Comparison of Nasal Acceleration and Nasalance Across Vowels

Elias B. Thorp, Boris T. Virnik, and Cara E. Stepp

J Speech Lang Hear Res 2013;56;1476-1484; originally published online Jul 9, 2013;

DOI: 10.1044/1092-4388(2013/12-0239)

This information is current as of October 22, 2013

This article, along with updated information and services, is
located on the World Wide Web at:
http://jslhr.asha.org/cgi/content/full/56/5/1476

American
Speech-Language-
Hearing
Association

JSLHR

Article

Comparison of Nasal Acceleration and Nasalance Across Vowels

Elias B. Thorp,[a] Boris T. Virnik,[a] and Cara E. Stepp[a]

Purpose: The purpose of this study was to determine the performance of normalized nasal acceleration (NNA) relative to nasalance as estimates of nasalized versus nonnasalized vowel and sentence productions.
Method: Participants were 18 healthy speakers of American English. NNA was measured using a custom sensor, and nasalance was measured using the KayPentax Nasometer II. Speech stimuli consisted of CVC syllables with the vowels (/ɑ/, /æ/, /i/, /u/) and sentences loaded with high front, high back, low front, and low back vowels in both nasal and nonnasal contexts.
Results: NNA showed a small but significant effect of the vowel produced during syllable stimuli but no significant effect of vowel loading during sentence stimuli. Nasalance was significantly affected by the vowel being produced during both syllables and sentences with large effect sizes. Both NNA and nasalance were highly sensitive and specific to nasalization.
Conclusions: NNA was less affected by vowel than nasalance. Discrimination of nasal versus nonnasal stimuli using NNA and nasalance was comparable, suggesting potential for use of NNA for biofeedback applications. Future work to improve calibration of NNA is needed to lower intersubject variability.

Key Words: velopharyngeal dysfunction, nasalance, nasalization, resonance disorders, acoustics

The *velopharyngeal (VP) port* is the opening between the pharynx and the nasal cavity, which speakers typically close during the production of most English phonemes through elevation of the velum and contraction of the posterior and lateral pharyngeal walls to close off the nasopharynx. Conversely, nasal phonemes (/m/, /n/, and /ŋ/ in English) and nearby vowels are typically produced with some degree of nasal coupling through opening of the VP port. Although this simplistic view is generally accurate, nasal coupling is nonzero for nonnasal productions, even in healthy adults (Gildersleeve-Neumann & Dalston, 2001), and the degree and timing of nasal coupling in healthy adults has been shown to vary as a function of dialect (Seaver, Dalston, Leeper, & Adams, 1991) and vowel context (Awan, Omlor, & Watts, 2011; Gildersleeve-Neumann & Dalston, 2001; Ha & Kuehn, 2006; Jennings & Kuehn, 2008; Kuehn & Moon, 1998; Kummer, 2005; Lewis, Watterson, & Quint, 2000).

Nasalance is the ratio of nasal to nasal-plus-oral acoustic energy and has been used to estimate the degree of nasal coupling in speech (Fletcher & Frost, 1974). The Nasometer II (KayPentax) is a popular commercially available system for measuring nasalance. It consists of a headset with directional microphones in front of the nose and mouth, separated by a large baffle pressed against the upper lip. Nasalance has been shown to be highly dependent on the vowel produced, reflecting the changes in oral–nasal transmissions as a function of vowel in typical speech (Awan et al., 2011; Gildersleeve-Neumann & Dalston, 2001; Jennings & Kuehn, 2008; Kummer, 2005; Lewis et al., 2000). In addition, children with VP disorders have been shown to produce significantly higher nasalance values for the high front vowel /i/ than for all other vowels (Lewis et al., 2000). Similarly, sentences loaded with high front vowels also showed significantly higher nasalance values compared with sentences loaded with high back, low front, low back, and mixed vowels (Awan et al., 2011). Increased nasalance during the production of high front vowels has been hypothesized to be due to energy transfer across the palatal structures, resulting in nasal acoustic transmissions. These transpalatal transmissions are believed to be caused by high impedance to sound transmission in the oral cavity and large palatal surface area exposed to the acoustic energy and are greatest during the production of the high front vowel /i/ compared with the vowels /ɑ/ and /u/ (Bundy & Zajac, 2006; Gildersleeve-Neumann & Dalston, 2001). Physiological differences are also seen as a function of vowel context. Healthy adults produce isolated

---

[a] Boston University

Correspondence to Cara E. Stepp: cstepp@bu.edu

Elias B. Thorp is now at Northwestern University, Evanston, IL.

Editor: Jody Kreiman
Associate Editor: Kate Bunton

Received July 30, 2012
Revision received September 27, 2012
Accepted January 18, 2013
DOI: 10.1044/1092-4388(2013/12-0239)

(nonnasal) high vowels with greater VP closure force than that used for low vowels. In addition, kinematic data show that nasalization of the vowel /i/ results in higher tongue positions; no articulation effects were seen as a result of nasalization of the vowel /ɑ/. The perceptual sequelae of these acoustic and physiological variations as a function of vowel context are not entirely clear.

Expert perceptual judgments are currently the clinical gold standard for determining the clinical significance of nasal resonance during speech. However, perceptual judgments have limitations even when provided by expert listeners. For example, there is disagreement about the optimal methods for perceptual judgments of nasality. Specifically, although nasality of speech is often rated using an equal appearing interval (EAI) rating scale (Dalston, Warren, & Dalston, 1991; Hardin, Van Demark, Morris, & Payne, 1992; Watterson, Lewis, & Deutsch, 1998), some have argued that an EAI is not a valid rating scale for nasality and recommend using the direct magnitude estimation (DME) method (Whitehill, Lee, & Chun, 2002; Zraick & Liss, 2000). More recently, Brancamp and colleagues have argued that there is no advantage to using the DME method (Brancamp, Lewis, & Watterson, 2010). Regardless, the best perceptual judgments require multiple listeners and careful methodologies that can be difficult to use in clinical environments. Previous perceptual studies of the effects of vowel context on nasality are somewhat inconclusive. All used a 7-point EAI scale in larger samples of listeners (11–63). The fundamental work of Lintz and Sherman (1961) found that low vowels (/ɑ/ and /æ/) produced by healthy speakers were consistently rated as more nasal than other vowels. This finding was later confirmed in hypernasal speakers (without a cleft palate), with listeners identifying /ɑ/ as having higher nasality than /i/, /ɛ/, u/, or /ʌ/ (Carney & Sherman, 1971). However, work by Counihan and Cullinan (1972) explored the effects of vowel on nasality ratings of the speech of healthy speakers using varied intensity levels and found no systematic effects as a function of vowel. Rather, differences as a function of vowel were strongly affected by the playback loudness level presented to listeners (Counihan & Cullinan, 1972). Finally, listeners rating consonant–vowel tokens with varying oral–nasal continua (ranging from /d/ to /n/) produced using an articulatory synthesizer required increased VP coupling to perceive the nasal consonant /n/ rather than /d/ when the vowel used was /a/, compared with when the vowel used was /i/ (Abramson, Nye, Henderson, & Marshall, 1981). This suggests that, for a similar level of VP coupling, /ɑ/ would be perceived as less nasal than /i/. In summary, current knowledge about the effects of vowel on listener perception of nasality is inconclusive, contrary to the consistent effects of vowel on nasalance.

The lack of correspondence in the effect of vowel on nasalance measurements versus listener perception of nasality could be related to technical aspects of the signal processing in making the nasalance measurement. For instance, different nasalance measurement systems such as the Nasometer II and the NasalView (Awan, 1998) have been shown to provide significantly different values for the same stimuli (Awan et al., 2011). Aside from slight hardware differences, the Nasometer and NasalView differ in filtering cutoffs and filter bandwidths applied to the raw acoustic signals. The Nasometer II utilizes a bandpass filter 300 Hz wide and centered at 500 Hz. The NasalView, however, does not filter input data and uses the full spectrum up to half the sampling rate. Thus, although current systems utilize filtering schemes that do not cause differences as a function of vowel, the filtering applied to either the nasal or the total acoustic signal could have a drastic effect on measured nasalance (Lewis & Watterson, 2003). Perhaps more interesting is that filtering of nasalance data could affect the correspondence between the effects of vowel on nasalance versus the effects of vowel on listener perception of nasality.

Although less utilized than nasalance, the acceleration measured from the nose surface has also been suggested as a correlate of nasalization (Horii, 1983; Laczi, Sussman, Stathopoulos, & Huber, 2005; Mra, Sussman, & Fenwick, 1998; Redenbaugh & Reich, 1985; Stevens, Kalikow, & Willemain, 1975), with many studies specifically using the mean ratio of nasal acceleration to acoustic output in decibels (Horii, 1983). By normalizing nasal vibrations (sensed with a wide-band accelerometer on the nose surface) by the total acoustic output (both nasal and oral as measured with a single microphone), variance within speakers due to changes in voice intensity can be reduced. In children, this ratio shows a difference of roughly 13 dB between nasalized and nonnasalized sentence productions (Mra et al., 1998). As proposed by Stevens et al. (1975), the use of nasal acceleration offers a variety of advantages, including low weight, ruggedness, and low power consumption. We have previously shown that applying filtering to nasal acceleration and total acoustic output can drastically increase the sensitivity and specificity of this ratio to vowel nasalization (Thorp, Virnik, & Stepp, 2012), compared with the simple ratio that has been previously explored (Horii, 1983; Laczi et al., 2005; Mra et al., 1998; Redenbaugh & Reich, 1985; Stevens et al., 1975). The resultant *normalized nasal acceleration* (NNA) is an estimate of nasalization that is optimally filtered to reduce the effects of vowel loading on the resultant signal.

The purpose of this study was to compare the discrimination of nasal and nonnasal speech using NNA relative to nasalance. In particular, we were interested in the effects of vowel (in syllables) and vowel loading (in sentences) on NNA and nasalance. In this study, healthy adults were asked to produce syllable pairs that contained a vowel in either a nasal (i.e., between two nasal consonants) or a nonnasal (i.e., between two nonnasal consonants) context (e.g., "mom" vs. "bob") and sentences loaded with either nasal or nonnasal consonants. For the purpose of this study, we assumed that the vowels produced in a nasal context were nasalized (produced with an open VP port) and that vowels produced in a nonnasal context were not nasalized (produced with a closed VP port). We hypothesized that both NNA and nasalance would show high discrimination of nasal versus nonnasal productions, with clear differences as a function of the nasal/nonnasal context. We further hypothesized that the effects of vowel and vowel loading would be reduced for NNA relative to nasalance.

Method

Participants

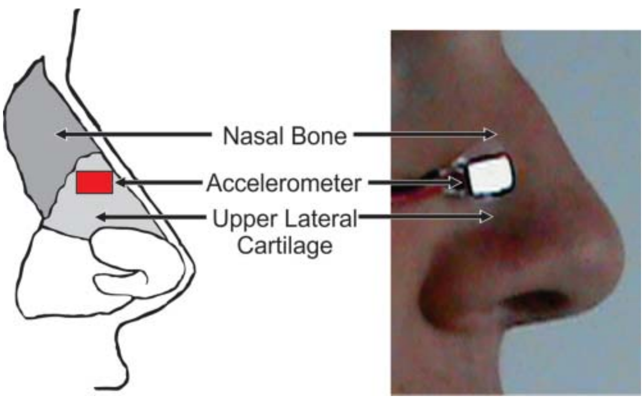
Participants were 18 healthy adults (nine female, nine male) who reported no history of speech, language, or hearing disorders. All participants were primary speakers of American English and were an average age of 22.5 years (*SD* = 2.5 years). A certified speech-language-pathologist (M. Braden; see Acknowledgments) reviewed all recorded speech samples and perceptually judged that no participants had any hyper- or hyponasality. Participants were tested during a single 30-min trial and were compensated $5 for their participation. All participants completed written consent in compliance with the Boston University Institutional Review Board.

Signals Collected

Nasalance data were recorded using the Nasometer II Model 6450 (KayPentax, Montvale, NJ). These data were collected using standard Nasometer II hardware and software with a sampling frequency of 11025 Hz. Before each testing session, the nasometer was calibrated using the KayPentax Nasometer II software.

NNA was recorded using a custom sensor that simultaneously measured nasal acceleration and acoustics. The nasal acceleration was measured using a BU Series 21771 accelerometer (Knowles Electronics, Itasca, IL), which was attached to the participant's nose using medical-grade double-sided tape. The accelerometer was placed inferior to the anteriormost point of the participant's right nasal bone over the upper lateral cartilage (see Figure 1; Lippmann, 1981). Nasal acceleration was normalized by the total acoustic output as measured by a standard headset microphone (Sennheiser PC131), which was placed approximately 8 cm from the mouth at a 45° angle from the midline. Both nasal acceleration and total acoustic output were sampled at 44100 Hz.

Figure 1. The left panel shows a diagram of accelerometer placement. Accelerometer (red) was placed on the skin directly inferior to the nasal bone (dark gray) on the upper lateral cartilage (light gray). The right panel shows the accelerometer placement on a typical healthy adult.



Testing Procedure

Participants produced a set of syllable and sentence stimuli two separate times: once using the Nasometer and once using the nose-placed accelerometer and headset microphone. The order of testing was randomized. The set of stimuli consisted of 16 syllable pairs, where eight contained only nasal consonants and eight contained only nonnasal consonants matched by place of articulation and vowel (see Table 1), as well as eight sentences (see Table 2). Four of the sentences contained only nonnasal consonants (Lewis & Watterson, 2003; Lewis et al., 2000), whereas the other four sentences contained many nasal consonants. Sentences were loaded with high front, high back, low front, or low back vowels (the full set of sentences can be seen in Table 2). Participants were instructed to read each syllable pair three times and each sentence once in a comfortable, clear speaking voice at their typical speaking rate.

Analysis

For syllable stimuli, analysis was performed only on the vowel. For nasalance data, the first author extracted vowels manually by using the KayPentax software provided with the Nasometer II. For NNA data, he manually extracted vowels using Praat. When processing sentence data, all speech production was included in the analysis, but pause time was removed. Since pause removal is a built-in function of the Nasometer II software, no additional processing was required. For NNA, an algorithm was developed and implemented in MATLAB to remove pause time. The root-mean-square (RMS) of the acoustic signal was calculated over a 250-ms window with 200-ms overlap. A threshold was set at 50% above the RMS of the acoustic signal during silence before speech, and windows for which the microphone level was below this threshold were removed prior to analysis.

Nasal acceleration and total acoustic output were digitally filtered offline in MATLAB using second-order Butterworth bandpass filters. Nasal acceleration was

Table 1. Syllable pair stimuli.

	Vowel and place							
	/ɑ/		**/æ/**		**/i/**		**/u/**	
Stimulus	**L**	**A**	**L**	**A**	**L**	**A**	**L**	**A**
Nasal	mɑm	nɑn	mæm	næn	mim	nin	mum	nun
Nonnasal	bɑb	dɑd	bæb	dæd	bib	did	bub	dud

Note. L = labial; A = alveolar.

Table 2. Sentence stimuli.

Vowel loading	Nasal	Nonnasal
High front	*Tim seems mean to Nick.*	*Bill sees the sleepy kid.*
High back	*Zoom to the new home soon.*	*Sue took the old blue shoes.*
Low front	*Ben scans the man's next plan.*	*Bess has dad's red cap.*
Low back	*Mark's blond mom yawns more.*	*Father got all four cards.*

bandpass filtered between 400 and 1000 Hz, and total acoustic output was bandpass filtered between 25 and 420 Hz. The lower bound of the nasal acceleration filter and the higher bound of the acoustic filter were determined by maximizing the average increase in effect size between nasal and nonnasal syllables when measuring NNA compared with nasalance for all participants. After filtering, the nasal acceleration was normalized (see Equation 1) by the total acoustic output to account for changes in vocal effort and overall loudness between words for an individual speaker (acceleration-to-acoustic ratio).

$$\begin{matrix}\text{Acceleration-to-}\\ \text{acoustic ratio}\end{matrix} = \frac{\text{RMS (filtered nasal acceleration)}}{\text{RMS (filtered acoustic output)}} \qquad (1)$$

This quantity was then normalized over the acceleration-to-acoustic ratio during a highly nasal production in order to reduce interspeaker variability due to differences in speaker anatomy. The acceleration-to-acoustic ratio was calculated over the production of an /m/ at a normal speaking volume. The sample used for this normalization (see Equation 2) was taken from the first /m/ in each participant's first production of the word *mom*. All statistical analyses were performed using this final value, the NNA.

$$\text{NNA} = \frac{\text{Acceleration-to-acoustic ratio}}{\text{Acceleration-to-acoustic ratio during } /\text{m}/} \qquad (2)$$

Statistical analyses were performed using Minitab Statistical Software (Minitab, State College, PA). A three-factor, repeated measures analysis of variance (ANOVA) was performed on the nasalance and NNA syllable vowel data to assess the effects of vowel (/ɑ/, /æ/, /i/, /u/), nasalization (nasalized or nonnasalized), place of articulation (labial or alveolar), and the Vowel × Nasalization interaction. Place of articulation was not a factor of interest in this study but was included in the analyses in order to fully characterize the speech stimuli used. A two-factor repeated measures ANOVA was performed on the nasalance and NNA sentence data to assess the effects of vowel loading (high front, high back, low front, low back), nasalization (nasalized or nonnasalized), and the Vowel Loading × Nasalization interaction. Post hoc Tukey's honestly significant difference (HSD) tests were applied to examine differences across vowels. All statistical analyses were performed using an alpha level of .05 for significance. Factor effects were quantified using the squared partial curvilinear correlation (η_p^2) as an estimate of factor effect size, which reflects the proportion of variance explained by each factor (Witte & Witte, 2010) in a repeated measures ANOVA.

Effect sizes (measured using Cohen's *d*) were calculated for both vowels and sentences as the difference between the mean measure for the nasalized productions and the mean measure for the nonnasalized productions, divided by the combined standard deviation of the two populations (Witte & Witte, 2010). A high effect size demonstrates a strong separation between the means as well as low variability within each population. Effect sizes were calculated for each individual participant using syllable vowel and sentence data.

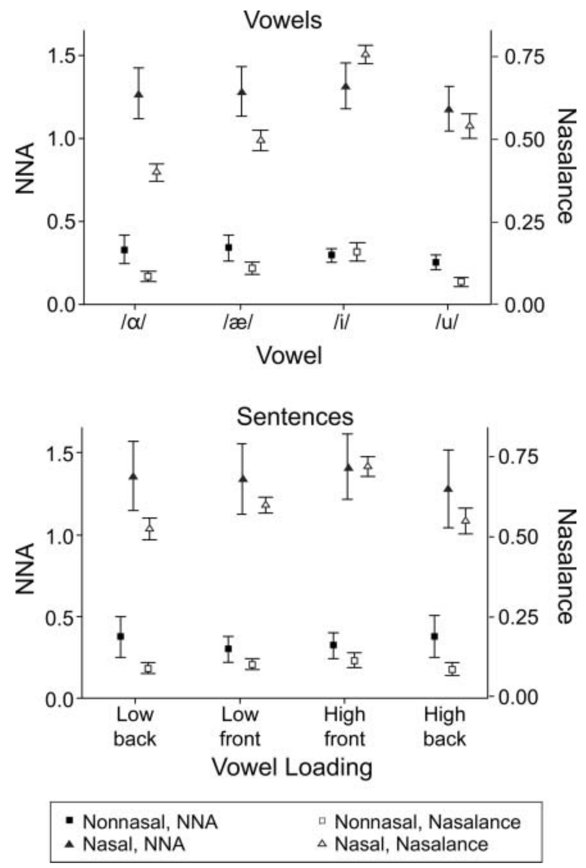
Finally, measures of sensitivity and specificity and associated parameters were determined for both nasalance and NNA to determine how accurately the measures could classify nasalized and nonnasalized productions. *Sensitivity* is defined as the ratio of true positives to the sum of true positives and false negatives, and it is the probability of a nasalized measurement given that the production was nasalized. *Specificity* is defined as the ratio of true negatives to the sum of true negatives and false positives, and it is the probability of a nonnasalized measurement given that the production was nonnasalized. The relationship between sensitivity and specificity is shown graphically by plotting the sensitivity against 1 – specificity at all potential nasalization thresholds (performed with a resolution of .000001) to produce a receiver operating characteristic (ROC) curve. The ROC curve demonstrates the discrimination performance of NNA and nasalance. Based on the ROC, the area under the curve (AUC) was determined using numerical integration (trapezoidal rule), and maximum positive likelihood ratios (LR+) were calculated as the maximum sensitivity/(1 – specificity).

Results

ANOVA Results for Syllable Pairs

The upper panel of Figure 2 shows mean values of nasalance and NNA during vowels as a function of syllable features of vowel and nasalization. A repeated measures three-factor ANOVA on NNA values (see Table 3) showed statistically significant effects of both vowel ($p = .035$) and nasalization ($p < .001$). No significant effects were found for place of articulation or the interaction of vowel and nasalization ($p > .05$). Although significant, the effect size for vowel was small ($\eta_p^2 = .03$), whereas the effect size for nasalization ($\eta_p^2 = .84$) was large (Witte & Witte, 2010). The

Figure 2. Mean normalized nasal acceleration (NNA) and nasalance values as a function of nasalization and either vowel (upper panel) or vowel loading (lower panel). Filled markers indicate NNA data. Unfilled markers indicate nasalance data. Triangles indicate nasal productions, and squares indicate nonnasalized productions. Error bars indicate 95% confidence intervals.



mean NNA was .63 (*SD* = .20) for all nasalized vowels and .15 (*SD* = .08) for nonnasalized vowels. Although the ANOVA showed a significant effect for vowel, application of post hoc Tukey's HSD tests did not show significant ($p > .05$) differences in NNA between any of the four vowels. A repeated measures three-factor ANOVA on nasalance values (Table 4) showed statistically significant effects of all factors: vowel ($p < .001$), nasalization ($p < .001$), place of articulation ($p < .001$), and the interaction between vowel and nasalization ($p < .001$). The effect size for place of articulation was small to moderate ($\eta_p^2 = .05$), whereas the effect sizes for all other factors were large ($\eta_p^2 = .49$–$.95$). The mean nasalance was .55 (*SD* = .16) for nasalized vowels and .10 (*SD* = .07) for nonnasalized vowels. Post hoc Tukey's HSD tests were applied to compare nasalance values across vowel and showed significantly reduced ($p < .05$) nasalance during production of /ɑ/ relative to all other vowels, during production of /æ/ relative to /i/, and during production of /u/ relative to /i/.

Table 3. Repeated measures analysis of variance (ANOVA) for NNA syllable pairs.

Source	*df*	η_p^2	*F*	p
Vowel	3	.03	2.9	.035
Nasalization	1	.84	1,363.0	<.001
Place	1	<.01	0.4	.549
Vowel × Nasalization	3	.01	0.7	.538

Table 4. Repeated measures ANOVA for nasalance syllable pairs.

Source	*df*	η_p^2	*F*	p
Vowel	3	.69	194.9	<.001
Nasalization	1	.95	4,546.0	<.001
Place	1	.05	14.2	<.001
Vowel × Nasalization	3	.49	85.0	<.001

ANOVA Results for Sentences

The lower panel of Figure 2 shows mean values of nasalance and NNA during production of sentences as a function of vowel loading and nasalization. A repeated-measures, two-factor ANOVA on NNA values (see Table 5) showed a statistically significant effect of nasalization ($p < .001$), but no significant effects were found for vowel loading or the interaction between vowel loading and nasalization ($p > .05$). The effect size for nasalization was large ($\eta_p^2 = .90$). The mean NNA was .72 (*SD* = .24) for nasalized sentences and .17 (*SD* = .10) for nonnasalized sentences. A repeated-measures, two-factor ANOVA on nasalance values (see Table 6) showed statistically significant ($p < .001$) effects of vowel loading, nasalization, and the interaction between vowel loading and nasalization. The effect sizes were all large ($\eta_p^2 = .53$–$.99$). The mean nasalance was .60 (*SD* = .10) for nasalized sentences and .10 (*SD* = .04) for nonnasalized sentences. Post hoc Tukey's HSD tests showed significantly ($p < .05$) increased nasalance during production of the high front vowel loaded sentences relative to all other sentences and during production of the low front vowel loaded sentences relative to high back and low back vowel loaded sentences.

Effect Sizes

Effect sizes between nasalized and nonnasalized syllable vowel and sentence productions are shown in Figure 3. The mean effect size for vowels was 15.4 (*SD* = 8.7) for NNA and 8.2 (*SD* = 2.0) for nasalance. Of the 18 participants, 15 showed higher vowel effect sizes using NNA than using

Table 5. Repeated measures ANOVA for NNA sentences.

Source	*df*	η_p^2	*F*	p
Vowel loading	3	.01	0.6	.614
Nasalization	1	.90	1,046.2	<.001
Vowel Loading × Nasalization	3	.04	1.8	.159

Table 6. Repeated measures ANOVA for nasalance sentences.

Source	*df*	η_p^2	*F*	p
Vowel loading	3	.66	78.0	<.001
Nasalization	1	.99	8,060.8	<.001
Vowel Loading × Nasalization	3	.53	44.3	<.001

nasalance. The mean effect size for sentences was 16.4 (*SD* = 8.2) for NNA and 11.2 (*SD* = 2.8) for nasalance. Twelve of the 18 participants showed higher effect sizes using NNA compared with nasalance. Whether computed using NNA or nasalance, for both syllable vowel and sentence data, all effect sizes were "very large" (Witte & Witte, 2010).

ROC Analysis

The ROC curve for syllable vowel data is shown in Figure 4. The ROC analysis shows high sensitivity and specificity for both nasalance and NNA. Both show excellent discrimination, reaching close to perfect detection (upper left corner). The AUC was .998 for nasalance and .991 for NNA. The higher the LR+, the greater the probability that a nasalized score is associated with an actual nasalized production, with values ≥10 representing a strong result (Dollaghan, 2007). Results from this study showed very strong discrimination for both nasalance and NNA. The maximum LR+ for nasalance was 135 (occurring with sensitivity = .94 and specificity = .99). The maximum LR+ for NNA was 103 (occurring with sensitivity = .72 and specificity = .99).

Figure 3. Effect sizes (Cohen's *d*s) between nasalized and nonnasalized vowel (left panel) and sentence (right panel) productions using nasalance and NNA for each of the 18 participants. High effect sizes indicate a strong separation between nasal and nonnasal productions as well as low variability within each group.

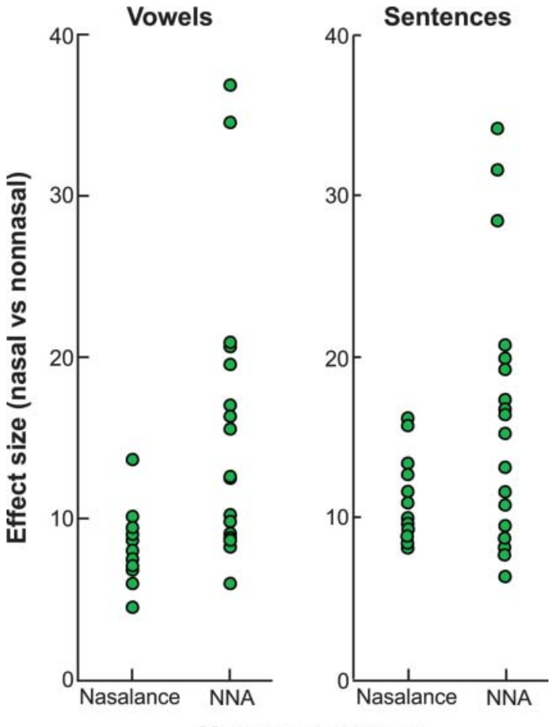
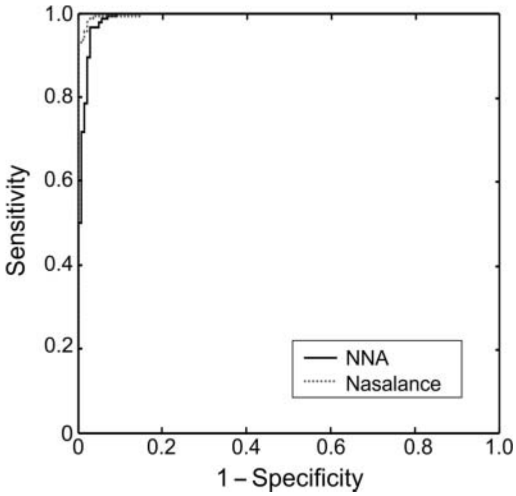


Figure 4. Receiver operating characteristic (ROC) curves for discrimination ability of NNA (solid dark line) and nasalance (dotted gray line).



Discussion

Our goal in this study was to characterize the ability of NNA to discriminate nasal from nonnasal productions and to compare this ability with nasalance. We hypothesized that NNA would be as sensitive and specific to vowels in a nasal context as nasalance and that the effects of vowel loading would be less pronounced using NNA compared with using nasalance. In fact, NNA was somewhat less sensitive and specific to vowels in a nasal context, although generally comparable with nasalance (both showed very strong discrimination). Vowel loading showed a marked effect on nasalance values but a less substantial effect on NNA. Effect sizes between nasalized and nonnasalized productions were larger when using NNA than when using nasalance for most participants.

Effects of Vowel and Nasalization on NNA and Nasalance

When analyzing the syllable vowel data, there was a significant effect of vowel on both NNA and nasalance. Although both nasalization estimates showed significant effects of vowel, the effect size using NNA was small (η_p^2 = .03), whereas the effect size using nasalance was quite large (η_p^2 = .69). Thus, for syllable vowel data, it appears that the use of NNA may reduce the effect of which vowel is being produced but does not remove this effect. Figure 2 highlights these findings. NNA values appear relatively stable across vowels; this qualitative observation is supported by the lack of significant post hoc findings. In contrast, nasalance values were strongly affected by vowel, with /i/ showing the highest nasalance values in post hoc testing.

For sentences, vowel loading had a significant effect on nasalance with a large effect size ($\eta_p^2 = .66$). No significant effect of vowel loading was found for NNA. These results parallel those for vowels (see Figure 2) in that NNA is relatively stable across changes in vowel loading, but nasalance is strongly affected, with sentences loaded with high front vowels (like /i/) showing higher nasalance values than the other sentences. It should be noted that the absence of vowel effects in NNA could be a result of higher intersubject variability in NNA data compared with nasalance data rather than a true resistance to vowel loading effects. Our results with nonnasalized sentences compare reasonably well with those of previous work using the Nasometer II, which found values ranging from .09 to .12 (Awan et al., 2011). Our data follow a similar pattern in the range of .09–.11.

Comparison of Nasalance and NNA Using Cohen's d *and ROC Analysis*

Figure 3 shows effect sizes (Cohen's *d*s) for each participant. For both vowel and sentence data, all *d*s for both NNA and nasalance were very large, which indicates that both measures provide excellent discrimination of vowel nasalization. The *d*s between nasalized and nonnasalized vowel productions were larger using NNA than nasalance for 15 of the 18 participants, likely due to the reduced effects of vowel loading. The average increase in vowel effect size using NNA relative to nasalance was 7.1. Sentence data mirror these results, with an average increase in effect size using NNA relative to nasalance of 5.3. Effect sizes were generally variable (see Figure 3), with *d*s ranging from 4.5 to 36.9.

Likewise, both nasalance and NNA were shown to be highly sensitive and specific to vowels in a nasal context (see Figure 4). Both measures had AUCs ≥ .99, which is indicative of very high diagnostic accuracy. In addition, both showed maximum LR+ values over 100, with "strong" values defined as ≥10. Maximum LR+ were slightly lower for NNA relative to nasalance (103 vs. 135), suggesting that NNA was slightly less sensitive and specific to vowels in a nasal context, although comparable with nasalance.

Although these results imply that NNA is highly sensitive and specific, with comparable performance to nasalization, these results should be interpreted with caution. Since NNA and nasalance cannot be measured simultaneously (because of the baffle of the Nasometer II, the total acoustic signal cannot be measured properly while it is being worn), NNA and nasalance measurements were performed on different sets of speech production. These comparisons between NNA and nasalance are based on the premise that the healthy participants produced speech similarly during the two trials. Trials lasted roughly 10 min each and were performed consecutively to minimize any changes in participants' speech production over time.

Applications, Limitations, and Future Directions

This potential clinical application of NNA is somewhat hindered by its degree of intersubject variability. Although the effects of vowel and place of articulation on NNA are small, as shown in Figure 2, standard deviations for both nasalized and nonnasalized productions are higher than those found for nasalance, likely due to between-speaker variance. One potential source of this variance is the normalization procedure used. Data of each speaker were normalized with respect to the /m/ in their first production of *mom* in the syllable set. Although use of this calibration may reduce interspeaker variation that results from differences in nasal anatomy, skin thickness, and sensor placement, differences in the style and loudness of this /m/ could contribute to intersubject variability. Indeed, many values of NNA were above 1 (see Figure 2), indicating that, as implemented, the measure is not bounded 0–1. Whereas Horii (1983) advocated the use of a sustained /m/ for normalization, our experience in healthy young adults has been that the use of an isolated nasal production results in increased variation across speakers, as speakers tend to produce the sound in very different ways and levels of effort. Future work to examine the reliability associated with a broad set of potential normalization procedures is needed to improve the clinical usefulness of NNA. Additionally, nasalance has been shown to provide information about vowel-specific effects on the time course of nasalization (Bae, Kuehn, & Ha, 2007). Future work is necessary to investigate the ability of NNA to provide temporal characterization of nasalization.

Most importantly, NNA must be studied in pediatric populations with velopharyngeal dysfunction and compared with perceptual measures. Specifically, NNA should be extended to a pediatric population to confirm the results of the present study, since nasalance values are known to differ between healthy adult and pediatric populations (Van Lierde, Wuyts, De Bodt, & Van Cauwenberge, 2003). In addition, although the filtering techniques used for this measure do reduce variation as a function of vowel loading, it is still unknown what effects the filtering may have on the relationship between NNA and listener ratings of nasality. Many studies have compared nasalance to listeners' perception of nasality and have calculated correlation coefficients (*r*s) ranging from .29 to .82 (Dalston et al., 1991; Lewis, Watterson, & Houghton, 2003; Watterson, Hinton, & McFarlane, 1996; Watterson et al., 1998; Watterson, McFarlane, & Wright, 1993). These studies used varying speech stimuli, varying rating scales, and listeners with varying levels of experience, which could account for the drastic differences in correlations. Similarly, past studies have shown varying correlations between the ratio of nasal acceleration to acoustic output and listener ratings of nasality (Horii, 1983; Laczi et al., 2005). Finally, perception of nasality can be modified through manipulation of the tongue position or mouth opening in addition to VP closure (Rong & Kuehn, 2012). Thus, although filtering of the acoustic and accelerometric data before computing this ratio has improved the sensitivity and specificity of the measure to nasalization (Thorp et al., 2012), more work is needed to determine the effect of this filtering on the relationship between perceived nasality and NNA.

Conclusions

Effects of vowel loading were reduced for NNA relative to nasalance, which showed large effects of vowel. Both NNA and nasalance showed high effect sizes (Cohen's *d*s) for discriminating between nasalized and nonnasalized productions; however, for 15 of the 18 participants, effect sizes between nasalized and nonnasalized vowel productions were larger for NNA than for nasalance. Both NNA and nasalance were highly sensitive and specific to vowels in a nasal context. More research is necessary to provide improved normalization procedures for this measure and to extend these results to a pediatric population.

Acknowledgments

We thank Maia Braden, MS, CCC-SLP, of the University of Wisconsin for her help in auditory–perceptual screening of participants and Emma Billard of Boston University for her helpful comments.

References

Abramson, A. S., Nye, P. W., Henderson, J. B., & Marshall, C. W. (1981). Vowel height and the perception of consonant nasality. *The Journal of the Acoustical Society of America, 70,* 329–339.

Awan, S. N. (1998). Analysis of nasalance: NasalView (the Nasalance Acquisition System). In W. Ziegler & K. Deger (Eds.), *Clinical phonetics and linguistics* (pp. 518–527). London, England: Whurr Publishers.

Awan, S. N., Omlor, K., & Watts, C. R. (2011). Effects of computer system and vowel loading on measures of nasalance. *Journal of Speech, Language, and Hearing Research, 54,* 1284–1294.

Bae, Y., Kuehn, D. P., & Ha, S. (2007). Validity of the nasometer measuring the temporal characteristics of nasalization. *Cleft Palate–Craniofacial Journal, 44,* 506–517.

Brancamp, T. U., Lewis, K. E., & Watterson, T. (2010). The relationship between nasalance scores and nasality ratings obtained with equal appearing interval and direct magnitude estimation scaling methods. *Cleft Palate–Craniofacial Journal, 47,* 631–637.

Bundy, E. L., & Zajac, D. J. (2006). Estimation of transpalatal nasalance during production of voiced stop consonants by noncleft speakers using an oral-nasal mask. *Cleft Palate–Craniofacial Journal, 43,* 691–701.

Carney, P. J., & Sherman, D. (1971). Severity of nasality in three selected speech tasks. *Journal of Speech and Hearing Research, 14,* 396–407.

Counihan, D. T., & Cullinan, W. L. (1972). Some relationships between vocal intensity and rated nasality. *The Cleft Palate Journal, 9,* 101–108.

Dalston, R. M., Warren, D. W., & Dalston, E. T. (1991). Use of nasometry as a diagnostic tool for identifying patients with velopharyngeal impairment. *Cleft Palate–Craniofacial Journal, 28,* 184–189.

Dollaghan, C. A. (2007). *The handbook for evidence-based practice in communications disorders*. Baltimore, MD: Paul H. Brookes.

Fletcher, S. G., & Frost, S. D. (1974). Quantitative and graphic analysis of prosthetic treatment for "nasalance" in speech. *Journal of Prosthetic Dentistry, 32,* 284–291.

Gildersleeve-Neumann, C. E., & Dalston, R. M. (2001). Nasalance scores in noncleft individuals: Why not zero? *Cleft Palate–Craniofacial Journal, 38,* 106–111.

Ha, S., & Kuehn, D. (2006). Temporal characteristics of nasalization in children and adult speakers of American English and Korean during production of three vowel contexts. *The Journal of the Acoustical Society of America, 120,* 1622–1630.

Hardin, M. A., Van Demark, D. R., Morris, H. L., & Payne, M. M. (1992). Correspondence between nasalance scores and listener judgments of hypernasality and hyponasality. *Cleft Palate–Craniofacial Journal, 29,* 346–351.

Horii, Y. (1983). An accelerometric measure as a physical correlate of perceived hypernasality in speech. *Journal of Speech and Hearing Research, 26,* 476–480.

Jennings, J. J., & Kuehn, D. P. (2008). The effects of frequency range, vowel, dynamic loudness level, and gender on nasalance in amateur and classically trained singers. *Journal of Voice, 22,* 75–89.

Kuehn, D. P., & Moon, J. B. (1998). Velopharyngeal closure force and levator veli palatini activation levels in varying phonetic contexts. *Journal of Speech, Language, and Hearing Research, 41,* 51–62.

Kummer, A. (2005). *The MacKay–Kummer SNAP Test–R: Simplified nasometric assessment procedures—Revised*. Montvale, NJ: KayPENTAX. Retrieved from www.kayelemetrics.com

Laczi, E., Sussman, J. E., Stathopoulos, E. T., & Huber, J. (2005). Perceptual evaluation of hypernasality compared to HONC measures: The role of experience. *Cleft Palate–Craniofacial Journal, 42,* 202–211.

Lewis, K. E., & Watterson, T. (2003). Comparison of nasalance scores obtained from the Nasometer and the NasalView. *Cleft Palate–Craniofacial Journal, 40,* 40–45.

Lewis, K. E., Watterson, T., & Quint, T. (2000). The effect of vowels on nasalance scores. *Cleft Palate–Craniofacial Journal, 37,* 584–589.

Lewis, K. E., Watterson, T. L., & Houghton, S. M. (2003). The influence of listener experience and academic training on ratings of nasality. *Journal of Communication Disorders, 36,* 49–58.

Lintz, L. B., & Sherman, D. (1961). Phonetic elements and perception of nasality. *Journal of Speech and Hearing Research, 4,* 381–396.

Lippmann, R. P. (1981). Detecting nasalization using a low-cost miniature accelerometer. *Journal of Speech and Hearing Research, 24,* 314–317.

Mra, Z., Sussman, J. E., & Fenwick, J. (1998). HONC measures in 4- to 6-year-old children. Horii Oral Nasal Coupling Index. *Cleft Palate–Craniofacial Journal, 35,* 408–414.

Redenbaugh, M. A., & Reich, A. R. (1985). Correspondence between an accelerometric nasal/voice amplitude ratio and listeners' direct magnitude estimations of hypernasality. *Journal of Speech and Hearing Research, 28,* 273–281.

Rong, P., & Kuehn, D. (2012). The effect of articulatory adjustment on reducing hypernasality. *Journal of Speech, Language, and Hearing Research, 55,* 1438–1448. doi: 10.1044/1092-4388(2012/11-0142)

Seaver, E. J., Dalston, R. M., Leeper, H. A., & Adams, L. E. (1991). A study of nasometric values for normal nasal resonance. *Journal of Speech and Hearing Research, 34,* 715–721.

Stevens, K. N., Kalikow, D. N., & Willemain, T. R. (1975). A miniature accelerometer for detecting glottal waveforms and nasalization. *Journal of Speech and Hearing Research, 18,* 594–599.

Thorp, E. B., Virnik, B. V., & Stepp, C. E. (2012, August). Normalization strategies for nasal acceleration to assess velopharyngeal function. *Conference Proceedings From the 2012*

Annual International Conference of the IEEE Engineering in Medicine and Biology Society (pp. 6459–6462), San Diego, CA.

Van Lierde, K. M., Wuyts, F. L., De Bodt, M., & Van Cauwenberge, P. (2003). Age-related patterns of nasal resonance in normal Flemish children and young adults. *Scandinavian Journal of Plastic and Reconstructive Surgery and Hand Surgery, 37,* 344–350.

Watterson, T., Hinton, J., & McFarlane, S. (1996). Novel stimuli for obtaining nasalance measures from young children. *Cleft Palate–Craniofacial Journal, 33,* 67–73.

Watterson, T., Lewis, K. E., & Deutsch, C. (1998). Nasalance and nasality in low pressure and high pressure speech. *Cleft Palate–Craniofacial Journal, 35,* 293–298.

Watterson, T., McFarlane, S. C., & Wright, D. S. (1993). The relationship between nasalance and nasality in children with cleft palate. *Journal of Communication Disorders, 26,* 13–28.

Whitehill, T. L., Lee, A. S., & Chun, J. C. (2002). Direct magnitude estimation and interval scaling of hypernasality. *Journal of Speech, Language, and Hearing Research, 45,* 80–88.

Witte, R. S., & Witte, J. S. (2010). *Statistics* (9th ed.). Hoboken, NJ: Wiley.

Zraick, R. I., & Liss, J. M. (2000). A comparison of equal-appearing interval scaling and direct magnitude estimation of nasal voice quality. *Journal of Speech, Language, and Hearing Research, 43,* 979–988.