Are glottalic mechanisms in Human Beatboxing really glottalic ?

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Abstract

This communication focuses on the production of ejectives and implosives in Human Beatboxing (HBB). To investigate ejectives and implosives (i.e. glottalic mechanisms), real-time Magnetic Resonance Imaging data was collected on one professional subject. MRI recordings were analyzed via a functional Principal Component Analysis of vocal tract contours. The findings show that glottalic mechanisms for this subject are produced with tongue root and velo-pharyngeal maneuvers to change the volume of the pharyngeal cavity rather than laryngeal raising or lowering. We think ejectives and implosives might better be described as obstruent consonants produced with pharyngeal compression or expansion and a closed glottis at least in Beatboxing.

Keywords: Human Beatboxing, rt-MRI, Ejectives, Implosives

1. Introduction

This communication focuses on the production of ejectives and implosives in Human Beatboxing (HBB). Human Beatboxing is a vocal technique where musicians imitate musical sonorities, such as instruments or electronic music, with their vocal tract. Human Beatboxing is a novel paradigm to study sound production mechanisms in the vocal tract among a population of highly trained subjects. To investigate ejectives and implosives, 2D real-time magnetic resonance imaging (rt-MRI) data was collected on one professional subject. The goal is to know whether ejectives and implosives in HBB are produced similarly or differently to glottalic mechanisms of the world's languages.

1.1. Ejectives and implosives of the world's languages

Most studies focus on the acoustic properties such as Voice Onset Time (VOT), burst intensity or F0 perturbations induced by the so-called glottalic mechanism on the following vowel. Little attention has been given to the glottalic mechanism itself.

Ejectives are produced by decreasing the volume between the closed glottis and the oral constriction, resulting in high positive pressure. Conversely, implosives are produced by increasing the volume in the supralaryngeal region between the closed glottis and the oral constriction, resulting in low negative pressure (Catford 1977; Ladefoged 1971). Volume and pressure variations during the so called glottalic stops are attributed to laryngeal raising (ejectives) and lowering (implosives).

Kingston (1985) attempted to run different aerodynamic models of stops in Tigrinya. The simulated data showed that laryngeal raising failed to increase sufficiently IOP to reach the expected pressure values of Tigrinya ejective stops. Increased contractions of the supraglottal cavity resulted in the expected values of pressure for ejectives. He attributes the additional contractions to tongue root retraction and/or vocal tract walls stiffening.

An MRI study of Oh and Lee (2018) found higher larynx position for ejectives compared to implosives in Hausa. Though, no comparison was made with pulmonic stops. Another MRI study of Sulaberidze et al. (2023) showed higher laryngeal position for ejectives stops compared to pulmonic stops in Georgian. They express doubts on sufficient laryngeal movement to increase IOP for ejectives. An interesting descriptive study of Hermes et al. (2016) using MRI reported tongue root retraction and advancement of the posterior wall of the pharynx to decrease the size of the supralaryngeal cavity during the production of ejectives in Tigrinya.

The role of laryngeal lowering during the production of implosives has also been questioned by Demolin (1995) and Demolin, Ngonga-Ke-Mbembe, and Soquet (2002). Based on MRI, they showed pharyngeal expansion during the production of implosives. The expansion results from laryngeal lowering and tongue root advancement. They question the relationship between tongue root advancement and laryngeal lowering.

Tongue root maneuvers might be involved in the production of both ejectives and implosives. Though, it is not clear how it relates to laryngeal height.

1.2. Ejectives and implosives in Human Beatboxing

The MRI recordings of professional beatboxer in the study of Proctor et al. (2013) reported systematic laryngeal lowering followed by an oral closure, a glottal closure and laryngeal raising. Similar characteristics have also been reported in other MRI studies (Patil et al. 2017; Dehais Underdown et al. 2023). Results on laryngoscopic investigations show pharyngo-laryngeal dilatation followed by pharyngo-laryngeal contraction. The pharyngeal compression is provoked by laryngeal raising and an epiglottal retraction while the glottis remains closed (De Torcy et al. 2014; Fabre 2018; Dehais-Underdown et al. 2021).

In Dehais Underdown et al. (2023), the authors reported systematic involvement of the tongue root in both ejectives and implosives but they did not quantify their observations. Similar observations were made in De Torcy et al. (2014) and Fabre (2018) who observed retraction of the epiglottis in their laryngoscopic analysis. Whether tongue root movements act independently of laryngeal raising or lowering in the production of

beatboxed ejectives and implosives remains to be verified.

Concerning aerodynamic studies of beatboxing, in his master's thesis, Fabre (2018) reports IOP values ranging from 20hPa up to 80hPa for 1 professional beatboxer. In Dehais-Underdown et al. (2021), the IOP reported for 5 subjects producing beatboxing ejectives reached between 40hPa and 100hPa. They also reported a voiceless bilabial implosive [ɓ̥] with high negative pressure reaching about −95hPa.

Along with Kingston's (reasonable) doubts on the sufficient laryngeal raising to increase IOP, extreme IOP in HBB raises questions about the nature of the gestures involved to produce ejectives and implosives in HBB. What are the gestures involved in raising and lowering the intraoral pressure for ejectives and implosives? In this study, we investigate the production of such sounds by means of MRI recordings of a single professional beatboxer. We think that (1) tongue root retraction is used to decrease the supralaryngeal volume for beatboxing ejectives and (2) tongue root advancement is used to increase the supralaryngeal volume for beatboxing implosives.

2. Methods

The subject (VP) of the study is a professional beatboxer. He was 32 years old at the time of the recordings and had practiced beatboxing for 15 years at the time.

2.1. Corpus & protocol

The corpus is composed of musical structures called "Beat Patterns" (BPs). They have same metric, rhythmic and melodic structure (see Figure 1). The metrics consists of 4 pulses and 9 sounds (musical notes). Rhythm is an alternation low/high, loud/soft and short/long sounds. Finally, the melodic parameters refer to the different timbres of the instruments. The phonetic structure of drums was manipulated to create 11 BPs in total. In this study, only 2 selected patterns are reported : [ɓ͡ʔ t͡sʼ ʔ͡ʃː t͡sʼ ɓ͡ʔ ɓ͡ʔ t͡sʼ ʔ͡ʃː t͡sʼ] and [ɗ͡ʔ t͡sʼ ↓ʔ͡ʃː t͡sʼ ɗ͡ʔ ɗ͡ʔ t͡sʼ ↓ʔ͡ʃː t͡sʼ] where [ɓ͡ʔ] and [ɗ͡ʔ] are (orally) unreleased implosives, respectively bilabial and dental; [t͡sʼ] is a dental ejective affricate and [ʔ͡ʃː] and [↓ʔ͡ʃː] are respectively pulmonic egressive and pulmonic ingressive affricates produced with an aryepiglottal stop and a post-alveolar fricative. The experiment consisted in repeating the audio examples of the *Beat Patterns* (BPs) of the corpus.

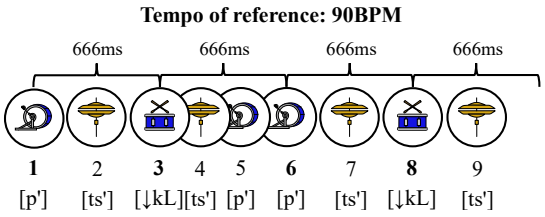


Figure 1: Beat pattern structure

2.2. Recordings

The MRI recording took place at Nancy Central Regional University Hospital (ClinicalTrials.gov Identifier: NCT02887053, RCB-ID n°CPP EST-III, 08.10.01). The data was acquired with a Siemens Prisma 3T scanner, Erlangen, Germany. The speaker was in supine position and a Siemens Head/Neck 64 coils was used. We used radial RF-spoiled FLASH sequence with TR = 2.22 ms, TE = 1.47 ms, FoV 192x192mm, flip angle = 5°, and slice thickness was 8 mm. Pixel bandwidth was 1670 Hz/pixel. Image size was 136x136, in-plane resolution was 1.6 mm, recorded at 50 fps and reconstructed with a non-linear inverse technique presented in Uecker et al. (2010). Audio was recorded at a sampling frequency of 16 kHz inside the MRI scanner with a FOMRI III optoacoustics fibre-optic microphone (FOMRI III, Optoacoustics Ltd., Mazor, Israel) and the recording software presented in Isaieva et al. (2022).

2.3. Analysis

The MRI data was quantified with a functional Principal Component Analysis (fPCA) from the open source script of Belyk and McGettigan (2022) based on the semi-automatic MRI contouring procedure presented in Belyk, Carignan, and McGettigan (2023).

The onset and offset of articulatory gestures of the *throat kicks* [ɓ͡ʔ] and [ɗ͡ʔ] as well as the *closed hi-hat* [t͡sʼ] were selected for the analysis. The snares [ʔ͡ʃː] and [↓ʔ͡ʃː] were analyzed but are not reported here. Onset were defined as the moment of maximal constriction when the oral closure was achieved and articulators were not in motion anymore. Offset were defined as the end of the ejective or implosive phase, that is the frame when articulators were not in motion anymore to either compress or expand the pharyngeal cavity.

The semi-automatic contouring procedure was performed and manual correction of erroneous contours was applied. The procedure consists of mainly 4 steps :

1. frames were registered and head movement correction was performed based on a reference frame taken at the middle of the recording;
2. a mask was automatically created based on tissue detection in the reference frame capturing a region of interest from the lower edge of the larynx to the lips. The mask was manually corrected;
3. automatic contouring was performed based on the mask using pixel intensity to distinguish vocal tract edges (high intensity) from the air contained in the vocal tract (low intensity);
4. finally, contours were manually corrected when needed.

The resulting vocal tract contours (n= 128) represent the antero-posterior coordinates (Y-axis) and the supero-inferior coordinates (Z-axis). Contours were smoothed and centered at the lips with the *fda package* implemented in the script of Belyk and McGettigan (2022). Then, the fPCA analysis was performed on the Y and Z coordinates to find variation of contours in comparison to the mean shape of the vocal tract. The five first components explain 87% of the variation in the data :

- PC1 represents 37% of the variation and was found to be related to laryngeal height.
- PC2 represents 23% of the variation and was not found to be related to a specific articulatory gesture. It possible that opposite gestures "cancel" each other resulting in PC score similar to the mean shape.
- PC3 represents 15% of the variation and was found to be related to advancement or retraction of the tongue root.
- PC4 represents 6% of the variation and was found to be related to velopharyngeal compression or expansion.

- PC5 represents 6% of the variation and was found to be related to labial aperture and tongue blade constrictions. It mainly relates to the oral gestures to produce [ʔ͡ʃː] and [↓ʔ͡ʃː] and will not be reported here.

We plotted the vocal tract pattern of variation along the Y and Z coordinates associated to each principal component score. Boxplot representing the variation of the scores were plotted on R for each sound to interpret the graphical representation of vocal tract deformation.

3. Results

Figure 2 shows the results of the fPCA analysis for PC1 (laryngeal height), PC3 (tongue root maneuvers) and PC4 (velo-pharyngeal maneuvers). For each component, a plot of the vocal tract deformation relative to the mean shape is displayed. The mean shape is represented in black and the deformation is represented by contours in pink and green. Pink contours show the vocal tract deformation when the component increases. Green contours show the vocal tract deformation when the component decreases. Boxplots illustrate the components variation for each sound. Onset and offsets are represented in different colors and each panel illustrates BP. Although PC2 explains 23% of the variation in the data, it is not shown because in the graphic representing tract deformation for PC2, no deformation was observed and only the mean shape was visible.

The onset and offset of [ɓ̥] show differences in the vocal tract configuration. PC1, related to laryngeal height (Figure 2a), tends to be higher and positive at the onset. It suggests that larynx is in higher position at the onset. Though, laryngeal height seems somehow variable at the onset and some overlap is observed with the offset values on the boxplot. PC3, related to tongue root maneuvers (Figure 2b), increases from the onset to the offset suggesting systematic tongue root advancement. Finally, there is a participation of the velo-pharynx as suggested by PC4 (Figure 2c). The 4th component is higher at the offset and suggests the pharyngeal cavity is wide and the velum is raised. In the recordings, the velopharyngeal port remains closed.

The dental implosive [ɗ̥] is also characterized by tongue root advancement and pharyngeal expansion. PC3 is higher at the offset compared to the onset which confirms tongue root advancement (Figure 2b). The magnitude of tongue retraction seems weaker but less variable for the dental implosive compared to the bilabial one. PC4 is closed to 0 at the onset and increases at the offset suggesting the pharynx expands and the velum raises. Once again, the velopharyngeal port remains closed throughout the mechanism. PC1 suggests the larynx is lower at the onset and higher at the offset. Moreover, the difference between larynx height at the onset and offset is low. This suggests that laryngeal height is not that different between the onset and the offset. This result is not in line with the traditional view that implosives are produced by laryngeal lowering.

Concerning the *hi-hat* [t͡sʼ], differences are observed depending on the pattern, though tongue root retraction is systematic in both pattern. Indeed, PC3 is decreasing between the onset and the offset (Figure 2b) which suggests that tongue root is retracting. In BP4 (i.e. [ɓ̥ t͡sʼ ʔ͡ʃː t͡sʼ ɓ̥ ɓ̥ t͡sʼ ʔ͡ʃː t͡sʼ]) the difference between the onset and the offset is greater than in BP5 (i.e. [ɗ̥ t͡sʼ ↓ʔ͡ʃː t͡sʼ ɗ̥ ɗ̥ t͡sʼ ↓ʔ͡ʃː t͡sʼ]). The gesture has a greater amplitude in BP4, meaning the tongue root retracts more. In BP4, PC1 indicates that the larynx is higher at the offset. In BP5 the larynx is lower at the offset which is not in line with the traditional description of laryngeal raising during ejectives. Moreover in this BP, differences between laryngeal height at the onset and offset is very low suggesting laryngeal height is not that different. Finally, velo-pharyngeal involvement is observed in the 2nd BP but not in the first one. Indeed, the data on PC4 shows no major differences between the onset and the offset in BP4 while in BP5, the decrease of PC4 suggests velum is lowered and pharyngeal cavity is narrowed. Velum lowering does not mean the velo-pharyngeal port is opened, on the recordings it stays closed.

4. Discussion

The MRI analysis confirmed tongue root maneuvers during ejective and implosive mechanisms. Tongue root retraction was observed during ejectives, such action would result in increased intraoral pressure. Tongue root advancement was observed during implosives, such action would result in a negative pressure. Moreover, pharyngeal involvement was observed, suggesting a possible role of the pharyngeal muscles to increase or decrease the volume of the pharynx. However, the data does not suggest that laryngeal height is responsible for volumetric variation of the pharyngeal cavity.

Tongue root advancement and retraction are caused by different muscles activation. Tongue root advancement or protrusion is produced by activating the genioglossus (GG) (Shall 2012; Sanders and Mu 2013; Stone et al. 2018). Contracting the GG pulls the tongue toward the mandible.

Tongue retraction or retrusion is thought to be caused by the activation of the styloglossus (SG) and the hyoglossus (HG) *(ibid)*. Contraction of SG pulls the tongue upward and backward. HG activation pulls the tongue downward and backward. By activating both the SG and HG, the tongue root retracts.

A study of Saigusa et al. (2004) suggests that tongue root retraction is caused by the pharyngeal superior constrictor (SPC). They identified that some of the SPC fibers insert in the Transverse (T) muscle at the base of the tongue. They think that the activation of both the SPC and T fibers may result in large retraction of the tongue root and to pharyngeal constriction.

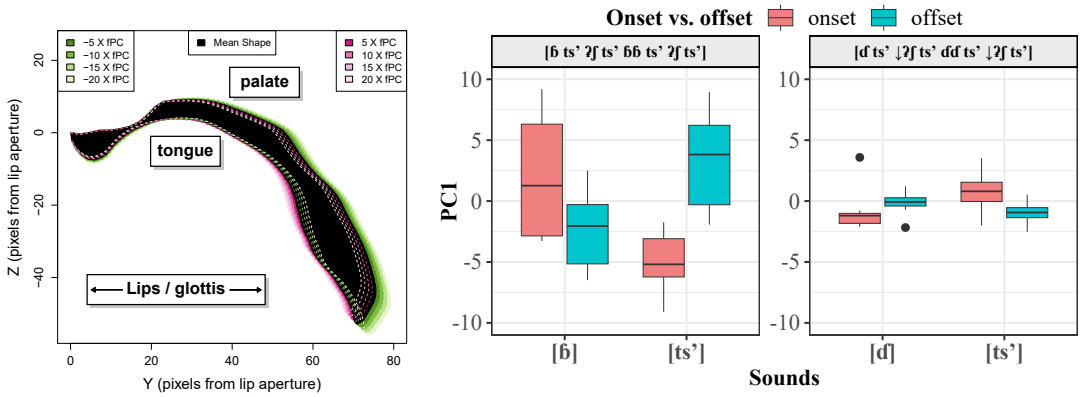
Tsumori et al. (2007) found that glossopharyngeal fibers of the SPC insert in the tongue root along with palatoglossus and styloglossus fibers. The authors suggest that the contraction of the SPC may play a role during swallowing

From a physiological point of view, Kokawa et al. (2006) investigated the production of the cardinal vowels /i a u/ based on naso-fibroscopy, X-ray fluorography and electromyography (EMG) of the SPC and GG muscles. Their findings suggest the activation of the SPC muscle retracts the root of the tongue while the activation of the GG protrudes the tongue root.

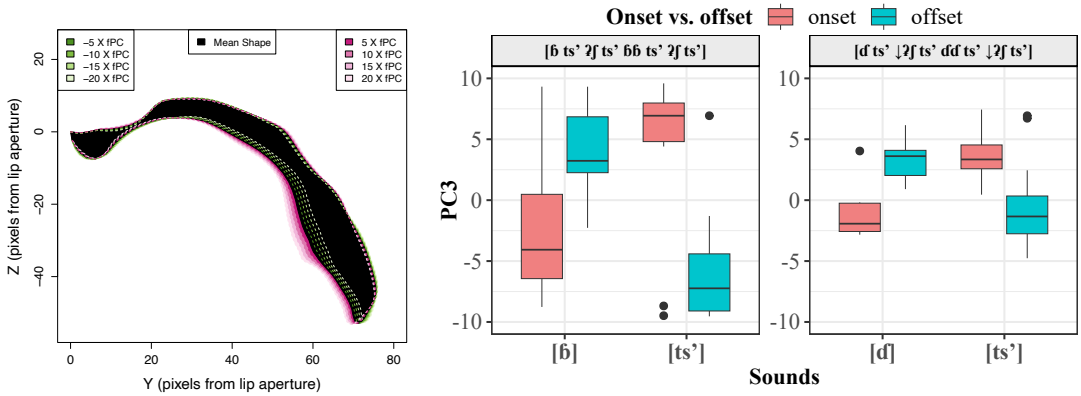
The action of the SPC muscle (and possibly the middle and inferior constrictors) may explain both tongue root maneuvers and differences in pharyngeal volume. If we consider that pharyngeal constrictors are responsible for volumetric variations, it is possible that laryngeal height is a mere consequence of contracting or relaxing pharyngeal constrictors.

5. Conclusion

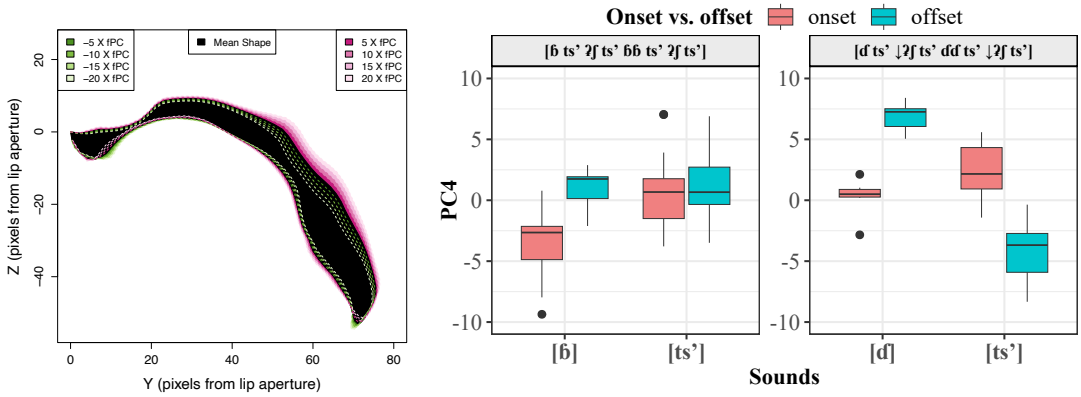
This study aimed to investigate the production of beatboxing ejectives and implosives. MRI recordings of a single professional beatboxer were analyzed via a fPCA analysis of vocal tract contours. The findings show that glottalic mechanisms, for this subject, are produced with tongue root and velo-pharyngeal maneuvers to change the volume of the pharyngeal cavity. Our results are not always in line with the textbook description of ejectives and implosives.



(a) Tract variation (left) and corresponding boxplot (right) of PC1 (laryngeal height).



(b) Tract variation (left) and corresponding boxplot (right) of PC3 (tongue root maneuvers).



(c) Tract variation (left) and corresponding boxplot (right) of PC4 (velo-pharyngeal maneuvers).

Figure 2: Left : Tract variation for fPC1, 3 and 4, black contours illustrate the mean shape of the vocal tract, pink contours indicate tract changes when a fPC increases while green contours indicates changes when a fPC decreases. Right : boxplot (n=96 frames) illustrating PC changes for each sound, colors indicate fPC variation between the onset (occlusion) and the offset (release).

Rather, we think ejectives and implosives might better be described as obstruent consonants produced with pharyngeal compression or expansion and a closed glottis (at least in beatboxing). A similar proposal has been made by Lindau (1979) who suggested to use the feature [expanded] pharynx for ATR vowels. She also proposes the features [neutral] [constricted] and [pharyngealized] to refer to differences in pharyngeal volume.

This novel working hypothesis needs to be verified on more beatboxers. It should also be tested on ejectives and implosives of the world's languages. If the hypothesis was to be confirmed, it would have several implications for the classification of stop and sound change.

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