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Application of linear discriminant analysis to the nasometric assessment of resonance
disorders: A pilot study

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ABSTRACT

Objective: Nasalance scores have traditionally been used to assess mainly hypernasality. However, resonance disorders are often complex, and hypernasality and nasal obstruction may co-occur in patients with cleft palate. In this study, normal speakers simulated different resonance disorders and linear discriminant analysis was used to create a tentative diagnostic formula based on nasalance scores for non-nasal and nasal speech stimuli.

Materials and methods: Eleven female participants were recorded with the Nasometer 6450 while reading non-nasal and nasal speech stimuli. Nasalance measurements were taken of their normal resonance and their simulations of hyponasal, hypernasal and mixed resonance.

Results: A repeated measures Analysis of Variance revealed a resonance condition-stimuli interaction effect ($p < .001$). A linear discriminant analysis of the participants' nasalance scores led to formulas correctly classifying 64.4% of the resonance conditions. When the hyponasal and mixed resonance conditions with obstruction of the less patent nostril were removed from the analysis, the resultant formulas correctly classified 88.6% of the resonance conditions.

Conclusion: The simulations produced distinctive nasalance scores enabling the creation of formulas that predicted resonance condition above chance level. The preliminary results demonstrate the potential of this approach for the diagnosis of resonance disorders.

56 KEYWORDS: Nasalance, nasometry, resonance, hypernasality, hyponasality, mixed
57 resonance

INTRODUCTION

The goal of the present investigation was to develop a tentative statistical procedure for nasometry data that could supplement clinicians' diagnostic assessment of resonance disorders in patients with craniofacial syndromes and other etiologies. In order to set the stage, we will first discuss the available literature. We will then outline our understanding of resonance disorders and our perception of shortcomings of the current assessment procedures before we suggest a potential solution.

Resonance disorders

The use of the term resonance in speech science vs. speech-language pathology is somewhat ambiguous. In a physical sense, resonance is the oscillatory response of a system to an impulse (McWilliams et al., 1990). Physics teachers like to illustrate the concept with one person pushing another on the swing. In speech science, the term resonance is used for the general frequency response of the vocal tract to the glottal source signal (Titze, 1994) while speech-language pathologists use the term 'resonance disorder' primarily for imbalances of oral and nasal resonance in speech (McWilliams et al., 1990). Common resonance disorders in this sense include hypernasality, hyponasality, cul-de-sac and mixed resonance. Hypernasality is a coupling of the oral and nasal cavities due to velopharyngeal dysfunction or oral-nasal fistulae, and it can be accompanied by nasal air emissions (Kummer 2008, McWilliams et al., 1990, Peterson-Falzone et al., 2001). Hyponasality is typically due to a partial blockage of the nasal passages. Complete nasal obstruction leads to denasality (Kummer 2008, McWilliams et al., 1990, Peterson-Falzone et al., 2001). An obstruction that traps sound in a blind pouch produces muffled speech with cul-de-sac resonance (Kummer 2008, 2011; McWilliams et al., 1990, Peterson-Falzone et al., 2001). The location of the obstruction

determines whether the cul-de-sac resonance is qualified as oral (e.g., resulting from microstomia), nasal (resulting from stenotic nares or a deviated septum) or pharyngeal (resulting from enlarged tonsils) (Kummer, 2011). Kummer (2011) defines mixed nasality as a combination of any of hypernasality, hyponasality and cul-de-sac resonance. Peterson-Falzone et al. (2001) and McWilliams et al. (1990) consider cul-de-sac resonance a variation of hyponasality, so by extension their definitions of mixed nasality (Peterson-Falzone et al., 2001) or hyper-hyponasality (McWilliams et al., 1990) also include hypernasality, hyponasality and/or cul-de-sac resonance.

Assessment of resonance disorders

The clinician's trained ear is considered the gold standard in assessing resonance disorders (Kuehn & Moller, 2000; Moon, 2009; Whitehill & Lee, 2008). However, listener's perceptual ratings have been described by some authors as difficult, subjective and of poor reliability (Keuning et al., 2004; Whitehill & Lee, 2008). Some of the lack of reliability may be attributed to the perceptual scales used (Whitehill et al., 2002) and inexperience (Brunnegård et al., 2012; Lewis et al., 2003).

For additional corroboration, the perceptual clinical evaluation of resonance disorders is often supplemented with instrumental measures. A popular indirect acoustic measure with wide clinical application is computerized nasometry, with instruments such as the Nasometer (KayPentax, Montvale, New Jersey) (Kuehn & Moller, 2000). The nasalance score reflects the proportion of oral to nasal sound energy in speech and is calculated as follows: $\text{nasalance} = \text{nasal} / (\text{nasal} + \text{oral}) \times 100$ (Fletcher, 1976). When there is excess nasal resonance, the scores for speech stimuli without nasal sounds are higher than normal, suggesting hypernasality. When there is a lack of nasal resonance, the scores for

speech stimuli loaded with nasal consonants are lower than normal, suggesting hyponasality (Kummer, 2008; Dalston et al., 1991a, 1991b).

The relationship between nasality ratings and nasalance scores is commonly evaluated in two ways. Sensitivity and specificity are used to find an appropriate cut off score that best distinguishes normal from disordered resonance. Correlation analyses are used to describe the relationship between nasalance scores and perceptual evaluations of the severity of resonance disorders. The Zoo Passage (Fletcher, 1976) is a text without nasal speech sounds and commonly used among English speakers to assess hypernasality. The best sensitivity and specificity results for the Zoo Passage were found with cut off scores between 26 and 32 with overall diagnostic efficiencies between .69 and .87 (Dalston et al., 1991a, 1993; Hardin et al., 1992). Hyponasality is commonly assessed using a text passage loaded with nasal consonants. In English, nasalance scores below 50 for the Nasal Sentences (Fletcher, 1976) have reported sensitivities of .48 to 1.00 and reported specificities between .79 and .91 (Dalston et al., 1991b; Hardin et al., 1992). Dalston et al. (1991b) found the sensitivity rose from .48 to 1.0 and, specificity rose from .79 to .85, when participants with audible nasal emissions were excluded. As some of these excluded participants were perceived to have both hyponasality and audible nasal emissions (a frequent feature of hypernasality), one could suspect that some of them may have had mixed forms of nasality.

Unlike hypernasality or hyponasality alone, the relationship between mixed or cul-de-sac resonance disorder and the nasalance score is less straightforward. By one account, the nasalance scores are expected to be normal or close to normal (Kummer et al., 1993). To date, the nasalance scores of only four individuals identified as having cul-de-

sac or mixed nasality have been published in the scientific literature (Kummer et al., 1993, Karnell et al., 2004, Van Lierde et al., 2011). McWilliams et al. (1990) and Peterson-Falzone et al. (2001) state that the instrumental assessment of mixed forms of nasality is “long overdue”.

We argue that the current assessment procedures could be improved in two ways:

1. The diagnostic categories should separate oral-nasal balance from other features of vocal tract resonance, in particular, cul-de-sac quality.
2. The nasalance measurement should simultaneously reflect aspects of hyper- and hyponasality to help guide the clinician’s assessment of oral-nasal balance.

Separating oral-nasal balance from cul-de-sac

For the purposes of the research presented below, we propose to separate the assessment of cul-de-sac resonance from the assessment of oral-nasal balance. We suggest that disorders of oral-nasal balance should be conceptualized solely in the categories of hypernasality (sound is transmitted through the nose because of velopharyngeal dysfunction), hyponasality (sound cannot be transmitted through the nose because of a blockage) and mixed nasality (sound is transmitted through the nose because of velopharyngeal dysfunction but the sound transmission is impacted by blockage).

We do not dispute the existence of cul-de-sac resonance but we suspect that the perceptual category cul-de-sac blends percepts of oral-nasal balance with other aspects of vocal tract resonance. Kummer (2011) provides a detailed description of obstruction locations as oral, pharyngeal and nasal. However, these could lead to quite variable perceptual impressions. Oral and pharyngeal constriction can lead to a cul-de-sac

quality without affecting oral nasal balance. For example, pharyngeal constriction may result in a “hot potato” voice quality (Bhutta et al., 2006), which would not affect oral-nasal balance per se. On the other hand, a case of nasal stenosis could be subsumed under mixed or hyponasal oral-nasal balance, with an additional cul-de-sac quality. We argue that by restricting the disorders of oral-nasal balance to hypernasality, hyponasality and mixed nasality, we can make better use of nasalance scores in clinical diagnosis. At the same time, observations such as cul-de-sac, nasal emission and nasal frication can be documented as additional perceptual features and add to the complete diagnosis. Such an approach reflects clinical practice using diagnostic schemes such as the Great Ormond Street Assessment '98 (Sell et al., 1999), which includes separate rating scales for both hyper- and hyponasality. This allows the clinician to document separate observations and comment on different aspects of a resonance disorder.

A different approach to nasalance measurement

Previous studies have mainly used cut-off scores to separate normal from hypernasal speakers. If we assume that all disorders of oral nasal balance can be subsumed under the categories of hypernasality, hyponasality or mixed nasality, it should be possible to construct a diagnostic measure that can simultaneously reflect aspects of hyper- and hyponasality to help guide the clinician’s assessment of oral-nasal balance.

The correlations between nasalance scores and perceptual measures as well as the reported diagnostic efficacies in previous studies have run the gamut from poor to strong (Bressmann et al., 2006; Brunnegård et al. 2012; Dalston et al., 1991a, 1993; Hardin et al., 1992; Karnell et al., 2004; Keuning et al., 2002; Nellis et al., 1992; Sweeney & Sell, 2008). We suspect that at least a part of the frequent disagreement

between listeners and nasalance scores may be attributed to mixed nasality. As an example, Bressmann et al. (2006), examined hypernasality and nasalance scores for an oral and a nasal stimulus with three nasometry systems. Measuring the oral stimulus (the Zoo Passage) with the Nasometer 6200, the normal group had a mean nasalance score of 13.45 (SD 5.94), the mildly hypernasal group averaged 17.68 (SD 9.59) and the group perceived to have moderate to severe hypernasality had a mean nasalance score of 34.06 (SD 18.96). Like Dalston et al's (1993) study, there's an overlap in the nasalance scores between the normal and the mildly hypernasal groups. For the Nasal Sentences, the normal group had a mean nasalance score of 57.90 (SD 6.69), the mildly hypernasal group averaged 40.94 (SD 11.54) and the moderate/severe hypernasal group had a mean nasalance score of 51.00 (SD 16.13). For the nasal stimulus, the mildly hypernasal group's mean nasalance score was well below the cut-off of 50 for hyponasality suggested by Dalston et al. (1991b), and well below the normal controls. This suggests the presence of mixed nasality among the cases that were diagnosed as mildly hypernasal. As the focus of Bressmann et al. (2006) was solely on hypernasality, no attention was paid to this finding.

Some efforts have been made to use the nasalance scores differently. The nasalance distance was introduced by Bressmann et al. (2000, 2006). The measure calculates the difference between the score from a nasally loaded stimulus and that of an oral stimulus to quantify how well the speaker can differentiate between oral and nasal sounds. The nasalance distance had greater sensitivity and specificity for the perception of hypernasality than the magnitude of the oral stimulus alone (Bressmann et al., 2006). Nasalance scores have also been used in conjunction with other measures. The Nasality Severity Index was introduced by Van Lierde et al. (2007) to aid the diagnosis of mild

hypernasality. It includes a perceptual evaluation along with aerodynamic measurements, nasometry and the Glatzel test (which measures condensation on a mirror placed below the nostril) in order to create an objective measure that “reflects the multidimensional nature of resonance” (Van Lierde et al., 2007). It will be interesting to see how this approach will fare in future research or clinical practice.

Hypernasality affects speech intelligibility and acceptability more than hyponasality (Shprintzen et al., 1979), so it is clinically more relevant. However, the attempt to fit every patient diagnostically along a one-dimensional continuum of hypernasality may not do the possible range of individual variability justice. Hypernasal resonance in combination with compromised nasal patency is common among patients with bilateral and unilateral complete cleft lip and palate (Fukushiro & Trindale, 2005) due to combinations of a deviated septum, a narrow vestibule and hypertrophic turbinates (Coston et al., 2009).

We propose that the diagnostic procedure should evaluate the nasalance scores for oral and nasal stimuli together to arrive at a comprehensive classification for the speaker’s resonance. Such a classification would be the first step towards an improved assessment of resonance disorders, aided by nasometry scores. The goal of this study was to assess the influence of velopharyngeal opening and nasal patency on nasalance scores. Normal speakers simulated hyponasality, hypernasality and mixed resonance. We used linear discriminant analysis to derive tentative formulas for the diagnostic categorization of speakers based on their nasalance values for oral and nasal stimuli.

The central hypothesis of this study was that the formulas derived from linear discriminant analysis would perform better than chance in predicting the resonance conditions based on nasalance scores. Since the data for this pilot study were based on simulations of different resonance disorders from normal speakers, we had an additional four hypotheses related to the characteristics of the participants' simulations. The first hypothesis was that the hyponasal resonance condition would have lower scores than the normal resonance condition (and the decrease would be greater for the nasal stimulus than the oral stimulus). The second hypothesis was that the hypernasal resonance condition would have higher scores than the normal resonance condition (and the increase would be greater for the oral stimulus than the nasal stimulus). The third hypothesis was that the mixed resonance condition (hypernasal resonance with one nostril occluded) would yield normal scores since, per Kummer et al.'s (1993) prediction, the effects of hypernasality and hyponasality would cancel each other out. The fourth hypothesis was that the nasalance distance for the normal resonance condition would be greater than that of the hypernasal, hyponasal or mixed resonance conditions. Bressmann et al. (2006) found that speakers with hypernasal resonance had a smaller nasalance distance than those with normal resonance. This was attributed to a decreased ability to differentiate oral from nasal speech sounds (Bressmann et al., 2006). The same should be true for the other resonance disorders, hyponasality and mixed resonance.

METHODS

Participants

Sixteen normal females were recruited from the student population at the University of Toronto. The participants were between 22 and 30 years of age (mean 24.1, SD 2.2) and

spoke English with the accent that is common to Southern Ontario. They reported normal hearing, no history of cleft lip and palate, no resonance disorder and no nasal congestion.

Participant Training

The participants' experimental task was to simulate different resonance disorders. As a first step, the first author explained the nature of different resonance disorders and practiced with the participants how to produce the associated resonance qualities. The following types of oral-nasal balance were discussed and practised with the participants:

- Normal voice. This voice quality was discussed with the participants but no practice was necessary for the normal resonance condition.
- For the hypernasal resonance condition, hypernasality was simulated by lowering the velum and nasalizing all speech sounds.
- Hyponasality was simulated by closing one nostril with the index finger. It has been estimated that up to 80% of individuals experience a nasal cycle, whereby one nostril is more patent than the other at various times throughout the day (Hixon et al., 2008; Principato & Osenberger, 1970; Stoksted, 1953). To compensate for this, the hyponasal resonance condition was repeated for the alternate nostril so that the higher and lower patency nostrils could be identified. This step generated the resonance conditions hyponasal high and hyponasal low.
- Mixed nasality was simulated by speaking with a lowered the velum and one closed nostril. Like the hyponasal resonance conditions, this was repeated with the other nostril blocked for the simulated resonance conditions mixed high and mixed low.

The first author taught the participants hypernasal resonance by demonstration. To help the participants identify when their velum was lowered, they were asked to hold a hand under their nose and repeat the interjection “hun”, and the word “mama”, until a nasalized vowel could be sustained. The participants were then asked to produce various nasal and non-nasal sounds, sustain nasalized vowels and repeat words and sentences with a voluntarily lowered velum. The participants were given time to practice their hypernasal resonance with the test stimuli before the recordings. Further demonstrations were provided as required. When the participants were comfortable with the hypernasal task, they were asked to practice speaking with a hypernasal resonance while placing a finger firmly over one ala of the nose in order to simulate a mixed nasality resonance.

Stimuli

The stimuli consisted of an oral and a nasal stimulus. The first two sentences of the Zoo Passage (“Look at this book with us. It’s a story about a zoo”) and the first of the Nasal Sentences (“Mama made some lemon jam”) were used (Fletcher, 1976), which are overall comparable to the complete passages (Bressmann, 2005). The abbreviated versions were used to keep the timeline reasonable and to make the simulation task better manageable for the participants. The order of the stimuli was randomized and they were read twice for each resonance condition. If a participant made a reading error, they were asked to reread the stimulus.

Recording Procedures

All the nasalance measurements and recordings took place in a quiet room. The Nasometer II 6450 (KayPentax, Montvale, NJ) was connected to an ASUS laptop computer (series X53U, Asus Canada, Montréal, QC) running the Windows 7 operating

system (Microsoft, Redmond, WA). The Nasometer was calibrated according to the manufacturers' specifications, prior to each day's data collection. The audio files and statistics were saved using the Nasometer software for each resonance condition.

Since the sound quality of the Nasometer is affected by a filtering algorithm centred at 500Hz with a 300Hz bandwidth, additional high quality audio recordings were made using a Zoom Q3 Handy Video Recorder (Zoom, Tokyo, Japan). The recordings were made with the device's internal directional stereo microphone with a signal resolution of 16 bit and a sampling rate of 44.1 kHz. The stereo microphone was placed 40cm from the participant's mouth. The recordings were saved as *.wav files.

Simulation Verification

While pinching a nostril is straightforward, the simulation of hypernasal resonance disorders is an unusual task for normal speakers without specific phonetic training. To verify the accuracy of the participants' portrayal of hypernasal resonance, both authors listened to the audio recordings of the sessions. The recordings were played from a laptop through a set of active loudspeakers (iHome iHM78 mini-speakers, Rahway, NJ) in a quiet office. A consensus decision was made as to whether or not the participants had successfully simulated and maintained a hypernasal resonance. As a result of this qualitative verification, five participants were excluded from the data analysis, leaving a total of 11 data sets in the study.

Data Analysis

The nasalance values collected for the oral and nasal stimuli across six different resonance conditions were analysed using SPSS 20.0 (IBM Canada Ltd, Markham ON).

The effects of resonance condition on nasalance scores were assessed with a repeated measures Analysis of Variance (ANOVA), followed by a series of paired post hoc t-tests. Due to nasal cycling, the nasal patency may be uneven between the two nostrils (Hixon et al., 2008, Principato & Osenberger, 1970; Stoksted, 1953). The nasalance scores for the hyponasal and mixed resonance conditions were originally coded as hyponasal left, hyponasal right, mixed left or mixed right. For the data analysis, the nasalance scores from blocking the right or left nostril were individually recoded into a higher and a lower patency nostril (less and more blocked, respectively) for every speaker based on the magnitude of the two nasalance scores for each nostril. This recoding generated the resonance conditions hyponasal high, hyponasal low, mixed high and mixed low.

The nasalance distance was calculated by subtracting the nasalance score for an oral stimulus from the nasalance score for a nasal stimulus (Bressmann et al., 2000, 2006). Nasalance distances were calculated for all resonance conditions and compared using a one-way ANOVA and post hoc paired t-tests.

In order to derive a diagnostic prediction based on the nasalance scores, we used linear discriminant analysis. A descriptive linear discriminant analysis was run on the nasalance scores, which were then classified using predictive discriminant analysis. With the within-subject design, there were eleven participants in each group. This was at least five times the number of predictors (Burns & Burns, 2009) and so we proceeded with both stimuli as predictors. It should be noted that this was a somewhat unusual application of the linear discriminant analysis, as the speakers were not independent. A within-subject design allowed for the experimental generation of different types of

resonance disorders while controlling for individual differences. The p-value for the ANOVAs and discriminant analysis was .05. Since multiple post-hoc t-tests were calculated the Holms-Bonferroni method was used to control for type I error, with α set to .05.

RESULTS

The means and standard deviations for the nasalance scores and the nasalance distances are shown in Table 1.

[TABLE 1 ABOUT HERE]

Repeated Measures ANOVA

A repeated measures ANOVA was run for the six resonance conditions, two stimuli and two repetitions. Where sphericity was violated, the Greenhouse-Geisser correction was used. There were significant effects for resonance condition ($F(2.902, 29.021) = 30.633$, $p < .001$), stimuli ($F(1,10) = 139.742$, $p < .001$) and a resonance condition-stimuli interaction effect ($F(5,50) = 50.187$, $p < .001$). There was no significant effect for repetition or any other interaction effect.

Post-hoc paired t-tests for the main effect of resonance condition (both stimuli combined) demonstrated that mean nasalance scores increased significantly ($p < .01$) from hyponasal low (mean 21.1, SD 18.5), to hyponasal high (mean 25.2, SD 21.2), to normal (mean 36.1, SD 26.4) and mixed low (mean 40.9, SD 16.1). There was no significant difference between normal and mixed low ($p = .273$). The highest mean nasalance scores were found for mixed high (mean 54.8, SD 18.1) and hypernasal

(mean 61.8, SD 18.0). These two resonance conditions did not differ from each other ($p = .181$) but both were significantly higher than all other resonance conditions ($p < .01$). A paired t-test for the main effect of stimulus (all resonance conditions combined) found the mean nasalance score of the oral sentence (mean 26.9, SD 24.2) significantly lower than the mean nasalance score for the nasal sentence (mean 53.0, SD 17.3; $p < .001$).

Paired t-tests of the resonance condition-stimulus interaction effect revealed the following: for the oral stimulus, the normal, hyponasal low, hyponasal high and mixed low resonance conditions were significantly different from each other ($p < .01$) but the hypernasal and mixed high resonance condition were not ($p = .490$). The mean scores increased from hyponasal low to hyponasal high to normal to mixed low to mixed high and hypernasal. The mean nasalance scores for the nasal stimulus were not significantly different for the normal and mixed high resonance conditions ($p = .419$) or the hyponasal high and mixed low resonance conditions ($p = .989$), but all remaining combinations of resonance conditions were significantly different from each other ($p \leq .01$). The lowest mean for the nasal stimulus was hyponasal low, followed by hyponasal high and mixed low, which were equivalent. At the higher end were normal and mixed high, whose means did not differ significantly, while the hypernasal resonance condition produced the highest mean nasalance score.

One-Way ANOVA for Nasalance Distance

A one-way ANOVA was run for the nasalance distance across the six resonance conditions. The effect of resonance condition was significant, $F(5,126) = 59.007$, $p < .001$. Paired t-tests revealed the mean nasalance distance for the normal resonance

condition was significantly greater than all other resonance conditions ($p < .001$). The mean nasalance distances of the hyponasal resonance conditions were significantly less than the normal and significantly greater than the hypernasal and mixed resonance conditions ($p < .001$), but the nasalance distance of the hyponasal high and the hyponasal low did not differ significantly based on the adjusted significance level ($p = .049$). The mean nasalance distance of the hypernasal resonance condition was significantly greater than the mixed low ($p = .003$) and the mixed high resonance condition ($p = .013$). There were no significant differences between the mean nasalance distance of the mixed high and the mixed low resonance conditions ($p = .598$). The nasalance distance means and their standard deviations can be found in Table 1.

Discriminant Analysis

In order to determine how the six resonance conditions differed with respect to their nasalance scores for the two stimuli and to derive a classification formula, both descriptive and predictive discriminant analyses were conducted. The nasalance scores for the oral and nasal stimuli were entered as predictor variables and the six simulated resonance conditions were used as the classification variables. As equal variances could not be assumed, (Box's M $p < .001$) a separate groups covariance matrix was used (Green et al., 2000). Two discriminant functions were calculated based on Wilks' lambda (combined $\Lambda = .134$, $\chi^2(10) = 255.110$, $p < .001$, residual $\Lambda = .573$, $\chi^2(4) = 70.786$, $p < .001$). This test indicated that the nasalance scores differentiated significantly among the resonance conditions after partitioning out the effects of the first discriminant function. As both tests were significant, both discriminant functions were interpreted. The differences among the six resonance conditions accounted for 76.6% of

the variance in values of the first two discriminant functions and 42.8% of the variance in values of the second discriminant function.

[TABLE 2 ABOUT HERE]

The canonical discriminant function coefficients are displayed in table 2. Discriminant function 1 gave greater weight to the oral stimulus maximally separating the presence of hypernasality from the absence of hypernasality. The second function gave greater weight to the nasal stimulus, maximally separating the presence of hyponasality from the absence of hyponasality. Based on table 2 the discriminant function formulas were

$$D1 = (.100) \text{ Oral} - (.048) \text{ Nasal} - .149$$

$$D2 = (-.021) \text{ Oral} + (.089) \text{ Nasal} - 4.162$$

Each participant's set of scores produced a pair of function values. The minimal Mahalanobis distance between that pair and those of the resonance condition centroids (displayed in table 3) determines which resonance condition the set of scores is predicted to belong to. When the predictive formulas were applied to the participants' nasalance scores, 64.4% of the resonance conditions were correctly classified. Of the 22 pairs of nasalance scores for the normal resonance condition, three were classified as hypernasal. For the hyponasal low resonance condition, two scores were classified as normal and five were classified as hyponasal high. In the hyponasal high resonance condition, three scores were classified as normal and six were classified as hyponasal low. The hypernasal resonance condition saw two tokens classified as normal and five classified as mixed high. The mixed low resonance condition had four scores classified

as hypernasal and two as mixed high. Finally, the mixed high resonance condition had ten scores classified as hypernasal and five classified as mixed low.

[TABLE 3 ABOUT HERE]

From a clinical point of view, hyponasality only becomes relevant if it is obstructive and nasal patency is reduced. In the hyponasal high and mixed high resonance conditions, nasal patency was less compromised. For a discriminant analysis, the attributes used to separate the groups are meant to discriminate quite clearly between the groups with minimal overlap between the categories (Burns & Burns, 2009). Therefore, these two resonance conditions were removed and the linear discriminant analysis was repeated with the remaining four resonance conditions.

[TABLE 4 ABOUT HERE]

Two significant discriminant functions were calculated, with a combined Wilks' lambda $\Lambda=.111$ and $\chi^2(6) = 184.993$, ($p < .001$) and a residual Wilks' lambda $\Lambda=.439$, $\chi^2(2) = 69.129$, ($p < .001$). The differences among the four resonance conditions accounted for 74.8% of the variance in scores of the first two discriminant functions and 56.1% of the variance in scores of the second discriminant function. The canonical discriminant function coefficients are displayed in table 4. Based on these coefficients, we derived the following discriminant function formulas:

$$D1 = (.099) \text{ Oral} - (.050) \text{ Nasal} + .068$$

$$D2 = (-.016) \text{ Oral} + (.094) \text{ Nasal} - 4.594$$

Table 5 displays the function values for the four resonance condition centroids. When the predictive formulas were applied to the participants' nasalance scores in the four resonance conditions, 88.6% of the simulations were correctly classified. For the normal resonance condition, one of the 22 sets of scores was misclassified as hyponasal. Two tokens in the hyponasal resonance condition were misclassified as normal. Two scores from the hypernasal resonance condition were also misclassified as normal, while one was misclassified as mixed. Finally, four scores in the mixed resonance condition were misclassified as hypernasal. A scatterplot of the centroids and function values is shown in Figure 1.

[TABLE 5 ABOUT HERE]

[FIGURE 1 ABOUT HERE]

DISCUSSION

The goal of the present study was to develop a tentative classification formula for different types of resonance disorders. The data for this experiment were obtained from eleven speakers who provided normal samples as well as simulations of different resonance disorders. The descriptive statistics for the results indicated that the simulations were overall successful and appeared reasonably similar to data that would typically be obtained from clinical participants. The outcomes of the linear discriminant analysis confirmed the central hypothesis of this study, namely, that the classification of the different disorders of oral-nasal balance was far better than chance. In the following paragraphs, our discussion of the findings will mirror the order of the results section.

506

507 A repeated measures ANOVA had a highly significant resonance condition-stimuli
508 interaction effect and revealed significant differences in scores across the resonance
509 conditions. A series of post hoc paired t-tests confirmed that the participants were able
510 to produce a wide range of significantly different nasalance scores. The observed
511 changes in the nasalance scores confirmed the first two hypotheses related to the
512 characteristics of the simulations. The hyponasal resonance conditions had lower
513 nasalance scores than the normal resonance condition and the difference was greater for
514 the nasal stimulus than the oral stimulus. The hypernasal resonance condition had
515 higher nasalance scores than the normal resonance condition and the difference was
516 greater for the oral stimulus than the nasal stimulus. The third hypothesis, that the mixed
517 and normal resonance conditions would yield comparable scores, was only partially
518 confirmed. For the nasal stimulus, the nasalance mean for the normal resonance
519 condition and the mixed high resonance condition were equivalent, however, the
520 nasalance mean of the mixed low resonance condition was significantly lower than the
521 normal resonance condition. Furthermore, for the oral stimulus, the mean nasalance
522 score of both the mixed high and mixed low resonance conditions were higher than the
523 normal resonance condition.

524

525 The mean for the oral stimulus in the normal resonance condition (10.3, SD 3.2) was
526 lower, and less variable, than previously found among normal speakers in Southern
527 Ontario. Using the Nasometer 6200 and similar or identical stimuli, reported values
528 have been 12 (SD 6) (Seaver et al., 1991), 13.45 (SD 5.90) and 11.62 (SD 4.33)
529 (Bressmann, 2005). For the same Nasometer model 6450 and stimulus, the mean was
530 13.12 (SD 6.35) (de Boer & Bressmann, in press). The mean for the nasal stimulus in

the normal resonance condition, 62.0 (SD 4.2) was comparable to, but less variable than, other studies with similar speakers. Previously reported means for nasal stimuli with the Nasometer 6200 were 61 (SD 7) (Seaver et al., 1991), 57.90 (SD 6.69) and 57.01 (SD 7.64) (Bressmann, 2005). Using the Nasometer 6450, the same nasal sentence was found to have a mean of 63.54 (SD 6.27) (de Boer & Bressmann, in press). The means for the nasal stimulus in the hyponasal resonance conditions were both well below the 50% cut-off score proposed by Dalston et al. (1991b) for the complete set of Nasal Sentences. Likewise, the mean nasalance score for the oral stimulus in the hypernasal resonance condition surpassed the proposed cut-offs of 28% (Dalston et al., 1993) and 32% (Hardin et al., 1992). In fact, the mean nasalance for the hypernasal resonance condition nearly matches the mean nasalance of 53 (SD 7.2) of a group of speakers reported to have severe hypernasality (Dalston et al., 1993).

The simulation of different resonance disorders by the normal speakers led to very clear-cut quantitative results. The simulation produced little of the overlap in nasalance scores between normal and mildly hypernasal resonance for the oral stimulus that can affect the exact calculation of cut-off scores in clinical research (Dalston et al., 1993; Bressmann et al., 2006). On the one hand, this may have been due to a relatively small range of scores produced by the speakers in this study for the normal resonance condition compared to the variability observed in previous research with larger groups (Bressmann, 2005; Gildersleeve-Neumann & Dalston, 2001; Seaver et al., 1991). On the other hand, the participants in the present study were instructed to produce only severe hypernasality. Perceptually, both investigators had the impression that the participants were successful at this task, and the nasalance scores for the hypernasal resonance condition confirmed this impression. It was the purpose of the present study to use

simulations to create prototypical nasalance profiles for different resonance disorders. In future clinical research it would be important to find out in how far such simulated profiles differ from actual clinical data.

The one-way ANOVA for the nasalance distance was highly significant, indicating the nasalance distances differed by resonance condition. The mean nasalance distance of the normal resonance condition was significantly greater than that of the hypernasal resonance condition, as expected from previous research (Bressmann et al., 2000, 2006). The present research demonstrated that hyponasal and mixed resonance disorders should also have significantly shorter nasalance distances. The fact that all the simulated disorders of oral-nasal balance had significantly shorter nasalance distances than the normal resonance condition confirmed the fourth hypothesis. While the nasalance distance in hypernasality is shortened because of elevated scores for oral stimuli, the nasalance distance for hyponasality is shortened because of lower scores for nasal stimuli. The nasalance distance for the mixed nasality resonance conditions were shortened by elevated scores for the oral stimulus, and for the mixed low resonance condition only, lowered scores for the nasal stimulus. While the ANOVA showed significant differences between the resonance conditions, the potential discriminative value of the nasalance distance was not evaluated in the present study. As both the nasal and oral stimuli were entered into the discriminant function, the addition of the nasalance distance would have been redundant.

The linear discriminant analysis classified 64.4% of the data correctly into the six resonance conditions, based on the nasalance scores. This result was better than chance alone (chance level 16.7%) and confirms the central hypothesis of the study. By

removing the hyponasal high and mixed high resonance conditions, where nasal obstruction had less impact on nasalance scores, a better rate of 88.6% accurate predictions was achieved, well above the 25% chance level. Some of this increase in classification accuracy was due to the decreased number of categories. In fact, the ratio of the predictions to chance decreased from 3.9 to 3.5 with the decrease in categories. However, this reduced the overlap in values between categories, thus allowing us to derive two first tentative formulas for a classification of resonance disorders.

While the present study was a pilot, we believe that this approach has potential. The classification formulas could be implemented as a computer application or even as an addition to future versions of the Nasometer software. The formulas would have to be refined for different languages and instruments. The formulas would provide the clinician with probability values for different disorders of oral-nasal balance which could serve as a helpful adjunct in the diagnostic process. It would also be possible to add other measures, including non-nasometry measures, into the calculations, similar to the Nasality Severity Index (Van Lierde et al., 2007).

There are some limitations to the resonance simulations and their validation. Blocking one nostril is a rather simplistic method of simulating hyponasality. In the clinical population, the blockage could be in medial or posterior locations along the nasal passage and nasopharynx. In the hyponasal resonance condition, the participants were instructed to speak normally, but we cannot know if they moved their velum differently. Without visualization of the velopharyngeal port, we cannot be absolutely certain whether and to what extent the participants lowered their velum throughout the hypernasal and mixed resonance conditions, either. Some of the participants may also

have produced nasal emissions. Whether such emissions would have been loud enough or would have created enough turbulent airflow to affect their nasalance scores is not known. However, as nasal emissions may co-occur with hypernasality in clinical populations, this was not considered to be detrimental to the simulations.

Another caveat for the interpretation of the study findings was the small sample size. Not all individuals who initially participated in the study could successfully simulate hypernasality. The successful simulations of hypernasality were also predominantly severe, leading to higher scores than would be found in many typical clinical populations. Although small, the sample size was large enough to show that the nasalance scores of mixed nasality may differ from hyponasality and hypernasality. More research with clinical populations will be needed to corroborate the validity of the tentative classification formulas. Ideally, an instrumental measure of nasal patency such as rhinomanometry (Williams et al., 1990) would complement such future research on the acoustic assessment of resonance disorders.

CONCLUSION

The present study used linear discriminant analysis as a potential tool in the assessment of resonance disorders. The simulations across the resonance conditions were distinct enough from each other to be used to derive a formula that predicted resonance above chance level. The initial results were promising and demonstrate the potential of this approach. The validity of the formula will have to be corroborated with a larger clinical sample size to reflect the full range of resonance disorders.

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- 737

738 TABLES

739 Table 1 - Mean nasalance scores and nasalance distances with standard deviations for
 740 oral and nasal stimuli by resonance condition (normal, hyponasal low, hyponasal high,
 741 hypernasal, mixed low and mixed high).

	Oral		Nasal		Nasalance distance	
Resonance						
condition	M	SD	M	SD	M	SD
Normal	10.2	3.2	62.0	4.2	51.7	3.8
Hypo Low	5.0	1.3	37.2	12.3	32.3	11.6
Hypo High	5.8	1.3	44.6	11.3	38.8	10.9
Hyper	53.2	20.2	70.5	9.9	17.3	14.8
Mixed Low	37.2	14.4	44.6	17.1	7.3	10.2
Mixed High	50.3	18.9	59.3	17.7	9.0	10.7

742

743

744 Table 2 - Canonical discriminant function coefficients derived from two predictors (oral
745 and nasal stimuli) and six resonance conditions (normal, hyponasal low, hyponasal high,
746 hypernasal, mixed low and mixed high).

747

	Function 1	Function 2
Oral	0.100	-0.021
Nasal	-0.048	0.089
(Constant)	-0.149	-4.162

748

749

750 Table 3 - Function values of group centroids for six resonance conditions (normal,
 751 hyponasal low, hyponasal high, hypernasal, mixed low and mixed high)

Resonance condition	Function 1	Function 2
Normal	-2.098	1.151
Hyponasal Low	-1.439	-0.945
Hyponasal High	-1.706	-0.306
Hypernasal	1.782	1.005
Mixed Low	1.433	-0.974
Mixed High	2.028	0.069

752

753

754 Table 4 - Canonical Discriminant Function Coefficients derived from two predictors
755 (oral and nasal stimuli) and four resonance conditions (normal, hyponasal low,
756 hypernasal mixed low).

757

	Function 1	Function 2
Oral	0.099	-0.016
Nasal	-0.050	0.094
(Constant)	0.068	-4.594

758

759

760 Table 5 - Function values of group centroids for four resonance conditions (normal,
761 hyponasal low, hypernasal and mixed low).

762

Resonance condition	Function 1	Function 2
Normal	-2.02	1.041
Hyponasal Low	-1.305	-1.189
Hypernasal	1.802	1.162
Mixed Low	1.522	-1.014

763

764

765

Figure 1 - Scatterplot of function values for the linear predictive analysis with group centroids.