airflow through the nasal cavity. Indeed, there is some evidence in the aerodynamic literature to support this interpretation. Netsell, Lotz, Peters, and Schulte (1994), for example, reported that average laryngeal airflow was greater during /ɑ/ than /i/ for women. Specifically, Netsell et al. reported that flows during /pi/ and /pɑ/ at 1.5 syllables per s were 127 and 140 ml/s, respectively. Flows during /pi/ and /pɑ/ at 3.0 syllables per s were 142 and 160 ml/s, respectively. For men, the airflow differences between /pi/ and /pɑ/ were less apparent. Although these findings were not reported to be statistically significant, they nevertheless imply that the women may have exhibited increased oral cavity impedance during production of /i/ as compared to the men.

Although a physiologic reason for reduced oral airflow during /i/ by women cannot be discerned by the methodology of the present study, it may be related to sex differences in oral-pharyngeal anatomy and differences in vowel production in general. McKerns and Bzoch (1970), for example, used videofluoroscopy to suggest that women differed from men relative to the configuration of the VP structures during closure. They further suggested that sex differences may exist in the insertion sites of levator veli palatini, palatoglossus, and palatopharyngeus muscles. Moon, Smith, Folkins, Lemke, and Gartlan (1994) suggested that the position of the velum during speech was determined by the relative contributions of the VP muscles rather than a single muscle in isolation. Using electromyographic (EMG) and photodetection techniques, they suggested that palatoglossus and levator functioned as part of a coordinative structure to position the velum during /i/ but not during /ɑ/. These studies suggest, therefore, that subtle sex differences in oral-pharyngeal anatomy (e.g., insertion sites of muscles) may interact with vowel-specific differences in muscle coordination to increase oral impedance in women.

Regardless of the physiologic basis for the sex-by-vowel effects in the present study, an additional point relative to the perceptual consequences of the data needs to be addressed. Although perceptual analysis of the audio data was not done, it is likely that the women sounded more nasal during /ini/ than /ɑnɑ/. Indeed, MacKay and Kummer (1994) reported that syllables containing /i/ were associated with higher acoustic nasalance than syllables containing /ɑ/. Moore and Summers (1973) reported that high vowels were perceived as more nasal than low vowels, at least in speakers with repaired cleft palate. A more interesting question, however, is whether the women of the present study sounded more nasal than the men during production of /ini/. As previously noted, some studies have suggested that acoustic nasalance is slightly higher in women than in men during production of nasal passages. If valid, the nasalance findings may suggest that listeners tolerate greater nasality in women than in men. This may occur because of the similarity of the fundamental frequency, the first formant, and the nasal formant during a VN context in women as compared to men. Indeed, because of anticipated differences in vocal fundamental frequency, we did not attempt a perceptual comparison of nasality between the men and women in the present study. We believe, however, that this question warrants further investigation.

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