EVALUATING THE VOWEL SPACE EFFECTS OF LARYNX HEIGHT USING LARYNGEAL ULTRASOUND

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1. INTRODUCTION

In this paper we apply laryngeal ultrasound to the task of evaluating the effect of larynx height on vowel formant frequencies. Our technique accurately quantifies change in larynx height, and from this basis we will demonstrate that, while larynx lowering generally yields expected lowering effects on formants, larynx raising has a lowering effect on F2 and F3 more characteristic of what has been labeled *pharyngealization*. There are two principal articulatory axes in the larynx, in addition to pitch control, associated with laryngeal acoustics: the axis of constriction and the axis of height. Therefore we attribute the formant effects observed in larynx raising to co-occurring laryngeal constriction.

Larynx height is generally assumed to correlate positively with the resonant frequencies of the vocal tract. In the simple uniform tube model of the vocal tract, lengthening or shortening the tube to represent change to larynx height yields this effect, since resonant frequencies are inversely proportional to vocal tract length (Stevens 1998: 139). Sundberg and Nordström (1976; 'SN76') studied resonance effects of larynx height. They provide simulated results using an acoustic model with 1.5 cm changes to pharynx length and canonical results from phonetic productions made by two participants with "informal estimations" that laryngeal displacements were about 1.5 cm from the normal position with "normal speaking voice pitch". It is noteworthy that SN76 do not manipulate the cross-sectional area of the epilaryngeal tube in their acoustic model. Overall their results indicate that formant frequency has a positive correlation with larynx height, but the strength of the effect differs by vowel: open vowels show the greatest effect for F1, and close (front) vowels show the greatest effect for F2. F3 and F4 are claimed to positively correlate for all vowels. Their claim is that pharynx length drives the first order effect of larynx height on vowel formant frequencies.

2. METHODS

Our objective was to repeat the basic protocol of the SN76 study testing subject's articulations but also to provide more robust observations for larynx height change. To accomplish this goal we collected laryngeal ultrasound data and processed it using optical flow analysis to calculate vertical change in larynx position.

Two phonetician participants (A and B) produced careful productions of [i æ *a* u] in normal (N), raised (R), and lowered (L) larynx states while attempting to maintain constant F0. Productions followed two different larynx height manipulation regimes: NRN and NLN, and NRNL and NLNR. Elicitations lasted ~6 seconds on average. Laryngeal ultrasound was manually administered using a 12L-RS probe with a 3.84 cm FOV connected to a LOGIQe portable ultrasound machine set to 8 MHz with a 2.0 cm depth. The probe is applied to the participant's neck, 1 cm posterior to the thyroid notch. Audio and video data were routed through a Canopus TwinPact100 AD video converter and captured using Sony Vegas 8.0.

Change in larynx height was observed using laryngeal ultrasound and quantified by means of an optical flow algorithm (Moisik et al. 2011), a block-wise, absolute differences method. Gradient methods for optical flow were avoided since ultrasound data do not meet assumptions of smoothness in the brightness pattern of images (Horn and Schunck 1981). To obtain larynx height change, the vertical components of the resulting velocity field vectors were averaged using a weighting based on estimated accuracy. This velocity function is then numerically integrated to yield position change.

The first three formants were obtained by sliding-Gaussian-window LPC analysis (8^{th} order) of the audio signal. Formant measurements are averages taken from ROIs defined for stable larynx height targets. F0 was measured to evaluate consistency. All computation was performed in MATLAB R2009a.

3. RESULTS

Change in formant frequency by vowel and larynx height condition is shown in "Figure 1" for Participants A and B. "Figure 2" shows box plots for change in larynx height by vowel and by larynx height condition. Larynx height targets are consistently achieved, but there is a tendency for elevated neutral position. The tendency was for the N_2 in N_1RN_2L and N_1LN_2R targets to be higher in elevation than N_1 , indicating undershoot in return to neutral height, which ultimately skews the mean value. For both raised and lowered, the change in height is usually on the order of 1 cm above or below neutral.

Relative formant changes expressed as percentages are presented in "Table 1". F1 uniformly raises with larynx height regardless of the neutral F1 value. This runs entirely contrary to SN76 where close vowels, particularly the front ones were claimed not to be sensitive to larynx height. The larynx lowering condition is less impactful on F1, with a tendency towards lower frequency, except for [u] where F1 actually rises for participant B despite larynx lowering.

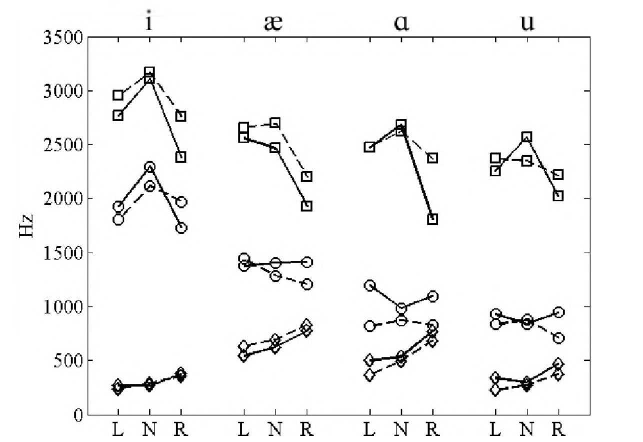

Figure 1. Formant change by larynx height (Participant A = dashed line; Participant B = solid line).

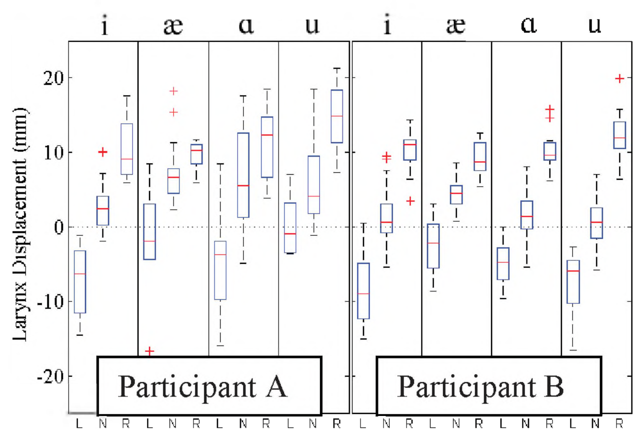

Figure 2. Average larynx height change by vowel, larynx height condition, and participant.

Table 1. Relative formant change averages (%).

		i	æ	*a*	u
F1	R	+36	+22	+43	+53
	L	−4	−12	−13	+5
F2	R	−20	−2	+8	+3
	L	−15	+2	+12	+6
F3	R	−20	−20	−25	−16
	L	−10	+1	−7	−8

F2 diverges from the expected pattern in a few cases: larynx lowering actually yields raised frequency for [æ *a* u], although [i] shows the anticipated lowering. Larynx raising also presents unexpected results; this time for [i æ] there is a drop in frequency. Finally, F3 is exhibits the familiar frequency drop for all vowels examined with respect to larynx lowering, but larynx raising once again surprises with an average F3 drop of −20.25% of frequency across the board. The production of neutral larynx height was judged auditorily in several cases to be closer to raised-constricted than to the lowered posture.

4. DISCUSSION AND CONCLUSIONS

Our data represent an altogether different picture from what was reported on by SN76. It is quantifiably clear from the laryngeal ultrasound that in terms of performance the target conditions for larynx height were achieved by both participants. While we cannot rule out the possibility that our results partially reflect simultaneous change in lingual configuration, we believe that any lingual co-adjustment reflects what is entailed articulatorily in raising the larynx, i.e. *pharyngealization*. The occurrence of pharyngealization may be a consequence of our strict control of F0: the pitch raising mechanism (CT muscles) counteracts constriction. Since we prevented pitch change from occurring, larynx raising associated with airway closure (as in swallowing) was induced. In phonetic terms, larynx raising entails epilaryngeal stricture. The uniform tube model does not account for the role of larynx height in epilaryngeal constriction (Esling 2005). Part of the mechanism involves retraction of the tongue in conjunction with larynx raising, and this might account for the more elevated than normal laryngeal height and undershoot of larynx raising during open vowels (evident in "Figure 2", particularly for Participant B). Pharyngealization in Tsez (Maddieson et al. 1997) shows parallels with our raised larynx data, with elevated F1 (for all vowels and particularly [i]) and lowered F3. For Tsez, F2 rises for back vowels, indicating fronting; this only occurred mildly for Participant B, but its absence is taken to reflect that tongue positions were as consistent as possible. Ladefoged and Maddieson (1996: 312-313) state that F2 and F3 show a tendency for convergence in the strident vowels in !Xóõ, which also feature strong epilaryngeal stricture. We leave the question of how this acoustic effect should be modeled for future research.

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