AERODYNAMIC PARAMETERS OF EJECTIVES AND PULMONIC STOPS[1]

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ABSTRACT

This paper presents preliminary results of an aerodynamic study of ejective, aspirated and unaspirated stops. Specifically, peak oral pressure, peak oral flow, area of flow and the interaction of each of these with place of articulation were examined. Differences between ejectives and voiceless stops were found in oral pressure (with ejectives having double or triple the value for pulmonic stops), oral airflow and area of flow (with ejectives showing a small and short peak of flow compared to aspirated stops). The rate of oral pressure build-up (slope) varied considerably in ejectives reflecting the less regular raising movement of the larynx. Concerning the effect of place of articulation, oral pressure was higher in velars than anterior places of articulation in ejectives but not in pulmonic stops. Oral airflow tended to be higher in alveolar stops than labials and velars in all stop categories.

Keywords: ejectives, oral pressure, oral flow

1. INTRODUCTION

The aim of this paper is to characterize the aerodynamic parameters of aspirated, unaspirated and ejective stops for linguistic, clinical, and modelling purposes. A second aim is to illustrate how aerodynamic data provide a window into speech articulation. Because aerodynamic properties of speech sounds derive from the action of the articulators (which may compress/rarefy the air and/or impede the airflow), pressure and flow patterns allow us to infer articulatory gestures and their timing in a non-invasive way. For example, oral pressure (P_o) and flow provide information about the degree of glottal constriction in stops [1]. Similarly, the peak of oral flow before (and after) fricatives, particularly /s/, indicates anticipatory glottal opening before the oral constriction is formed [2].

While the aerodynamic characteristics of voiced and voiceless stops are well-described, e.g., [3, 4, 5, 6], there is only a limited amount of aerodynamic data on ejectives, e.g., [7, 8, 9]. This paper focuses on ejectives and compares them to aspirated and unaspirated pulmonic stops. We describe specifically (i) peak oral pressure, (ii) oral flow, (iii) area of oral flow, and (iv) the interaction of each of these with place of articulation in ejective and pulmonic stops. A detailed description of the pressure and flow patterns of ejectives will contribute to a better understanding of production and aerodynamic properties of stops in general.

The articulation and acoustics of ejectives (and implosives) are only relatively well-understood, in part due to (i) their phonetic variation across languages (see cross-language comparisons of the acoustic characteristics of ejectives in [10, 11, 12]), and (ii) their gradual differentiation from pulmonic stops, such that in some languages plain voiceless stops are variably ejective (e.g., Shekgalagari, Ikalanga, Amharic), and plain voiced stops may be realized as implosives. Despite their variation in realization, the category ejective will be used here to describe their aerodynamic properties which, as their articulatory and acoustic properties, may vary in each language.

2. BACKGROUND

We first review the oral pressure and flow patterns of ejectives as described in previous studies and illustrated in our data. Ejective stops are produced with a glottalic egressive airstream mechanism, using the air enclosed between the closed glottis, the closed velum, and a closure in the mouth. A rapid upward movement of the larynx reduces the volume of the oropharyngeal cavity and thus compresses the air within that cavity which is pushed out with a strong burst when the oral constriction is released. This is illustrated in Fig. 1 (left) which shows the sequence [ap'a] produced by a trained phonetician (see section 3.1). When the larynx is raised the air pressure in the oral cavity increases to values as high as 20-30cmH_2O (double or triple the value for pulmonic stops). Because the volume of the oral cavity sealed at both ends is relatively small (ranging from approximately 100cm^3 for labials to 30cm^3 for velars, [13, 14]), a small elevation of the closed glottis makes a large percentage reduction in volume, resulting in high P_o values.

The P_o rise in ejectives is frequently less steady and more variable than for the corresponding plain voiceless stops (with a typical 'hat' shape). This is illustrated in Fig. 2 which shows different P_o pulses of ejectives for the same speaker, some with a relatively steady P_o rise, some with a two-stage increase, or a concave shape (delayed oral pressure build up) (cf. [9]) —what they all have in common is a high increase in oral pressure before the oral release. A less steady rise in oral pressure reflects the relatively less regular, and variable in time, upward movement of the larynx (which increases air pressure in the oral cavity) compared to the large and steady column of air through the open vocal folds for plain voiceless stops. Note that the oral pressure peak, which typically occurs at closure release for plain stops, may occur before oral release in ejectives (approximately 25ms in Fig. 1) indicating that larynx elevation may be completed a few tens of ms before the stop release. This is corroborated by data on larynx movement —obtained with high-speed video recording— and simultaneous aerodynamic and acoustic data, [15].

Figure 1: Waveform, 0-7 kHz spectrogram, oral pressure (in cmH_2O), and oral flow (in l/sec) for [ap'a] (left) and [ap^{h}a](right). The release of the oral closure is indicated by a vertical bar.

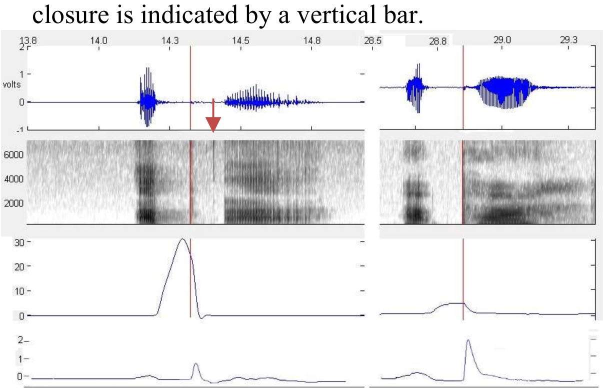
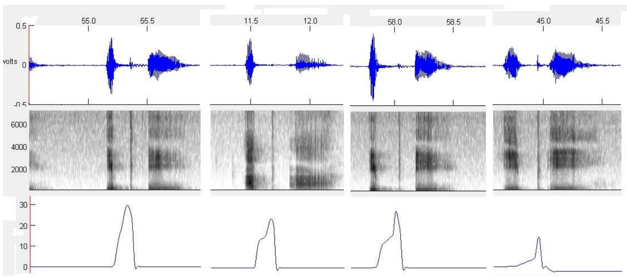


Figure 2: Variation in oral pressure pulses (in cmH_2O) for [ap'a] for a single (male) speaker.



The release of the glottal closure typically lags behind the oral release (glottal lag) or may be synchronic with the oral release (see e.g. [10] for cross-language differences). In Figure 1 (left), the arrow indicates the release of the glottal closure (the vertical bar on the spectrogram at time 14.4) which takes place approximately 80ms after the oral release. When the oral closure is released, the high oral pressure behind the closure creates a high amplitude burst[2] not followed by noise (referred to as low or absent 'post-burst noise amplitude' in the literature) – this is because, differently from plain stops, the glottis remains closed at the point of oral release for ejectives such that there is insufficient rate of flow through the oral constriction to create noise. Figure 1 illustrates the small and short burst of oral flow for ejectives – reflecting the limited air volume enclosed in the oral cavity – as opposed to the large and longer flow for aspirated stops with an open glottis. The time interval between oral release and onset of glottal vibration – VOT with low or inexistent noise– may range between 23ms-80ms in different languages (Ingush, Hausa, Quiche, Navajo, Tigrinya, Amharic and Waima'a, [11, 12]) and is characterized by P_o and oral flow to 0 as the glottis remains closed.

3. METHOD

3.1. Data acquisition

Aerodynamic and acoustic data were obtained for target words read in a carrier sentence by one male and one female phonetician in a laboratory setting. The carrier sentence was 'Say__'. The target consonants – aspirated [p^h t^h k^h], unaspirated [p t k] and ejective stops [p' t' k'] – were preceded and followed by /a/, with stress on the second syllable, e.g. [a'p^ha][3]. Six repetitions for each word were recorded, giving 108 tokens in total.

The subjects' productions were recorded using National Instruments PCI-6013 data acquisition hardware and the Matlab Data Acquisition Toolbox (20kHz sample rate per channel and 16 bits/sample). Oral pressure was obtained by a catheter inserted into the pharynx via the nasal cavity and connected to a pressure transducer (Biopac TSD160C). The invasive nature of the procedure limited the number of potential subjects. Oral airflow and nasal airflow were collected with a split Rothenberg mask and a Fleisch pneumotachograph with Biopac TSD160A pressure transducer. The airflow and oral pressure signals were lowpass filtered at 50Hz. Statistical tests were, unless otherwise indicated, conducted on the pressure and flow measurements using one-way ANOVAs in R.

3.2. Measurements

The following measurements were obtained: (1) oral pressure at onset and offset of P_o build-up, (2) duration of pressure build-up, (3) peak oral pressure, (4) peak oral flow, (5) duration of flow, and (6) area under the curve (AUC) of flow in litres[4].

The onset of oral pressure build-up in measurement (1) was defined as the point in time that oral flow drops to the baseline (i.e., complete oral closure) and P_o begins to rise. Measurements (1) and (2) were intended to allow us to calculate the rate of P_o build-up (or slope). However, because the P_o rise varied considerably for ejectives (showing one-stage, two-stage and concave increments, see Fig. 2), the slope was not calculated to avoid averaging across disparate shapes. The AUC, that is, the 2-dimensional region below the oral airflow curve, that captures the rate of flow over time, was calculated with Matlab.

4. RESULTS

We present the results of the measurements, looking in particular at the behavior of ejectives relative to other voiceless stop types, and at possible place of articulation dependencies concerning pressure and flow values. Results will be presented separately for the female and the male speakers since ANOVAs indicated that the speaker factor interacted with stop type and place in oral pressure and flow values.

4.1. Peak oral pressure

As reported in earlier findings, ejectives have much greater oral pressure than aspirated and unaspirated stops (M= 31.3, 6.5, 4.6, respectively for the female speaker and M= 26.1, 11.15, 9.18 for the male speaker), see Fig. 3.

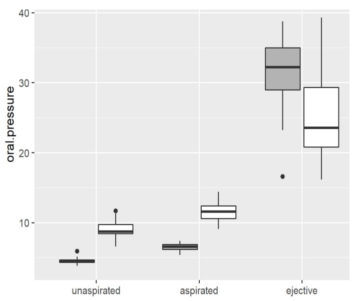
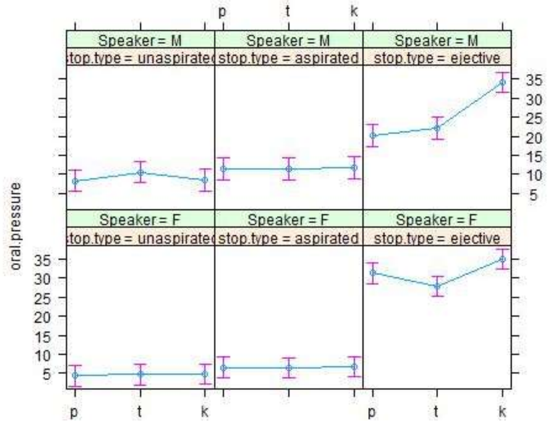


Figure 3: Average peak oral pressure (in cmH_2O) for unaspirated, aspirated and ejective stops for a female (grey) and a male (white) speaker.

The effect of stop type on oral pressure was significant for the male [$F_{(2, 51)}$: 60, p <0.01] and female speaker [$F_{(2, 51)}$: 287.4, p <0.000], with ejectives showing higher P_o values than both aspirated and unaspirated stops for both speakers (p<0.0001 in all cases). The difference between aspirated and unaspirated stops was smaller and did not reach significance for any of the two speakers (p=0.512 and p=0.365 for the male and female speakers, respectively).

Fig. 4 shows oral pressure for the three stop types broken down by place of articulation. Because there was a significant interaction between stop type and place of articulation, separate one-factor ANOVAS were performed. Among ejective stops, oral pressure is higher in velar than in labial (p <0.01) and alveolar stops (p <0.01) for the male speaker. For the female speaker, only the P_o differences between [k’] and [t’] approach, but do not reach, significance (p= 0.176). Labial and alveolar ejectives show similar pressure values for both speakers. Within the unaspirated series, only the alveolar stop shows higher oral pressure values than labial (p= 0.001) or velar stops (p= 0.01) for the male speaker. No effect of place of articulation was found in the aspirated series in any of the two speakers.

Figure 4: Average peak oral pressure for unaspirated, aspirated and ejective stops by place of articulation for a male (M) and female (F) speaker.



4.2. Peak oral flow

As expected, aspirated stops, with a continuous flow of air through the open glottis at release, exhibit a considerably higher peak flow and longer duration of high airflow than ejective and unaspirated stops. Ejectives show a short and small peak of oral flow at release reflecting the limited volume of air enclosed in the oral cavity compared to aspirated stops. The peak flow for ejectives is intermediate between that obtained for aspirated and unaspirated stops (M= 0.536, 1.265, 0.315, respectively for the female speaker and M= 0.833, 2.302, 0.228 for the male speaker), see Fig. 5. The larger peak flow for ejectives than unaspirated stops is presumably due to the higher oral pressure for the former. All the paired comparisons across stop types were significant for both the female and the male speaker (p< 0.000 in all cases except p<0.01 for ejective vs unaspirated for the female speaker).

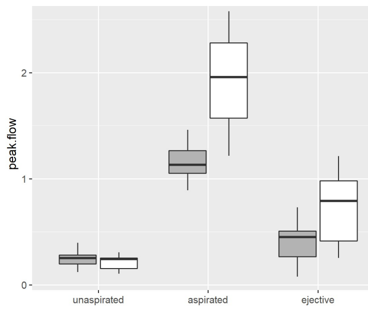
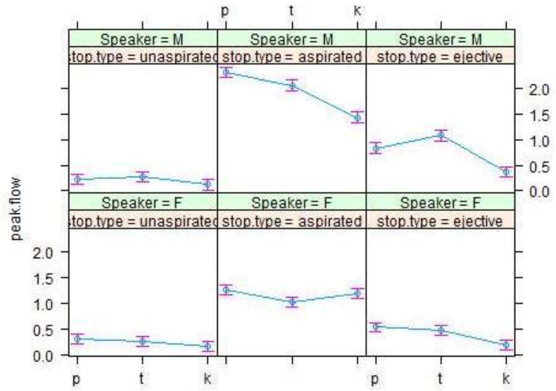


Figure 5: Average peak flow (in l/s) for unaspirated, aspirated and ejective stops for a female (grey) and a male (white) speaker.

The effect of place of articulation patterns rather consistently across stop type for the two speakers (Fig. 6). Peak oral flow is significantly lower for velars than more anterior places of articulation for all stop types (all differences p<0.001, except no difference between /k/ vs /t/ for aspirated stops for the female speaker). Alveolars tend to show significantly higher peak flow values than labials (within ejectives and unaspirated stops (p <0.01) for the male speaker), or similar peak flow values to labials (the rest of paired comparisons).

Figure 6: Average peak flow for unaspirated, aspirated, and ejective stops by place of articulation for a male (M) and female (F) speaker.



4.3. Area of flow

The values for area of flow (i.e., area under the curve) show a very similar pattern to those for peak oral flow both for stop type and place of articulation. The only difference between the two sets of measurements was that while the female speaker had lower peak flow values for aspirates than the male speaker, see Fig. 5, (due to the lower absolute P_o values for the female), the area of flow was comparable for both speakers, Fig. 7, (due to the longer duration of flow for the female compared to the male speaker which offset the lower peak flow). One-way ANOVAs showed that aspirated stops have a significantly larger area of flow, $p<0.0001$ for both speakers, than ejective and unaspirated stops which do not differ between them (M= 0.154, 0.014, 0.008, respectively for the female speaker and M=0.163, 0.021, 0.006 for the male speaker), see Fig. 7.

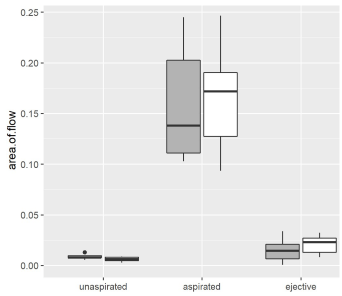


Figure 7: Average area of flow (in litres) for unaspirated, aspirated and ejective stops for a female (grey) and a male (white) speaker.

The effect of place of articulation on area of flow was comparable to that observed for peak oral flow: anterior places of articulation have a significantly larger area of flow than velars for both speakers. For the male speaker, the differences are only significant for labial/alveolar vs velars for all stop types (ejective, unaspirated, aspirated; $p<0.01$ in all cases). For the female speaker the differences are significant for labial vs alveolars/velars ($p<0.01$ in all cases).

5. DISCUSSION

The finding that ejectives show much greater *oral pressure* than pulmonic stops is in accord with the reports of earlier researchers. Because the volume of the oral cavity between the oral and the glottal closure for ejectives is relatively small, a small elevation of the larynx makes a large reduction in volume, resulting in high P_o values. Differences in P_o between aspirated and unaspirated stops may be attributed to differences in glottal resistance during the stop closure [16]. Aspirated stops, with the vocal folds maximally apart, tend to have higher oral pressure than unaspirated stops, with a smaller glottal opening because the vocal folds begin to approximate during the stop closure. The difference in P_o between aspirated and unaspirated stops, however, did not reach significance (as in other studies, e.g., [17]). Concerning place of articulation, the higher P_o expected for velars than more anterior places of articulation – due to a smaller oral cavity volume and faster P_o rise – was only observed in ejectives but not pulmonic stops. In fact, the effect of oral cavity volume on pressure values has not been consistently found by other investigators (e.g., [3]). As suggested in [5], for voiceless stops the fast increase in P_o associated with glottal abduction may simply outweigh supraglottal place effects.

The results show decreasing *peak oral flow* and *area of flow* for aspirated > ejectives > unaspirated stops. Aspirated stops, with a large and continuous flow of air through the open glottis, when released have high peak flow and longer duration of high airflow (and hence larger area of flow). Unaspirated stops have a smaller and more brief airflow peak (and area of flow) than aspirated stops due to the smaller glottal opening: during the stop closure, the vocal folds begin to adduct, and on release there is glottal vibration which offers considerable resistance to transglottal and oral flow. The small and short peak of airflow for ejectives (with a closed glottis) reflects the limited volume of air enclosed in the oral cavity. Peak airflow may vary with place of articulation, with alveolars showing a tendency to have greater airflow than velars and labials, and velars showing the lowest peak airflow, in all stop categories. The higher airflow in alveolars is in accord with previous results for aspirated stops in [18, 19, 20]. The lower peak and area of flow values for velars in all stop categories is unexpected given the usually higher P_o values, and longer VOT, for back compared to anterior stops. The fact that the Rothenberg mask picks up more readily oral flow closer to the transducers (as is the case for anterior places of articulation) – just as in microphone popping– may have played a role.

There is ample room for further investigation of aerodynamic parameters in non-pulmonic stops. Our preliminary results have thrown some light on the production and aerodynamic features of stop types.

5. REFERENCES

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[2] Demolin (2004) reports a higher amplitude burst for ejectives than pulmonic stops, but Seid et al (2009) report the opposite.

[3] As one reviewer pointed out, the results from such metalinguistic task divorced from context and natural realizations should be taken with caution. But because the results are in agreement with previous studies, we feel confident that they reflect ejective realisation in natural languages.

[4] AUC was calculated integrating flow rate (in l/s) with respect to time (s), therefore, the unit for time becomes eliminated.