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Active cavity expansion through lingual adjustments to place of constriction in voiced geminates

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Geminate voicing is cross-linguistically not preferred (Ohala 1997). Voicing requires both active and passive cavity expansion to maintain a pressure gradient across the vocal tract. Maintainting length contrast and sustained voicing during closure is key for languages like Bengali that make both length and laryngeal contrast in the articulation of stops. Previous studies have reported that stop closure durations and pre-geminate vowel durations vary with laryngeal contrast. Studies have also shown that coarticulatory resistance (CR) varies with change in place of articulation (Recasens 1997). This paper reports results from the analysis of formant transitions in the VC:V (vowel-geminate stop-vowel) context for partial recovery of the area function behind the geminate constriction using the anti-symmetric Fourier component coefficient. Voiced geminates exhibit significantly higher and positive coefficients than their voiceless counterparts. This implies that measured Fn values for voiced geminates are lower than their neutral tract formant values. Without ruling out the role of passive cavity expansion, we conclude that in order to delay the pressure equalization, the lingual constriction in voiced geminates is maintained at an anterior location in Bengali. Locus Equation (LE) slopes have been shown to have an inverse relationship with CR (Iskarous 2010). Analysis of the slopes of first order F2 (second formant) LEs indicate that voicing significantly increased the LE slopes compared to the voiceless geminates ($p < 0.05$). This suggests lower resistance to vowel coarticulation in voiced geminates.

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1. INTRODUCTION

Studies on the production of voiced geminates have shown that maintaining voicing during gemination requires adherence to the Aerodynamic Voicing Constraint (AVC)[1] that specifies that a pressure differential be maintained between the sub-glottal and oral cavities. A general mechanism of oral cavity expansion is one way to maintain this pressure differential. While previous studies have shown that active cavity expansion may include strategies such as lowering the larynx, lowering the tongue body, raising the velum, and expanding the pharyngeal walls[2,3], what has not been shown so far is if the location of the lingual constriction could also be made anterior in voiced geminates to achieve the goal of active oral cavity expansion. In this paper on Bengali voiced and voiceless geminates, we show that lingual adjustments to the place of constriction of stops can help in oral cavity expansion, and aid in increasing the perceptual salience of geminate stops.

Constraints of the articulatory system make it challenging to sustain voicing[3]. One of the acoustic cues essential for the perception of voiced stops is voicing sustained for the closure duration of the stop. This is known to aid the realization of a voiced-voiceless laryngeal contrast[4,5,6]. Moreover, aerodynamic challenges to voicing are known to significantly affect the length of closure duration. Length plays a key role in the phonemic realization of the singleton-geminate contrast, especially in the intervocalic context. Several languages that make the cross-linguistically rarer voiced-voiceless distinction for geminates (such as Bengali, Japanese, Hindi, and Pattani Malay) employ strategies to maximize sustained voicing during closure duration. Active oral cavity expansion for the duration of the occlusion is one such strategy.

Bengali was chosen for this study because it exhibits both length as well as a laryngeal contrast in the realization of stops. Bengali is primarily spoken in the East Indian state of West Bengal, and in Bangladesh, among other places in the world. Previous work on voiced and voiceless Bengali geminates shows that despite the reliance on secondary acoustic cues for the perception of the length contrast, voicing during closure plays a key role in distinguishing voiced geminates from their voiceless counterparts[4,7,8].

This paper focuses on strategies for sustained voicing during closure to aid the perception of voiced geminates, especially lingual adjustments for active cavity expansion; and consequently, cues like V-C (vowel-consonant) and C-V (consonant-vowel) coarticulatory resistance (CR). It is organized as follows: Section 2 will focus on the articulatory constraints of producing voiced geminates, the acoustic features of geminates, the historical roots of geminate stops in Modern Indo Aryan (MIA) languages such as Bengali, the use of partial estimation of vocal tract area using anti-symmetric Fourier coefficients, the relationship between F_2 Locus Equations and coarticulatory resistance, and the scope of this research. Section 3 will highlight the protocol for collection of acoustic data, and details of the three studies conducted (linear mixes effects models used for the analysis of closure durations, area function coefficients and F_2 Locus Equations). Section 4 reports the results of the experiments conducted, and Section 5 comprises a discussion of the results and our concluding remarks.

2. ACOUSTIC PROPERTIES OF GEMINATION

In this section we discuss the relevance of the Aerodynamic Voicing Constraint, the attendant acoustic cues associated with gemination, and also the anti-symmetric Fourier Coefficients that help in understanding the volume of the cavity behind the constriction.

A. VOICING AND ARTICULATION: AERODYNAMIC VOICING CONSTRAINT

The relationship between voicing and maintaining a long closure duration, is subject to the Aerodynamic Voicing Constraint (AVC)[1]. Long closure duration is known to inhibit voicing, and this is reflected in cross-linguistic patterns in geminate stops towards a preference for voicelessness[3,9,10].

Voicing requires pressure in the oral cavity (P_{oral}) to be lower than the pressure in the sub-glottal cavity (P_{sub}), in order to maintain continuous airflow through the glottis. For optimal voicing, this pressure difference must be kept as high as possible (δ P_{glot} = P_{sub} - P_{oral} = max)[1]. At the same time, pressure in the oral cavity must be kept higher than the atmospheric pressure ($P_{oral} > P_{atmospheric}$) for plosion. Since the production of obstruents causes air to build in the oral cavity, if the pressure difference across the glottis cannot be maintained, voicing will cease.

The compliance or 'give' of the soft components of the articulatory system (such as the vocal tract walls and cheek tissue) allows for some expansion. Such passive methods of oral cavity expansion improve the duration of voicing by slightly increasing the volume available to accommodate the accumulating air. This depends upon the availability of soft tissue behind the constriction. Thus, place of articulation will have an effect on closure duration.

Passive cavity expansion is not enough to sustain voicing for the duration of speech segments. For the articulation of stops, sustained voicing during the closure duration requires active expansion of the oral cavity for pressure differential maximization. Strategies such as lowering the larynx, lowering the tongue, elevating the soft palate, and expanding the pharyngeal walls are employed by different languages to increase the volume of the cavity behind the constriction[3]. Voiceless segments do not require oral cavity expansion, because the length of the closure duration is not affected by such articulatory constraints.

In the case of voiced geminates, AVC makes the phonetic realization of [+voice] even more challenging. Partial devoicing during the closure duration of voiced geminates has been observed in languages such as Sienese Italian and Japanese[6,11]. In Bengali, voicing has been shown to shorten closure duration for both geminates and singletons[8] . To preserve the voicing and length contrast, the limitations of the articulatory system need to be overcome through active cavity expansion (for a longer closure duration).

One strategy for increasing the volume behind the constriction in lingual stops is through minor adjustments to the position of the tongue. If the constriction shifts to an anterior direction during the articulation of voiced geminates, the volume of the cavity will increase. This would also aid passive cavity expansion as there would be a minor increase in the amount of soft tissue available in the cavity.

B. ACOUSTIC FEATURES OF GEMINATION

Durational and non-durational cues also play a role in the phonemic length distinction of geminate stops. The importance of length was also established by Abramson[12], when it was shown to be perceived in word-initial voiceless stops in Pattani Malay, despite the absence of a signal. Cross-linguistically, closure duration is known to be a salient perceptual cue for the singleton-geminate contrast in intervocalic or word-medial positions. For stops, this is a period of no (in the case of the former) or low (in the case of the latter) glottal excitation in-between two segments with high amplitude signals. This makes relative differences in length one of the most significant perceptual cues for singleton-geminate distinction, despite cross linguistic variation[5,7]. In addition, analysis of word-initial geminate stops has also shed light upon the importance of secondary acoustic cues in the disambiguation of this contrast. Work on Bengali geminates has been sparse, with voiceless geminates being the focus of most studies.

In languages like Pattani Malay, disambiguation of word-initial geminates relies on secondary acoustic cues such as the burst amplitude of the stop, and the fundamental frequency of the following vowel[13,14,15]. Here, the reduced reliability of closure duration makes other cues essential to the identification of the singleton-geminate contrast. These are relevant to a discussion about voiced geminates, because the effects on the length of closure duration make it important for listeners to depend on other acoustic cues for perception.

Ghosh[8] compared inter-vocalic voiced and voiceless geminates with inter-vocalic singletons in Bengali. Their study corroborated the findings of the work on word-initial geminates in Pattani Malay, namely, secondary, non-durational acoustic cues (burst amplitude and F_0 of neighboring vowels) also play a role in the

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[1] Here, and elsewhere, δ P_{glot}, refers to unit change in glottal pressure.

distinction of intervocalic geminates. Ghosh[8] also discusses V-to-V coarticulation, but only in the context of voiceless dental geminates. In this paper, coarticulation and its interaction with place of articulation and the presence/absence of voicing in geminates is discussed.

Ghosh[8] underscores the importance of closure duration for inter-vocalic singleton-geminate contrast. Ghosh[8] showed that although closure duration was lowered when voicing occurred, it was still significantly different for singleton and geminate voiced stops. This makes it important to study strategies that help increase the salience of closure duration length in languages that maintain a laryngeal contrast among geminates.

In this study, intervocalic voiced and voiceless geminates are compared to observe the effects of voicing on closure duration, place of constriction, and coarticulatory resistance. Dental, retroflex, and velar places of articulation were chosen to examine lingual adjustments and for the analysis of F_2 locus equations.

C. STOP CONSONANT LENGTH CONTRASTS IN BENGALI

Bengali has bilabial, dental, retroflex, and velar stops, with length and laryngeal contrast. This leads to four possibilities for stops, for every place of articulation. The following examples illustrate the contrast in the dental place of articulation:

(1) a. pa**t**a *‘leaf’*

b. pa**t**ːa *‘whereabouts’*[4]

(2) a. aː**d**i *‘origin’*

b. a**d**ːi *‘fine muslin’*

One source of intervocalic geminates is the assimilation of consonant clusters from Sanskrit. Modern Indo Aryan (MIA) extensively and drastically assimilated hetero-organic CC (in a few cases, CCC and CCCC) clusters from Old Indo Aryan[16]. Evidence of gemination as an assimilation strategy is seen in Pali (and subsequently, its daughter languages). Unlike languages such as Japanese in which voiced geminates are only seen in loan words, many MIA languages, such as Hindi, Marathi and Bengali have lexical items with such segments. Some examples of cluster simplification from Sanskrit to Pali as found in Masica[16]:

(3) a. bha**kt**a → bha**t**ːa *‘meal, food’*

b. mu**dg**a → mu**g**ːa *‘mung bean’*

c. t͡ʃa**kr**a → t͡ʃa**k**ːa *‘wheel’*

d. pa**kv**a → pa**k**ːa *‘cooked, ripe’*

e. ni**dr**aː → ni**d**ːaː *‘sleep’*

f. pu**ʃk**ara → pu**k**ːara *‘blue lotus’*

g. ta**tv**a → ta**t**ːa *‘reality’*

D. LINGUAL ADJUSTMENTS FOR ACTIVE CAVITY EXPANSION AND COARTICULATORY RESISTANCE

Early analyses of oral cavity geometry through acoustic measures were conducted by Schroeder[17] and Mermelstein[18]. Schroeder[17] demonstrates the methodology for modeling the area function; further elaborated in Iskarous[19]. In Iskarous[19], this methodology is considered for the partial recovery of area functions of the oral cavity. The relationship between the anti-symmetric Fourier Coefficients and cross-sectional area of the tube can be used to determine ‘frontness’ through sets of formants obtained from recorded speech. The model uses formula 1:

$$a_{2n-1} = -2\frac{F_n^{CO} - f_n^{CO}}{f_n^{CO}} \tag{1}$$

Here, a_{2n-1} is the Anti-Symmetric Fourier Coefficient associated with a formant, F_n^{CO} refers to the measured formant, f_n^{CO} to the formants of a neutral tube in the closed-open (CO) condition, and ‘n’ is a natural number indicating the formant being studied (the first formant would be F_1, for instance). The lengths of the tubes are assumed to be 17.5 cm for males, and 16.5 cm for females, for estimating neutral formant values.

In Figure 1, the spatial Fourier transform of the logarithm of the area function (AF)[19] is shown on the y-axis. The x-axis is a measure of the length of the cavity (in cms) behind the constriction. In Figure 1, as the coefficients lower and become negative, the length of the cavity behind the constriction (‘back’) increases:

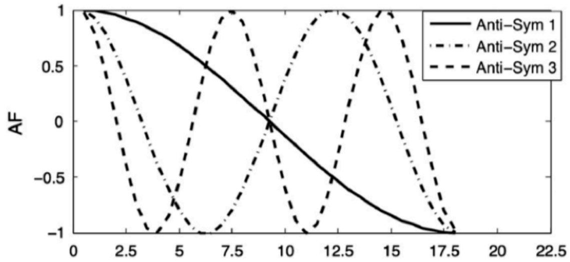

Figure 1: The relationship between symmetric and anti-symmetric Fourier components for F_1 and F_2 and length of the oral cavity[19]. AF on the y-axis is the unitless spatial Fourier transform of the logarithm of the area function. The x-axis is the length of the cavity behind the oral constriction (in cms).

In this paper, the recovery of partial information about the area function of the vocal tract behind the geminate constriction is carried out using the anti-symmetric components of the area function. The neutral coefficient values are estimated from the given tube lengths, and formant values are extracted from different parts of the vowels adjoining the geminate stops. The coefficients calculated are analyzed as follows: Higher and positive coefficients from the F_1 and F_2 values imply that measured F_n values are lower than their neutral tract formant values. This in turn implies a higher tongue position in case of F_1, and a more anterior tongue position in the case of F_2.

Studies have also shown that coarticulatory resistance (CR) varies with change in place of articulation[20]. Consonants with different places of articulation, and by extension, constriction locations, covary with the amount of tongue dorsum involvement. Anticipating voiced gemination, the tongue dorsum may be moved in an anterior direction so as to facilitate voicing through active expansion of the cavity behind the constriction. This leads to the prediction that different amounts of CR may be observed in the pre-geminate vowel offsets for voiced and voiceless geminates, as a consequence of planning for different constriction locations.

Moreover, in the C-V context, the difference in constriction location may result in persevatory effects that may change the CR observed for different laryngeal contexts. Analyses of vowel onsets in the C-V and vowel offsets in V-C contexts would also shed light on the asymmetry between anticipatory and carryover coarticulatory propensity between voiced and voiceless geminates.

First order F_2 Locus Equations (LE) have been used to model the variation in coarticulatory resistance due to phonetic contexts[21,22,23]. F_2 values were compared for vowel nuclei and vowel-consonant boundaries, in both V-C (to study anticipatory effects) and C-V (to study carryover effects) contexts. LE slopes are an index of coarticulatory resistance (CR) and were derived using formula 2[22]:

$$F2_c = \beta + \alpha F2_v \tag{2}$$

Here, $F2_c$ refers to the F_2 values measured at 95% of V_1, and $F2_v$ refers to the F_2 values measured at 50% of V_1 for the V-C context (offset of the pre-geminate vowel). In the C-V context (onset of the post-geminate vowel), $F2_c$ refers to the F_2 values measured at 5% of V_2, and $F2_v$ refers to the F_2 values measured at 50% of V_2. The intercept of the linear relationship between $F2_c$ and $F2_v$ is represented by β. LE slope is measured using $\alpha = \rho\left(\frac{\sigma_c}{\sigma_v}\right)$. Here, ρ is the correlation coefficient. σ_c refers to the standard deviations of F_2 values at 95% and 5% of V_1 and V_2, respectively. σ_v refers to the standard deviations of F_2 values at 50% of V_1 and V_2 (vowel nucleus). Steeper slopes are a measure of greater coarticulation and lower coarticulatory resistance. In Ghosh[8], variation in CR has been linked to changes in place of articulation and vowel quality, but not gemination. In this paper, slopes of first-order F_2 Locus Equations are compared for voiced and voiceless geminates to test if lingual adjustments result in asymmetrical coarticulatory effects in the V-C and C-V contexts.

E. RESEARCH QUESTIONS

In order to understand the influence of voicing on gemination, we analyze the effect of voicing on the closure duration. A significantly shorter closure duration is predicted across all three places of articulation for voiced geminates; a universally attested pattern. Since, shorter closure durations for voiced geminates may endanger the singleton-geminate contrast, we expect strategic lingual adjustments to ensure enlargement of the cavity behind the constriction to sustain voicing. We analyze the Anti-Symmetric Fourier Coefficient to observe shifts in the tongue position at the offset and onset of the geminates.

The consequence of lingual adjustments would be changes in coarticulatory resistance patterns, between voiced and voiceless geminates. We analyze first order locus equation slopes, known indices of CR, to ascertain differences in CR between voiced and voiceless geminates; both in the V-C and C-V contexts.

3. MATERIALS AND METHODS

A. MATERIALS

Five male and five female native speakers of Bengali from West Bengal participated in this study (ages 21-28, with a median age of 23). All subjects were students at the English and Foreign Languages University, and reported no known speech or hearing difficulties. All subjects had received formal instruction in Bengali till the secondary school level. None of the participants had prior linguistic training.

Thirty six Bengali words were chosen with intervocalic geminate stops. Eighteen items had voiced geminate stops, while the other eighteen had voiceless geminate stops. Dental, retroflex and velar places of articulation were equally represented.

Items consisted of $V_1C{:}V_2$ sequences in a carrier phrase, where V_1 is from the set /a, o, ɔ, i, u/, and V_2 is from the set /a, e, i, o, u/. The items were placed in a carrier sentence, and the block of sentences was repeated four times.

All recordings were carried out using a fixed cardioid condenser microphone (Shure Beta 53), and digitized with a sampling rate of 22.5 kHz. The carrier sentences were displayed one at a time on a computer screen, with the subject changing sentences using a trackpad.

The recordings were analyzed in Praat 6.0.4[24]. Audio files were annotated using Prosodylab-Aligner[25], and the segmental boundaries were manually checked and corrected to ensure accuracy. Boundaries to mark closure durations and bursts were added to the textgrids using a script for inserting components[26]. These were also checked and corrected manually, wherever needed.

The analysis of F_2 Locus Equations and the Partial Area Function Estimation Models required formant values. Formant frequencies were measured at 10 evenly spaced points in the vowels (with the baseline for male speakers at 4000Hz and 4500Hz for female subjects), using method proposed by Escudero et al.[27] for calculating the optimal formant ceilings. Burg formant ceiling optimization was then applied to the formant ceilings (using the methods proposed by Escudero et al.[27]) for variance minimization, and corresponding F_1 and F_2 values for the ceilings were collected from from 20 evenly-spaced parts of the vowel.

B. METHODS

Linear Mixed Effects (LME) models were used for analyzing the effects of voicing on Closure Duration, Partial Area Function Estimates, and the F_2 Locus Equations.

For the first part of this study, closure durations of voiced and voiceless geminates were compared. The LME model was fitted for laryngeal contrast with two levels- voiced and voiceless. For the full model, laryngeal contrast, place of articulation, and vowel identity of V_1 and V_2 were taken as fixed effects. Intercepts for sex, subject and iteration were taken as random effects. The null model had all the same effects, except for laryngeal contrast.

The analysis of the Anti-Symmetric Fourier Component was carried out for V_1 and V_2 separately. The LME model was fitted between a_1 and laryngeal contrast with two levels; voiced and voiceless. Laryngeal contrast, vowel identity, and place of articulation of the geminate were taken as fixed effects. Random effects were intercepts for items, iterations, and by-item and by-iteration random slopes for the effect of laryngeal contrast. The same model was then used to analyze a_2. The Lobanov normalized a_1 and a_2 values were taken at 95% of V_1 and at 5% of V_2.

For F_2 Locus Equations (LE), F_2 values at the vowel nucleus were analyzed with F_2 values obtained from the vowel-geminate boundary, to find out if voiced geminates offered a significantly different amount of coarticulatory resistance than voiceless geminates. F_2 values obtained from 55% and 95% of V_1 were chosen for the V-C cluster. Values from 5% and 50% of V_2 were analyzed for the C-V cluster. LE slopes obtained from V-C_{Voiced} and C_{Voiced}-V were compared with V-$C_{\text{Voiceless}}$ and $C_{\text{Voiceless}}$-V respectively for both V_1 and V_2. The LME took laryngeal contrast, place of articulation, and sex as fixed effects, and slopes for subject as the random effect.

4. RESULTS

A. ANALYSIS OF CLOSURE DURATION

In Figure 2, closure durations (in milliseconds) have been grouped by place of articulation (POA) and laryngeal contrast, and have been represented by box-and-whisker plots. The lower and upper horizontal sides of every box plot represent the first and third quartile of the distribution respectively, while the horizontal lines at the center of the box represent the median value. The whiskers in every box plot represent all values of closure duration that are less than 1.5 times away from the quartile value they are closest to (for instance, in the top left box plot, the vertical line extending from 180-220 ms approximately represents all closure durations, within 1.5 times of the third quartile for voiced dental stops). Closure duration values that fall within the range of the first and third quartile are enclosed within the box. The dots represent outliers, or values that are at a distance more than 1.5 times the quartile value they are closest to. This method for summarizing and graphically representing data distribution is kept consistent for all box-and-whisker plots in this paper.

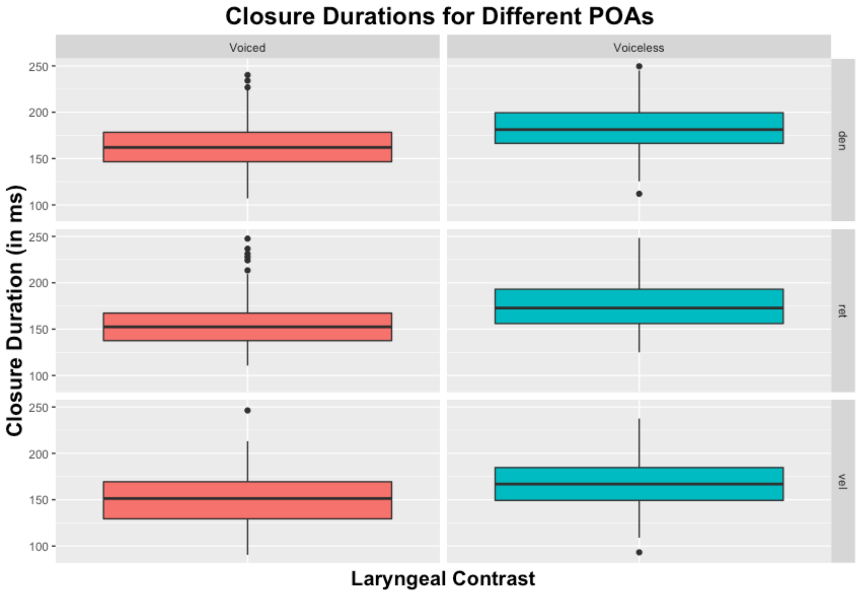

Figure 2: Closure Duration Patterns from Voiced and Voiceless Geminates

The values for voiced geminates were distributed around a mean closure duration of 156.4678 ms with a standard deviation of 27.2009 ms, while voiceless geminates had a mean value of 176.4679 ms and a standard deviation of 27.7948 ms. The likelihood ratio tests of the full model with laryngeal contrast against a model without laryngeal contrast showed that closure durations for voiced geminates were significantly shorter by 20 ms (± 5.101 standard error, t= 3.934) than voiceless geminates. The model also showed that place of articulation (POA) has an effect on closure duration. This finding is consistent with previous studies[8].

In the data collected, closure durations of voiced geminates for all three places of articulation (POAs) are consistently lower than their voiceless counterparts. Closure duration decreases with change in place of articulation (dental > retroflex > velar), as discussed by Hayes and Steriade[28] and Ohala[10]. The effects of voicing on closure duration are significant for all three places of articulation. Compared to the model's estimate of mean of 165.019 ms for voiced dental geminates, retroflex closure durations are shorter by 9.984 ms (±3.654 standard error, t= -2.732) and velar closure durations are shorter by 17.162 ms (±3.654 standard error, t= -4.697).

B. ANALYSIS OF ANTI-SYMMETRIC FOURIER COMPONENT

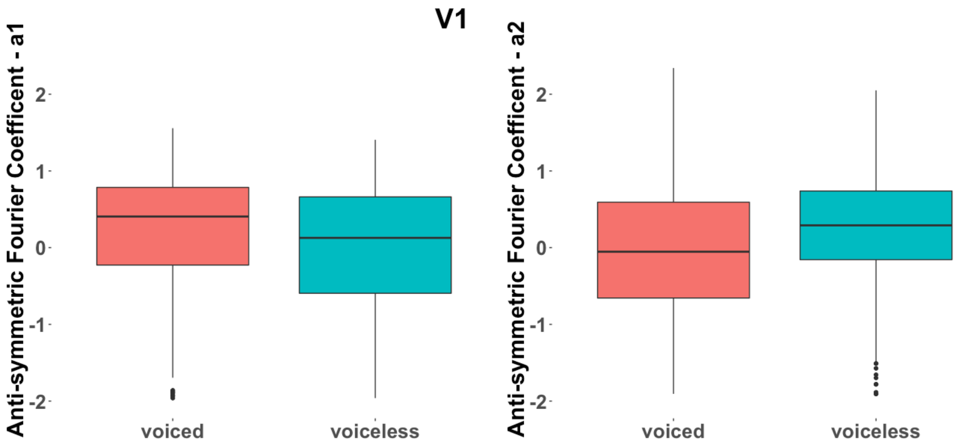

Figure 3: V1 patterns from the first and second Fourier coefficients

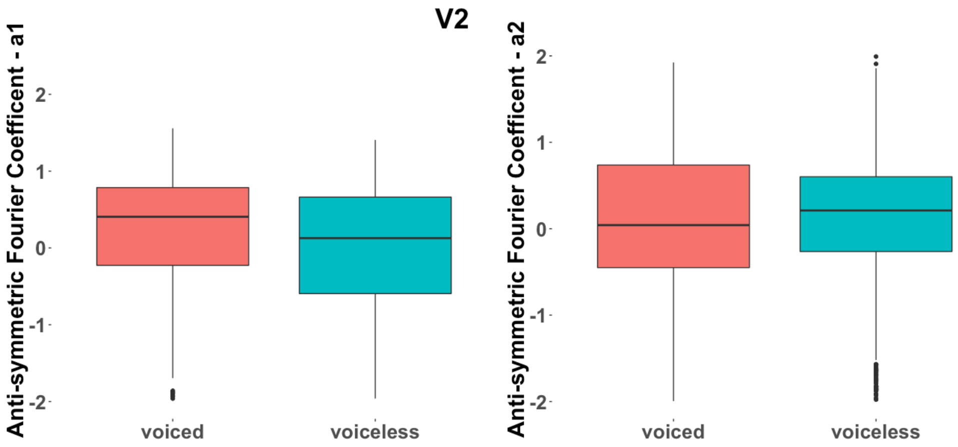

Figure 4: V2 patterns from the first and second Fourier coefficients

Figure 3 and Figure 4 are box plots that represent the anti-symmetric Fourier coefficients a_1 and a_2 (corresponding to the observed first and second formant values) for the pre-geminate vowel offset (V_1) and post-geminate vowel onset (V_2) that compare the voiced and voiceless contexts. As observed in the figures, median a_1 values are higher for voiced stops and all median values for both V_1 and V_2 are positive values.

At the vowel offset of V_1, the mean a_1 value for voiced geminates was 0.1170, with a standard deviation of 0.9497, while voiceless geminates had a mean a_1 value of -0.1158 and standard deviation of 1.0352. For the effect of laryngeal contrast on a_1, the LME obtained a p=0.0088 by conducting likelihood ratio tests of the full model with laryngeal contrast, against a model without laryngeal contrast. a_1 values for voiceless geminates were found to be significantly lower (by a difference of 0.2984 units, ± 0.0725 standard error) than those of voiced geminates, while the coefficients for voiced geminates were higher and positive. This indicates a longer tube behind the place of constriction, in all vowel contexts. No significant effect was found on a_2 (p=0.2487), indicating that tongue height was not affected by voicing.

For V_2, the mean and standard deviation values for a_1 were 0.1382 and 0.9549 respectively for voiced geminates, while voiceless geminates showed a mean value of -0.1367, with a standard deviation of 1.0254. The same LME model was used as V_1 to obtain p=0.0099 for the effect of laryngeal contrast on a_1 at vowel onset of V_2, indicating that the coefficients for voiceless geminates were significantly lower (by a difference of 0.2703 units, ± 0.1003 standard error) than those for voiced geminates. The coefficients obtained for a_1 were positive, indicative of an anterior constriction. No significant effect of voicing were found when the model was used to analyze a_2 (p=0.4267).

C. ANALYSIS OF F_2 LOCUS EQUATIONS

In vowel offsets of the V-C clusters, the mean locus equation (LE) slope for voiced geminates was 0.6703, with a standard deviation of 0.2267. For voiceless geminates, mean LE slope was 0.5408 and standard deviation was 0.2182. The analysis of the full and null LME models for V-C clusters showed that this difference of 0.1295 in the slopes of the locus equations was significant (p=0.0062, ±0.0461 standard error). Voicing significantly increased the LE slopes compared to the voiceless geminates (this result is further represented in Figure 6). This suggests lower resistance to vowel coarticulation in voiced geminates, as a consequence of higher tongue dorsum involvement and an anterior shift in the constriction location.

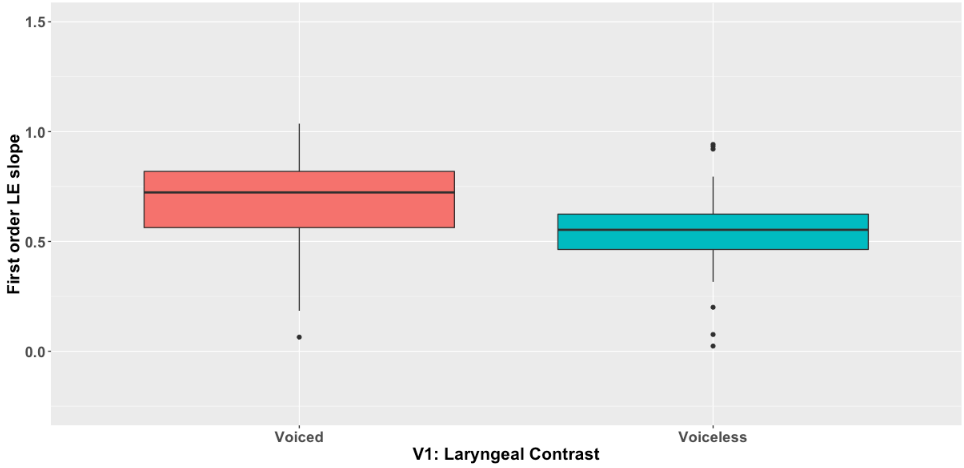

Figure 5: Boxplot comparing First Order Locus Equation slopes for voiced and voiceless geminates (V-C context)

This relationship between the locus equation slopes and voicing is seen in the box-and-whisker plot in Figure 5 (this plot uses the same visual representation as Figure 2). A majority of slope values are higher for the pre-geminate vowels, if the consonants following them are voiced geminates.

Figure 6 represents the values from the V-C offset. F_2 values at the vowel nucleus, that is, the x-axis ($F2_v$ from 2), are plotted against the F_2 values at the V-C boundary (95% of V_1), that is, the y-axis ($F2_c$ from 2). The slope of the plot of voiceless geminates (blue) is found to be significantly lower than that of voiced geminates (red). Based on the steeper slopes associated with the voiced geminates we surmise that the voiced geminates exhibit greater coarticulation and lower coarticulatory resistance compared to their voiceless counterparts.

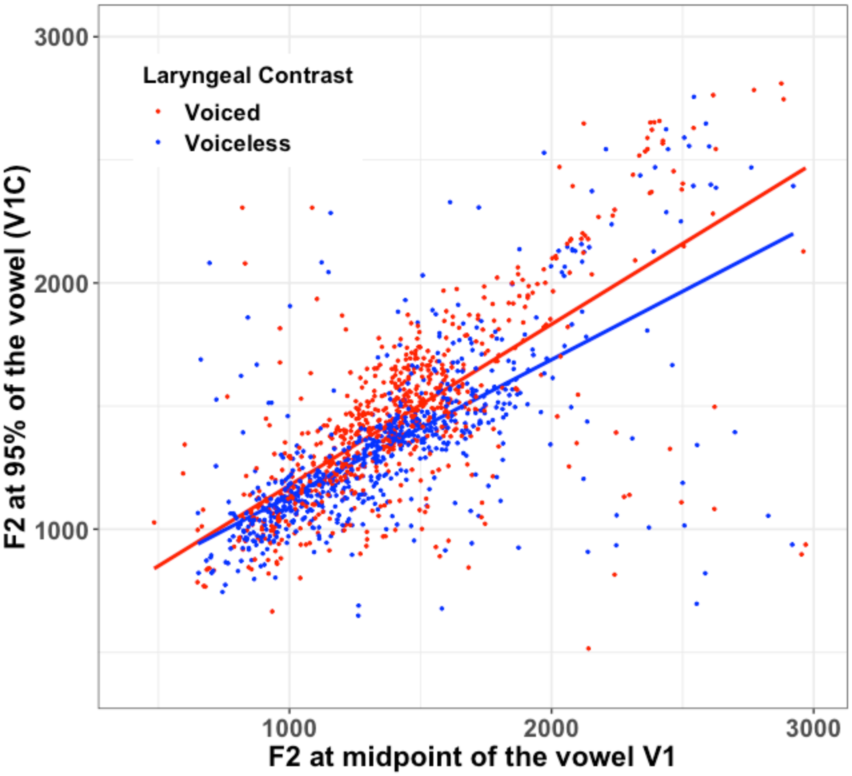

Figure 6: Plot of F_2 values at the vowel nucleus and vowel-consonant boundary

The results for the C-V onset context were not significant. This indicates that the effects of voicing on coarticulatory resistance are no longer appreciable after the occlusion is released. Since F_2 Locus Equations are influenced by the amount of tongue dorsum contact, this may be indicative of lingual adjustments not being maintained after the burst.

5. DISCUSSION

Geminate closure duration is affected by voicing. In order to produce a geminate with a longer closure duration, articulatory constraints of voicing need to be overcome through effective strategies for active cavity expansion. While previous studies have pointed out the presence of active oral cavity expansion strategies, such as lowering the larynx, lowering the tongue, elevating the soft palate, and expansion of the pharyngeal walls[2,3], previous work does not show if similar expansion of the oral cavity can also be achieved through slight adjustments to lingual place of constriction.

In this study, closure duration for voiced geminates was found to be significantly shorter than voiceless geminates, indicating the effect of the Aerodynamic Voicing Constraint (AVC) on the length of the constriction. Based on the analysis of the Anti-Symmetric Fourier Coefficients, we claim that lingual adjustments towards an anterior place of constriction may also help achieve active cavity expansion in voiced geminates. We find that voiced geminates exhibit significantly higher and positive coefficient values compared to their voiceless counterparts. The implication for this finding is that the observed F_1 values for voiced geminates are lower than their neutral tract formant values. At least in the V-C context, an anterior shift in the lingual constriction helps delay pressure equalization in voiced geminates, allowing them to be voiced for a longer duration.

Studies on the effects of place of articulation on degree of coarticulatory resistance indicate that changes in tongue position would be accompanied by complementary changes in coarticulatory resistance. We find that the effects of coarticulatory resistance (CR) in the V-C context are significantly different between voiced and voiceless geminates. However, effects of CR in the C-V context are not significant. Our findings lend support to a hitherto unattested claim that voicing induces lingual adjustments for active cavity expansion in contrast with earlier findings[8,29]. This effect is significant only in the anticipatory direction (V-C context), which implies that, at least in Bengali, lingual adjustments are a consequence of speech planning.

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