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BRIEF COMMUNICATION

Effects of Nasal Port Area on Perception of Nasality and Measures of Nasalance Based on Computational Modeling

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Objective: **This study examined the relation between nasal port area, nasalance, and perceptual ratings of nasality for three English corner vowels, /i/, /u/, and /a/.**

Design: **Samples were simulated using a computational model that allowed for exact control of nasal port size and direct measures of nasalance. Perceptual ratings were obtained using a paired stimulus presentation.**

Participants: **Four experienced listeners.**

Main Outcome Measures: **Nasalance and perceptual ratings of nasality.**

Results: **Findings show that perceptual ratings of nasality and nasalance increased for samples generated with nasal port areas up to and including 0.16 cm^2 but plateaued in samples generated with larger nasal port areas. No vowel differences were noted for perceptual ratings.**

Conclusions: **This work extends previously published work by including nasal port areas representative of those reported in the literature for clinical populations. Continued work using samples with varied phonetic context and varying suprasegmental and temporal characteristics are needed.**

KEY WORDS: *nasal port area, nasalance, nasality, velopharyngeal function*

Perceptual rating is considered the gold standard for assessment of oral-nasal resonance. Numerous studies have attempted to show the relation between velopharyngeal orifice size and perceived nasality (e.g., Carney and Morris, 1971; Carney and Sherman, 1971; Dalston et al., 1991; Kummer et al., 2003; Brancamp et al., 2010). These studies have failed to show a clear, linear relation between the measures but indicate that continued research is needed to better understand the relationship and ultimately to guide clinical management. Bunton and Story (2012) reported a set of data generated using a computational model and found a high correlation between ratings of nasality by experienced clinicians and direct measures of nasalance for nasal port areas ranging from 0 to 0.05cm^2. While this study demonstrated the feasibility of computational modeling to understand the perceptual phenomena of nasality, the range of nasal port sizes was not representative of velopharyngeal opening sizes reported in the literature for patient populations (e.g., Laine et al., 1988). The goal of the present study is to extend this work to include larger nasal port area sizes (0.04 to 0.5 cm^2) and to further understanding of the relation between perceptual ratings of nasality, measures of nasalance, and nasal port area. Because the nasal port area sizes explored in this study are clinically representative, findings will provide a basis for future studies exploring how speaker-specific compensatory strategies (e.g., vocal quality and/or vocal tract shape changes) may affect measures of nasalance and ratings of nasality.

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Method

Simulation of Audio Samples

Vowel samples with varying degrees of nasal port coupling were generated with a computational model. Use of a computational model that is representative of the structure and function of the speech production system can be used to produce human-like speech sounds for which all parameters are under experimental control. Details of the modeling specific to the present study can be found in Bunton and Story (2012) and more generally in Story (2013). In brief, three vowels /i/, /u/, and /a/, were simulated with 24 equally incremented values of the nasal port area that ranged from 0.04 cm^2 to 0.5 cm^2. Waveforms were generated for each vowel condition and used as stimuli for the listening experiment. Three audio files containing all stimuli for the three different vowels (Vow[i]series, Vow[u]series, Vow[-

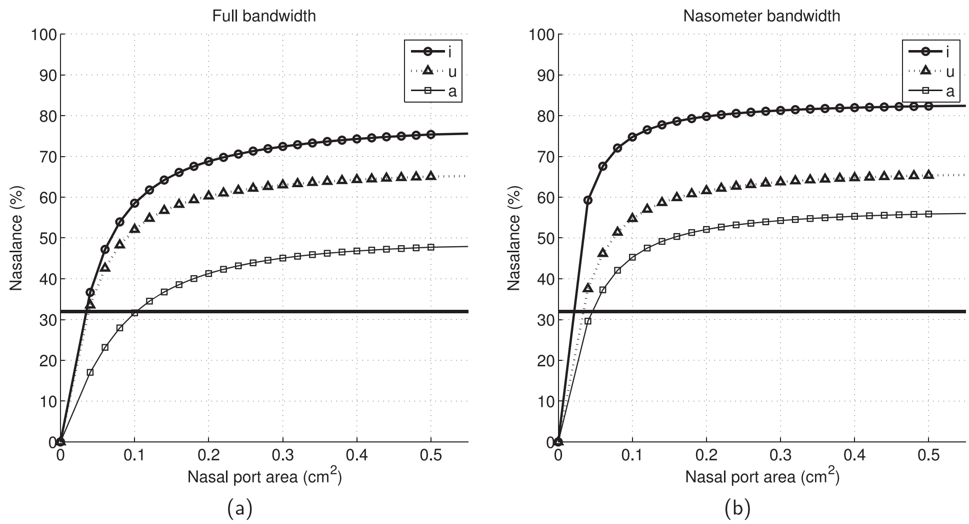

FIGURE 1 Direct measures of nasalance plotted against nasal port area (cm^2) for the full bandwidth (a) and the Nasometer bandwidth (b).

a]series) are available as supplemental online content <link needed for supplemental materials>.

Measures of Nasalance

Nasalance was calculated directly from the radiated pressure signal available at the nares and at the lips for any given simulated vowel according to the equation

$$\text{Nasalance} = 100 \times P_n/(P_o + P_n)$$

where P_n and P_o are the RMS pressures at the nares and lips, respectively. For each vowel, two nasalance values were calculated. First with the raw signals, which are referred to as "full bandwidth," and second with the pressure signals at the nares and lips bandpass filtered (fourth-order Butterworth) with cutoff frequencies of 350 Hz and 650 Hz prior to determining the RMS values of P_n and P_o. The second condition was included to emulate the filtering performed by the commercially available Nasometer system (Fletcher et al., 1989; Kay Pentax, 2012).

Auditory Perceptual Rating of Nasality

The listening panel consisted of four speech-language pathologists with more than 6 years of clinical experience working with individuals with resonance disorders. All listeners were female, native English speakers, and passed a hearing screening. Procedures were identical to those reported by Bunton and Story (2012), in which each listener heard a pair of vowels and was asked to determine which sample they perceived as having greater nasality. Responses were recorded using a horizontally oriented "slider scale," with the slider button positioned at the scale's midpoint (Hillenbrand & Gayert, 1994). The vowel pair included one sample in which the nasal port area was set to zero (i.e., not coupled to the vocal tract) and one in which the nasal tract was coupled to the vocal tract with an area between 0.04 and 0.5 cm^2. Sample order was randomized and balanced for order of presentation; this created a total of 48 pairs per vowel for presentation (24 nasal part area settings × 2 orders). Each pair was presented to listeners four times; thus, each listener rated 576 samples (48 pairs × 3 vowels × 4 repetitions). An overall rating for each stimulus was then derived on the basis of the mean rating across the listeners. Interrater reliability was assessed using the intraclass correlation coefficient (Shrout & Fleiss, 1979) and was 0.95.

Results

Nasalance

Measures of nasalance are presented in Figure 1. In Figure 1a, nasalance calculated across the entire bandwidth is plotted against the nasal port area, whereas in Figure 1b, the nasalance was calculated based on the Nasometer bandwidth (Fletcher et al., 1989). Within each panel, a bolded reference line at 32% nasalance is shown. This is the clinical cutoff value proposed for patients whose speech was perceived with significant hypernasaly (Dalston et al., 1991).

For the full bandwidth, the nasalance values rose steadily as nasal port areas increased from 0.04 cm^2 to 0.2 cm^2. For larger nasal port areas, nasalance values plateaued. The nasalance values based on the Nasometer bandwidth increased until the nasal port area reached 0.18 cm^2 and then plateaued. This general pattern was consistent across vowels, with nasalance values highest for the vowel /i/, followed by /u/ and /a/.

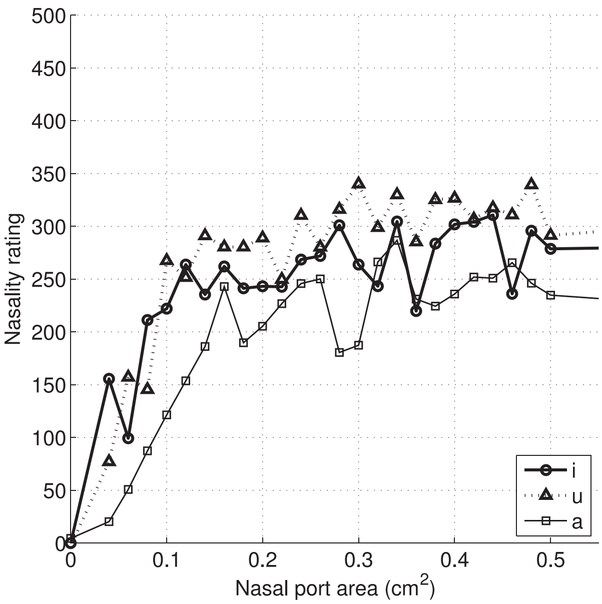

FIGURE 2 Mean nasality ratings across listeners plotted against nasal port area (cm^2). Individual vowels are represented by shape and line type within the figure.

Auditory Perceptual Rating of Nasality

Mean nasality ratings across listeners are plotted in Figure 2 as a function of nasal port area. Samples with larger numbers were judged by the listeners to be more nasal than samples with smaller numbers. Visual inspection of the figures indicates that ratings of nasality increased for all three vowels until the nasal port area reached 0.16 cm^2. Nasality ratings for samples generated with larger nasal port areas had a shallow slope or plateaued. It appears that samples generated with nasal port areas greater than 0.16 cm^2 did not represent an increase in nasality for listeners. This finding is interesting given that listeners did not use the full rating scale to rate nasality. A range of 0 to 500 was allowed in the user interface; however, mean ratings were between 0 and 350.

Individual listener data, shown in Figure 3, shows variability in ratings across listeners. Listener 1 had the greatest variability in nasality ratings across the range of nasal port areas. This listener also consistently rated nasality lower for /i/ compared with the /a/ and /u/. Listeners 2 and 3, those with the most experience (>10 years), showed similar overlap in ratings and vowels. Listener 4 rated the vowel /a/ with consistently lower values than the other two vowels. Interestingly, this listener had the least clinical experience (6 years) and specialized in voice rather than resonance disorders.

Nasalance and Nasality

To examine the relation between measures of nasalance and mean perceptual nasality ratings, correlation coefficients were calculated. Separate coefficients were calculated for the full-bandwidth nasalance scores and the limited bandwidth scores. Correlation coefficients were greater than 0.94 for all vowels and bandwidths.

Discussion

The aim of the current study was to examine the relation of perceptual ratings of nasality, measures of nasalance, and nasal port area using a computational model to precisely control area. The current study extends previously published modeling work by including nasal port areas representative of those reported in the literature for clinical populations (i.e., 0.04 to 0.5cm^2).

Vowel Differences

Nasalance measures were similar for the full bandwidth versus the Nasometer bandwidth. Nasalance was highest for the high front vowel /i/ followed by the high back vowel /u/ and finally the low back vowel /a/. This is consistent with data published by Bunton and Story (2012) for small nasal port area.

Perceptual ratings of nasality showed no vowel differences based on the group data. A difference in vowels was seen for individual listeners; however, it was variable. Two listeners (listeners 2 and 3) rated nasality for the three vowels similarly. Listener 4, on the other hand, rated /i/ and /u/ similarly and /a/ as less nasal. Listener 1 rated /u/ and /a/ similarly and /i/ as less nasal across nasal port area size. Bunton and Story (2012) reported consistently higher ratings for the high vowels /i/ and /u/ compared with the low vowel /a/.

Inconsistency in vowel ratings is noteworthy given previously published data reporting that low vowels are perceived as more nasal than high vowels in normal speakers (Lintz and Sherman, 1961). The vowels simulated in the present study were based on area functions generated from a normal male speaker (Story, 2008) but with precisely controlled oral-nasal coupling. One explanation for the different findings could be that vocal tract shape did not vary as nasal port area increased. A normal speaker would have the flexibility to move the articulators to change the acoustic impedance of the oral cavity relative to the acoustic impedance of the nasal cavity, thus adjusting the degree of nasality in a given production (Fant, 1960).

Nasality Ratings and Nasalance

High correlations were found between auditory-perceptual ratings of nasality and measures of nasalance for data reported in the present study and the study by

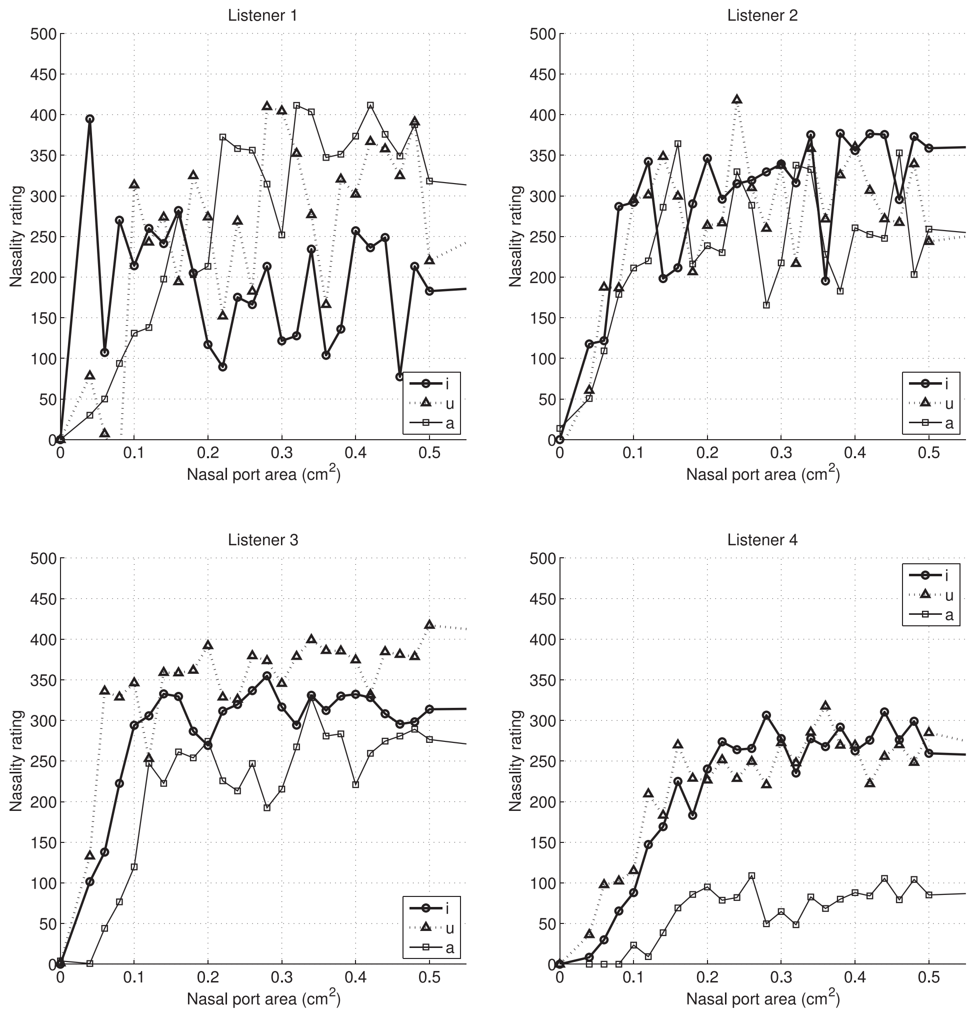

FIGURE 3 Individual listener nasality ratings plotted against nasal port area (cm^2). Individual vowels are represented by shape and line type within the figure.Audio FilesVow[i]series Simulations of the vowel /i/ with nasal port area ranging from 0.04 to 0.5 cm^2. Area increases incrementally in 0.02-cm^2 steps, resulting in 24 samples.Vow[u]series Simulations of the vowel /u/ with nasal port area ranging from 0.04 to 0.5 cm^2. Area increases incrementally in 0.02-cm^2 steps, resulting in 24 samples.Vow[a]series Simulations of the vowel /a/ with nasal port area ranging from 0.04 to 0.5 cm^2. Area increases incrementally in 0.02-cm^2 steps, resulting in 24 samples.

Bunton and Story (2012). These values are higher than the modest correlations ($r = .31$; Watterson et al., 1993) or the moderate correlations ($r = .63$; Brancamp et al., 2010) previously reported. Differences in study design may help explain the findings. One assumption made when correlating perceptual ratings and instrumental measures is that they rely on the same factors. Listener ratings of nasality, however, may include variables such as suprasegmental features such as pitch, rate, and context. Nasalance measures are strictly calculated based on the radiated acoustic energy. In the simulated samples, suprasegmental variables were held constant across the vowel (except f0, which varied by 15 Hz). A higher correlation between the two measures might therefore be predicted. For a real speaker producing a connected speech sample, these variables change over time; therefore, the correlation between measures may not be as high.

Nasal Port Area

If we collectively examine the data set published by Bunton and Story (2012) and the present data set, it appears that listeners were able to detect nasality in sustained vowel samples generated with a nasal port area greater than 0.01 cm^2, and the nasality ratings increased until that area reached 0.16 cm^2. Nasality ratings were relatively flat for samples generated with nasal port areas greater than 0.16 cm^2. These findings are consistent with reports on the clinical category of gross inadequacy and perceived hypernasality defined as a velopharyngeal area greater than 0.2 cm^2. Speakers with velopharyngeal areas ranging from 0.1 to 0.19 cm^2

are clinically classified as borderline/inadequate, and it has been reported that speech is not perceived as hypernasal and that normal aerodynamic patterns are seen for speakers in this category (Warren, 1979). Data from the present study suggest that listeners are able to perceive nasality in vowel samples generated with nasal port openings comparable to this clinical category. It is also interesting that ratings plateaued for samples with nasal port areas greater than 0.16 cm^2. This could represent a saturation point for vowels. Ratings of alternative speech samples, such as connected speech, could explain the difference in findings.

Conclusions and Future Directions

Results of the present study, in conjunction with previously published data (Bunton and Story, 2012), document nasal port areas that correlate with distinct regions of nasality ratings. Nasal port area needs to exceed 0.1 cm^2 for listeners to detect nasality in a sustained vowel sample. Samples generated with nasal port areas greater than 0.16 cm^2 do not appear to result in increased nasality ratings. Continued work in this area, including samples produced with varied articulatory configurations, respiratory effort, suprasegmental characteristics, and changes in oral and nasal impedance will allow for a more complete explanation of the relation between auditory-perceptual ratings of nasality, nasal port area, and the acoustic characteristics of nasalized vowels. This continued work will allow for direct evaluation of the effects of speaker-specific compensatory adjustments on ratings of nasality and may help guide treatment techniques.

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