ACOUSTIC EVIDENCE OF ARTICULATORY ADJUSTMENTS TO SUSTAIN VOICING DURING VOICED STOPS[1]

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ABSTRACT

The present study seeks to provide acoustic evidence of articulatory adjustments to initiate and sustain voicing during stops. First, using aerodynamic and acoustic data, it examines variations in the amplitude of voicing in phrase-initial voiced stops in Spanish and English and relates these variations to articulatory adjustments to preserve a low oral pressure and voicing.

Second, a correlation is sought between oral pressure and voicing amplitude during stop closure. The correlation is significant for all Spanish (4) and English (2) speakers; as oral pressure rises, voicing amplitude decreases. The study concludes that articulatory adjustments to keep a low intraoral pressure for voicing may be inferred from the time course of voicing amplitude during the stop closure. Significant differences between prevoiced stops in the two languages are found, with overall higher values for oral pressure and lower values for voicing amplitude in English than in Spanish.

Keywords: voiced stops, voicing amplitude, aerodynamics, acoustics, Spanish, English.

1. INTRODUCTION

It is known that it is difficult to sustain voicing during obstruents due to the 'Aerodynamic Voicing Constraint' (AVC) [6, 7]. During the stop closure air accumulates in the oral cavity, oral pressure rises and the pressure differential ($P_{subglottal}$-P_{oral}) falls below the threshold for voicing (1-2 cmH_2O, [3]). Thus in English, voicing ceases after a few tens of ms in medial and final voiced stops, and vocal fold vibration may not occur in phrase-initial stops. Many languages, however, use voicing during the stop closure to cue the voiced-voiceless contrast (e.g., Spanish, French, Catalan, Dutch) which suggests that languages have found ways to circumvent the AVC.

Previous studies [8, 10] have provided evidence of a number of ways in which speakers may slow down or reduce the build-up of oral pressure (P_o) during stop closure, and thus allow phonation to last longer or initiate earlier. Three basic mechanisms have been reported:

- passive expansion of the oropharyngeal walls by reducing the level of muscle contraction.
- active enlargement of the oral cavity (lowering the larynx, elevating the soft palate, advancing the tongue root, depressing the tongue body).
- releasing airflow through an incomplete oral or velopharyngeal closure.

The use of such adjustments varies across languages, thus languages with typically prevoiced stops (e.g., Spanish and French) show a significantly higher incidence of pressure-lowering adjustments than English with little, if any, voicing during voiced stop closure [9]. The specific adjustments used (i.e., nasal leak, oral leak, larynx lowering, etc.) vary within and across speakers and segments, and possibly across languages [1, 10].

Aerodynamic data (e.g., oral and subglottal pressure, oral and nasal airflow), and less often physiological data, are customarily examined to determine the occurrence of voice-facilitating gestures during voiced stops. Such pressure-lowering gestures, however, have consequences on the amplitude of voicing[2] and may therefore be observed in the sound pressure signal. Given that subglottal pressure may be assumed to be constant, a decrease in oral pressure during the stop closure will increase the transglottal pressure difference and thus transglottal airflow, and the vocal folds will vibrate at larger amplitudes.

This paper focuses on describing the variations in the relative *amplitude of voicing* during stop closure caused by articulatory adjustments directed at lowering the P_o and hence sustain or initiate voicing. We are thus interested primarily in changes in the amplitude of voicing, since they offer clues to the less accessible aerodynamic and physiological variations across languages and subjects. By restricting ourselves to acoustic data, however, it is not possible to differentiate the way in which such pressure changes have been accomplished. Nonetheless, it is possible to infer that a P_o lowering maneuver to preserve or initiate voicing has indeed taken place.

We first present acoustic and aerodynamic evidence from Spanish and English illustrating how a variety of articulatory maneuvers during phrase-initial voiced stops affect oral pressure and voicing amplitude, and then correlate oral pressure changes with voicing amplitude.

2. MATERIALS

Oral pressure, nasal airflow, oral flow and audio were recorded for utterance-initial /b/, /d/, /p/, /t/ and /m/ produced by 10 Spanish speakers and six English speakers ten to thirteen times each. Only the results for 4 Spanish speakers (3 female, F1, F2, F9 and 1 male, M6) and the 2 English speakers who had prevoiced stops (one male, M3, one female, F6) will be reported here. This was a subset of the data analyzed in [9] (see this work for further experimental details). The subjects were instructed to read the following sentences as if they were a dialogue between A and B in order to obtain two isolated utterances, with the segment of interest being the beginning of the second utterance (the /b/ in Bárbara, the /d/ in Débora, etc).

A: ¿Cómo se llama ella? (‘What’s she called?’)
B: **B**árbara [**D**ébora, **P**aula, **T**ábata, **M**arta].

Some English speakers produced ‘Dolly’ instead of ‘Deborah’ because the tube measuring oral pressure interfered with the production of the middle consonants. All sentences were sampled at 22.050Hz.

3. AMPLITUDE OF VOICING AND VOICING ADJUSTMENTS

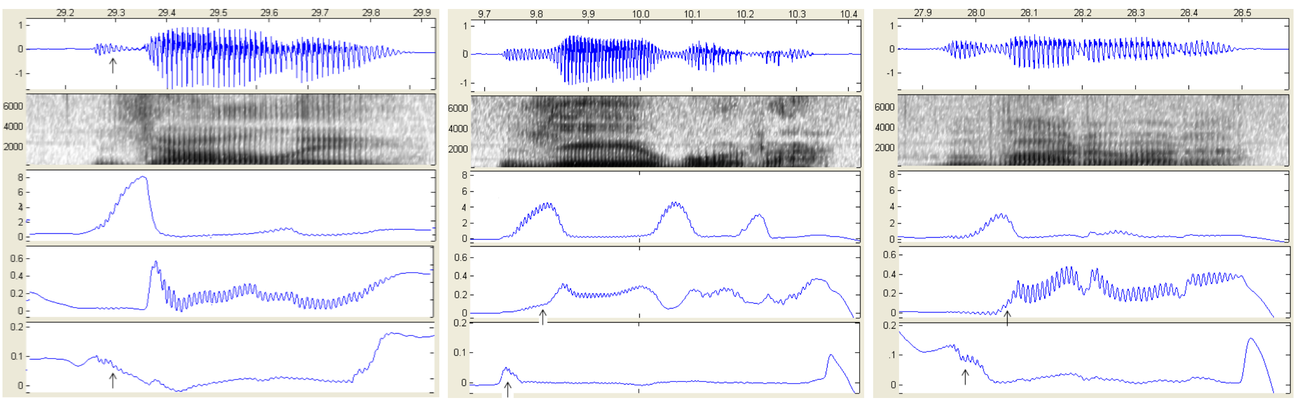
In this section we examine the time course of amplitude of voicing, on the one hand, and oral pressure and oral/nasal flow variation, on the other, and relate these parameters to physiological adjustments to initiate/prolong vocal fold vibration during voiced stop closure.

It has been commonly observed that the amplitude of voicing typically decreases during the closure for the voiced stop [4]. This is because during the stop closure, oral pressure rises and transglottal flow is reduced, thus diminishing the amplitude of voicing; as transglottal pressure equalizes the vocal folds cease to vibrate, resulting in passive devoicing. The decrease in voicing amplitude is illustrated in Fig. 1a showing an English prevoiced stop (only 16.8% of the English tokens were prevoiced in our data vs. 83.2% devoiced); the amplitude of voicing increases in the first few glottal pulses and then decreases as intraoral pressure rises. Note the nasal flow (bottom panel) during the first third of the stop revealing a delayed closing of the velum relative to the oral closure. The nasal leak slows down oral pressure buildup (third panel) and helps achieve the transglottal pressure difference needed to initiate voicing. The waveform illustrates the increasing amplitude of glottal pulsing during the prenasalized portion, followed by decreasing amplitude of voicing when the velum begins to close (indicated by the arrows).

Spanish voiced stops (predominantly prevoiced; 85.6% in our data) do not typically show a marked decrease in the amplitude of glottal vibration (or cessation of voicing), suggesting additional articulatory adjustments to assist the continuation of vibration. Examination of Figs. 1b and 1c shows that the amplitude of the waveform is maintained (1b) or increases and then decreases only slightly (1c) during the time that the oral closure is maintained. In both Figures, nasal leak (see arrow in the bottom panel) occurs during the initial part of the stop closure to help initiate voicing and oral flow (due to incomplete oral closure; see arrow in the penultimate panel) occurs during the latter portion of the closure most likely to sustain voicing.

Figure 1: Waveform, 0-7 kHz spectrogram, oral pressure (in cmH_2O), oral flow and nasal flow (in l/s). (a) Example of decreasing amplitude of voicing in English /d/ in ***D****olly* (M3). (b) (c) Sustained amplitude of voicing with nasal leak followed by oral leak for Spanish /d/ in ***D****ébora* (F2) and /b/ in ***B****árbara* (M6). (d) Increasing amplitude during cavity expansion in Spanish /d/ in ***D****ébora* (M3). (e) (f) Implosivized tokens of Spanish /b/ in ***B****árbara* (M6) and (F1). See text for the arrows.

(a) (b) (c)



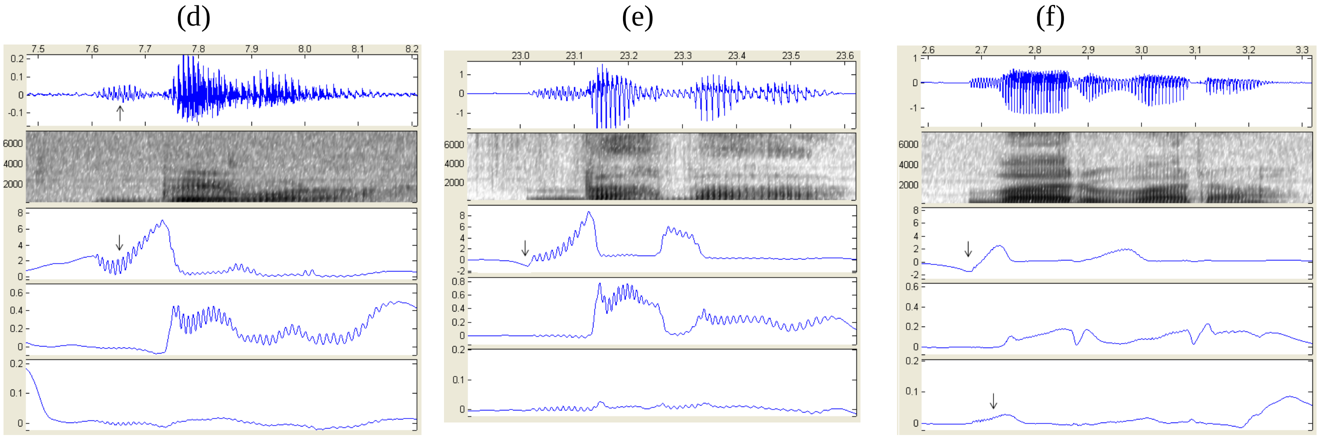


Fig. 1d shows increasing amplitude of the glottal pulses during the dip in oral pressure (concave pressure rise; panel 3) most likely due to a cavity enlargement maneuver [5]. That is, the cavity-expanding gesture during this interval amply accommodates the air flowing through the vocal folds, oral pressure momentarily decreases and transglottal flow and voicing amplitude increase.

Finally, Figs. 1e and 1f show negative pressure while the oral closure is held (indicated by the arrows in panel 3). Such implosivization of voiced stops reflects a cavity-enlarging gesture (generally larynx lowering) to assist the initiation of voicing. In Fig. 1e this cavity-expanding gesture most likely continues during stop closure as indicated by the slow oral pressure buildup and the increased amplitude of voicing till oral pressure reaches approximately 6cm H_2O. Note the sustained amplitude of voicing in Fig. 1f due to nasal leak (see arrow in last panel) during the stop closure.

We have used aerodynamic data to illustrate the motor strategies (nasal leak, oral leak, cavity enlarging gestures) used by Spanish and English speakers to initiate and sustain voicing during the stop closure. Such adjustments have observable consequences on the voicing amplitude, therefore acoustic data may be used to reveal the use of voice initiating/sustaining gestures, although it is not possible to know which specific adjustment the speaker made.

3. VOICING AMPLITUDE

The claim made in this paper is that variations in the voicing amplitude during stop closure allow us to infer articulatory adjustments aimed at lowering the oral pressure and thus sustain or initiate voicing. In order to support this claim, it is crucial to prove that amplitude of voicing is related to variations in oral pressure (since other factors may affect voicing amplitude, e.g. degree of vocal fold adduction). This is the purpose of this study. We hypothesized that oral pressure variations during stops should inversely correlate with voicing amplitude.

3.1. Acoustic analysis

The amplitude characteristics of voicing, as well as oral pressure at each voicing peak, were measured in the voicing lead interval for the voiced stops. Amplitude and oral pressure values over the voicing interval were extracted and correlated. Following [2], there were as many amplitude (and pressure) values as periods in the prevoiced interval. Each of the amplitude values was obtained by taking the first peak amplitude in the FFT spectrum of a 6 ms Hamming window centered at the glottal pulse for that period. The following vowel amplitude was measured to normalize the amplitudes measured in the voicing lead. The amplitude of the vowel was obtained by measuring the amplitude of the first harmonic in the spectrum of a 25 ms analysis window, which started at the third pulse after the burst, as suggested by [2]. The oral pressure was measured at the peak of each glottal pulse using Matlab.

The first two glottal pulses were not included in the correlational data. The inclusion of the first two glottal pulses creates a cluster of data points at low pressure and low amplitude values reflecting incipient laryngeal vibration rather than oral pressure effects.

3.2. Results

Due to space limitations, only the results for the initial labial stop in '***B**arbara*' will be presented here. Variation in normalized voicing amplitude during stop closure as a function of oral pressure for the individual Spanish and English speakers is shown in Figure 2. For all Spanish and English speakers voicing amplitude is inversely correlated with oral pressure; as oral pressure rises, voicing amplitude decreases. The relationship is significant for all speakers ($p < 0.001$), suggesting that oral pressure is responsible for variations in voicing amplitude. The correlations are moderate to high, between 0.53 and 0.84. The squared r values indicate that oral pressure accounts for 66% of the variance in amplitude for Spanish speaker F9, and 70% for English speaker F6. A linear regression line is fitted to the data for each speaker.

Fig. 2 shows that, in spite of a few negative pressure values for English speaker F6 (reflecting implosivization), English speakers exhibit significantly higher oral pressure values than Spanish speakers during prevoicing (mean = 3.75 cm/H_2O (SD = ±2.7) vs. 1.40 cm/H_2O (SD = ±1.35); $t_{(672)}$ = 8.85, p< 0.001), suggesting lesser passive enlargement and/or less effective active maneuvers for the former. The normalized voicing amplitude for Spanish was, on average, -8.4dB (SD = ± 5.5), which as expected was significantly higher than for English (mean = -11.3dB, SD = ± 5.6); $t_{(672)}$ = 5.62, p < 0.001). These results should be taken with caution as only a few speakers are analyzed.

4. CONCLUSIONS

In the first part of the study, examination of the aerodynamic and acoustic data indicated that increased amplitude of voicing during stop closure was achieved by articulatory adjustments to preserve a low oral pressure to initiate/sustain glottal vibration. The results of the study provide new data on intraoral pressure and amplitude values during Spanish voiced stops and additional data for English. Our data show the existence of a direct relationship between oral pressure and amplitude of voicing. We found significant differences between prevoiced stops in the two languages, with overall higher values for oral pressure and lower values for voicing amplitude in English than in Spanish.

Given the relationship between oral pressure and voicing amplitude, the present study suggests that articulatory adjustments to keep a low intraoral pressure for voicing may be inferred from the time course of voicing amplitude during the stop closure. The data raise the fundamental issue of the target specification for Spanish voiced stops which seems to include a laryngeal setting for voicing *and* the use of articulatory strategies to produce vocal fold vibration, as opposed to English voiced stops. It also raises the question of the inter- and intra-speaker variability in the choice of gestures to facilitate voicing, and how such variability can be accounted for by phonological models.

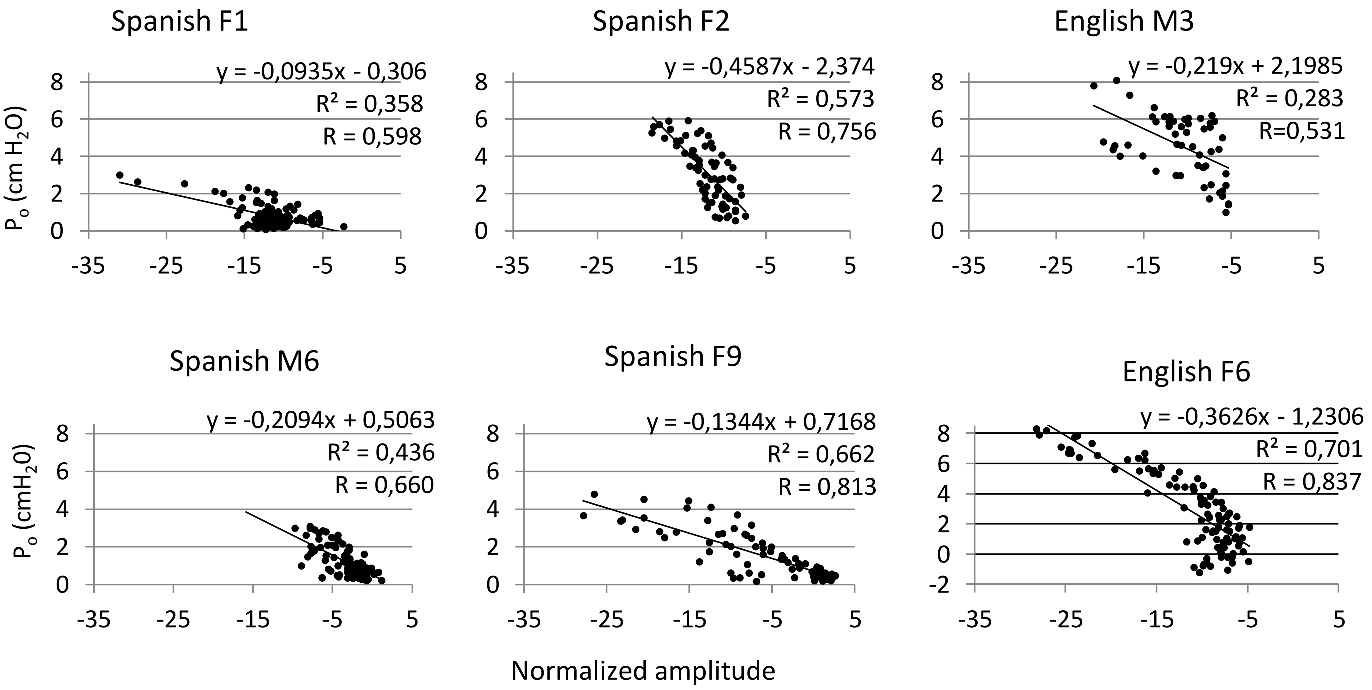


Figure 2: Linear regression and scatter plots of oral pressure (ordinate) and normalized amplitude of voiced stop lead (abscissa) in four Spanish and two English speakers (F=female; M= male). The voicing amplitude was normalized with reference to the following vowel amplitude. Zero at the abscissa indicates an amplitude equal to that in the following vowel. Each dot represents one measurement. Spanish F1, n=120; Spanish F2, n=80; Spanish M6, n=95; Spanish F9, n=77; English M3, n=60; English F6, n=120.

5. REFERENCES

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[2] Other factors affecting voicing amplitude are changes in subglottal pressure and degree of glottal adduction.