Temporal coordination of glottalic gestures in Karitiana

Didier Demolin & Luciana Storto

Université de Sorbonne Nouvelle, Paris 3, Laboratoire de Phonétique et Phonologie
&
Departamento de Linguística, Universidade de São Paulo

Karitiana, a Tupi language spoken in Brazil, has no glottal stop in its phonological inventory. However, as many other Tupi languages, Karitiana presents a number of interesting phenomena related to the phonetic realization of glottal stops and to the temporal realization of glottalic gestures. A frequent, but not systematic, phenomenon is the occurrence of vowels with a final burst in word internal VC sequences, in CVC words ending with a final unreleased voiceless stop and before nasals. Electroglottographic (EGG) measurements reveal that the vowels' final burst are articulated with a closing gesture of the glottis. This is contrary to the expected opening gesture necessary to produce a voiceless stop. EGG data clearly show the superposition – partial or complete - of the oral closure with a closed glottis. The phenomena helped us explain two phonological processes in the language: the unreleased nature of voiceless stops in word-final position, and the lenition of morpheme-final voiceless stops and nasals when followed by vowel-initial morphemes.

1 Introduction

Karitiana, an endangered language from the Arikém branch (Tupi family) spoken in the state of Rondonia in Brazil, shows interesting phenomena concerning glottalic consonants. Indeed, as several other languages of this linguistic family, Karitiana has no clear glottal stop in its phonological inventory, even though glottal stops do exist phonetically. Glottal stops in Karitiana are predictable in the onset of stressed syllables (Storto 1999). In addition, the language presents a number of interesting phenomena related to the phonetic realization of glottal stops and to the temporal realization of glottalic gestures, as do other Tupi languages.

A frequent, but not systematic, phenomenon is the occurrence of vowels with a final burst in CVC words ending with a final unreleased voiceless stop (Figure 1 a & b). The phenomenon also appears word internally (Figure 5). In such instances, it is often the case that vowels which are ending with bursts precede most of the allophones of the Karitiana nasals, all of which are voiced. In order to understand the phenomenon, there are three main questions to be addressed: (1) Why is there a burst at the end of vowels before stops and nasals? (2) How can we describe this phenomenon precisely? (3) Does it reflect anything particular about the phonological system of the language?

To help answer these questions, three speakers participated in experiments in which acoustic and EGG data were recorded simultaneously. This was motivated by some observations made in the field (Storto & Demolin 2002) that led us to hypothesize that voiceless stops might involve a closure of the glottis simultaneous with the oral closure necessary to produce these consonants. One important thing to note from the start is that data of this paper come from a small set and are limited in amount. However the occurrence of bursts at the end of vowels observed for every subject who participated in the study makes the description of this phenomenon potentially important for future investigations. The paper has therefore to be considered as a purely descriptive contribution to a phenomenon that should receive a more detailed and quantitative treatment in the future. This is particularly true because recent observations made by the authors in Dâw and Pirahã suggest that the phenomenon presented here might not be specific to Karitiana. This could influence the phonological pattern of these languages in various ways as we will discuss in the final part of the paper.

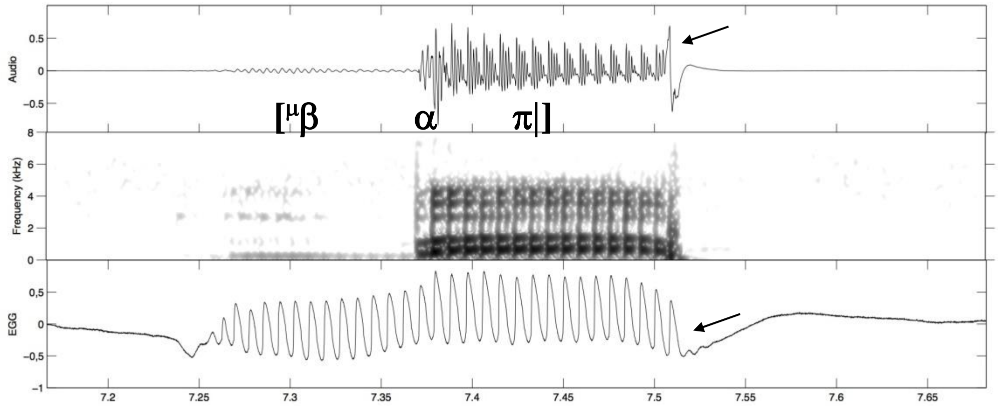

Figure 1a. Audio waveform, wide band spectrogram and EGG signal of the word [$^{\mu}$βαπ|] ‘lame’. Arrows show the burst at the end of the vowel on the audio waveform and the interruption of the EGG signal.

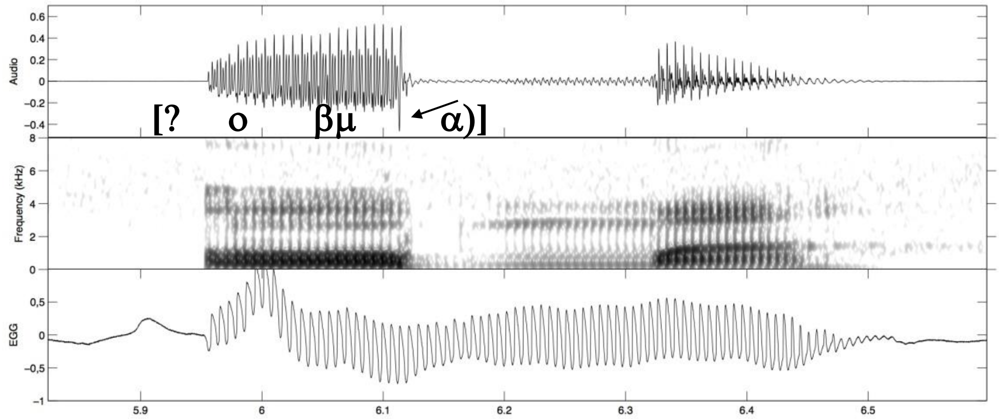

Figure 1b. Audio waveform, wide band spectrogram and EGG signal of the word [?οβμα)] ‘pierced’. The arrow show the burst at the end of the vowel on the audio waveform.

2 Material and method

2.1 Method

Data were obtained in several recording sessions. First, data were collected with three male speakers who were recorded with acoustic and electroglottographic EGG signals simultaneously. The second session involved three speakers recorded with acoustic and EGG signals, oral airflow (Oaf) and intraoral pressure (Ps) for bilabial consonants. Finally, data were obtained with six speakers with the acoustic signal during a session which was designed to obtain recordings from vowels in different contexts.

The EGG system was a Fourcin Laryngograph. Acoustic data were obtained with a Shure head microphone. This allows recording the sound signal with a constant distance from the lips of the speakers. The aerodynamic data were obtained with the MacQuirer system designed by Scicon.

Figure 2. Electrode position on one side of the thyroid cartillage (Laryngograph system). Electrodes are posited on each side of the thyroid cartillage at level of the vocal folds. A weak induced electric flow emitted through the electrodes measures the glottal resistance.

2.2 Material

The relevant words were recorded in isolation and in short carrier sentences. Each word or sentence was repeated three times. Table 1 gives a sample of the words containing post-vocalic bursts and phonetic occurrences of glottal stops which have been observed in the recordings of the first experiment.

Table 1. Data recorded showing some of the words where post-vocalic bursts and glottal stops were observed.Numbers indicate the occurrence of bursts at the end of vowels in the data.

[γεπ|] (2)	‘flea’	[ηοβμα)] (2)	‘drowned’
[ναμ|] (3)	‘’	[οπι)μ|] (1)	‘spinal cord’
[απιβμβικ|] (2)	‘to stumble’	[ο)μβι] (1)	‘basket’
[καβμ|] (2)	‘now’	[?ο)μ|] (1)	‘shadow’
[οπι)] (2)	‘to cut’	[?οπ|] (1)	‘hole’

<table>
<tr><td>[μβαπ|] (3)</td><td>‘lame’</td><td>[?οτ?ο˥π|]</td><td>‘species of egret’</td></tr>
<tr><td>[αμαΝ|] (1)</td><td>‘to plant’</td><td>[?οτ?οτ|]</td><td>‘’</td></tr>
<tr><td>[πο)μ|] (1)</td><td>‘bird species’</td><td>[?οβμα)]</td><td>‘pierced’</td></tr>
<tr><td>[οπο] (3)</td><td>‘’</td><td>[?ο?ι) σοκο?ι)]</td><td>‘not to tie up’</td></tr>
</table>

2.3 Electroglottography

In order to clarify the interpretation of the data, a short word about electroglottography seems necessary. Most data analyzed for the paper, that is, those data elicited with three speakers, as mentioned above, show synchronized recordings of the audio waveform and of the EGG signal. The essential difference between both is that the EGG signal measures the impedance at the glottis, i.e. the contact between the vocal folds, while the acoustic recording (audio waveform) shows short time pressure variations produced by the opening and closure of the glottis (Figure 3).

The important thing to bear in mind is that the EGG technique essentially transduces the vocal fold contact area. Accordingly, we will not refer to ‘closing’ or ‘opening’ but to ‘contacting’ and ‘decontacting’ phases of the vibratory cycle. Therefore the EGG is sensitive to the covert changes of the contact area during glottal closure, and it also reflects the growth and loss of contact area along the length of the vocal folds as glottal closure and opening succeed each other (Baken & Orlikoff 2000). During the closed phase of the vocal fold oscillation the electrical pathway is optimized by the contact of the vocal folds. There are, however, degrees of contact. Over the course of the ‘closed’ phase of each glottal cycle, the contact of the vocal folds varies from minimal (valley represented in the signal) to maximal (represented by a peak in the signal) as contact involves more of the vertical dimension of the vocal folds (see Hayward 2001 for more details).

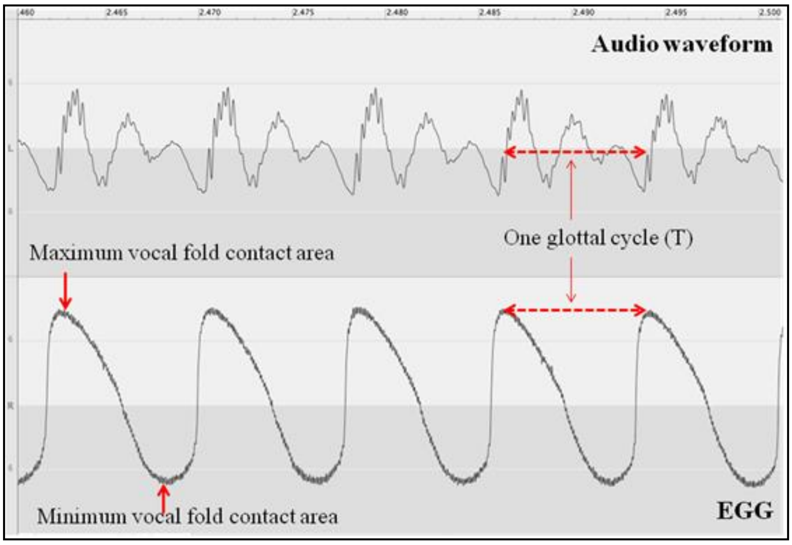

Figure 3. Audio waveform and electroglottographic (EGG) displays of the recording of a vowel, illustrating the difference between both signals. EGG shows maximum vocal fold contact area when the signal reaches a peak and the minimum when it is low as indicated by the arrows. The comparison of both signals is given for one glottal cycle (T) as shown by the double arrows on both signals.

2.4 EGG and glottal stops in Karitiana

The first set of analyzed data concerns the realization of glottal stops in various positions in words. This will permit to differentiate the acoustic and EGG signals of glottal stops from those of other phenomena described later in the paper.

Figure 4 shows the spectrogram and audio waveform of the words [?o)?ι)σoκo)?ι)] 'not to tie up'. Figure 4 displays the EGG signal and the audio waveform of the same words. In order to make the discussion about the interpretation of the EGG recordings clear it is worth examining these data in detail.

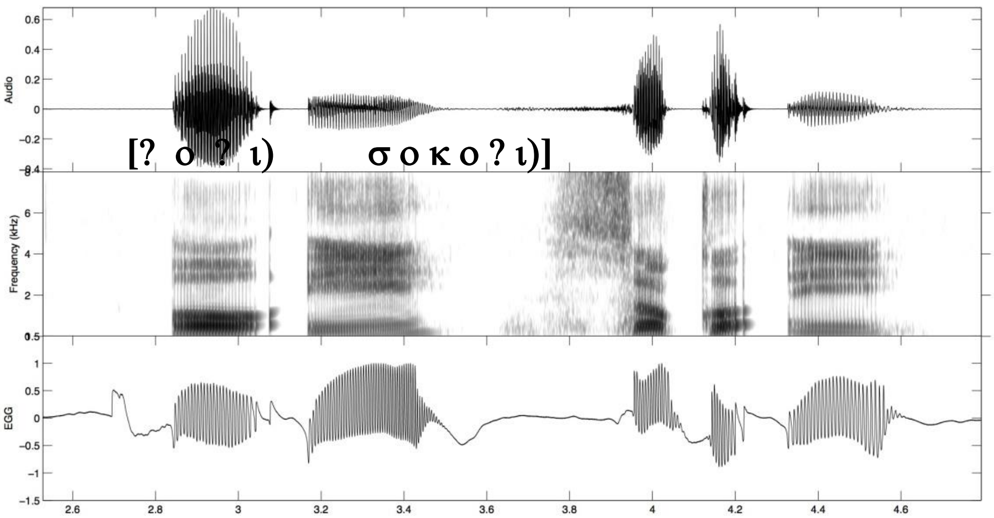

Figure 4. Audio waveform, wide band spectrogram and EGG signal of the word [?o?ι)σoκo?ι)] 'not to tie up'. The EGG shows that glottal stops start by a sharp increase in the signal. Then there is a gradual decrease of the signal until a fall occurs before the following vowel. The second and third [?] show a couple of abrupt opening and closure after the preceding vowel. The lowering of the EGG signal before [σ] and during [κ] (indicated within boxes) indicate the loss of contact between the vocal folds.

Glottal stops are generally realized by a beginning that is either abrupt or marked by a few glottal pulses. They end by an abrupt start on the first vibratory cycle of the following vowel. This can be seen on the spectrogram and audio waveform of Figure 4 for each vowel coming after a glottal stop. The EGG show that glottal stops start by an abrupt increase in the signal. This is due to the vocal folds contact giving little resistance to the electric flow. Then, there is a gradual decrease of the signal because there is little change in the resistance during the glottal closure. The second and third glottal stops show a couple of changes in contact and loss of contact and closure at the end of the preceding vowel.

The other important thing to note on the EGG signal is the transition between a glottal stop and the following vowel. Since there is no more contact between of the vocal folds, there is a drop in the signal at this moment. This is different from the transition between the voiceless consonants [σ] and [κ] where it can be seen that there is an increase in the EGG signal due to the adduction of the vocal folds for the following vowel. When the glottis opens after a vowel before a voiceless consonant there is a gradual decrease in the signal because there is no more contact between the vocal folds.

3 Vowels with a closing burst

The phenomenon has been observed in three different contexts: (1) within words in VC sequences where C is a voiceless stop ; (2) word finally before a final unreleased voiceless stop and (3) before nasal consonants. The contexts are presented separately in the following sections.

3.1 A glottal burst at the end of a vowel before a voiceless stop

Two examples of vowels ending with a burst are given in Figures 1a and 1b (representing the single vowel of the word *mbap and hobma*) and in Figure 5 (the first vowel of the word *apimbik*). Both show that the last vowel's cycle is realized by a clear burst on the audio waveform. Figure 1a shows the waveform and spectrogram of a word ending with an unreleased voiceless bilabial stop while Figures 5 give the audio waveform, the spectrogram and the EGG signal of an intervocalic voiceless bilabial stop.

The EGG signal of Figure 5 suggests that the vowel with a burst and the following voiceless stop are produced with an adduced glottis. The initial glottal stop, observed phonetically in this instance of the word [ʔαπιμβικ|] 'to push' shows an abrupt increase on the EGG followed by a gradual decrease of the signal. This is due to fact that there is a resistance at the glottis, as the vocal folds are in contact. The gradual decrease in the signal is the consequence of a change in the vocal fold contact area, as there is less contact in the lower part of the vocal folds. The final part of the glottal stop displays a fall in the EGG due to the opening of the glottis.

The vowel [a] shows a burst at the end in the waveform. The EGG signal shows an increase towards the end of the vowel, followed by a reduction of the signal's amplitude and leveling of the signal. This reduction in amplitude is due to the fact that the bilabial closure for [p] is accomplished while the focal folds are still vibrating. The EGG signal suggests that the intervocalic [p] is realized with an adduced glottis, i.e. with contact between the vocal folds. The EGG signal during the intervocalic stop [p] starts by a small diminution. This is followed by an increase which then stays almost flat before a final diminution. This suggests that there is little change in the impedance at the glottis. The strong burst on the audio waveform at the end of [p] is likely due to the fact that the larynx moves from a low position for [a] to a higher position for [i] which increases the air pressure in the sealed volume between the glottis and the lips. This results in a strong burst similar to ejective consonants.

The final consonant, the unreleased final voiceless velar stop [k] shows a loss of contact at the beginning when the EGG signal goes down. This is immediately followed by an increase and a flattening of the EGG signal. This suggests that there is a gradual increase in contact between the vocal folds. The contact between the vocal folds in the final part of the unreleased stop [κ|] prevents air pressure the rise behind the velar closure. This likely explains why there is no burst at end of this consonant.

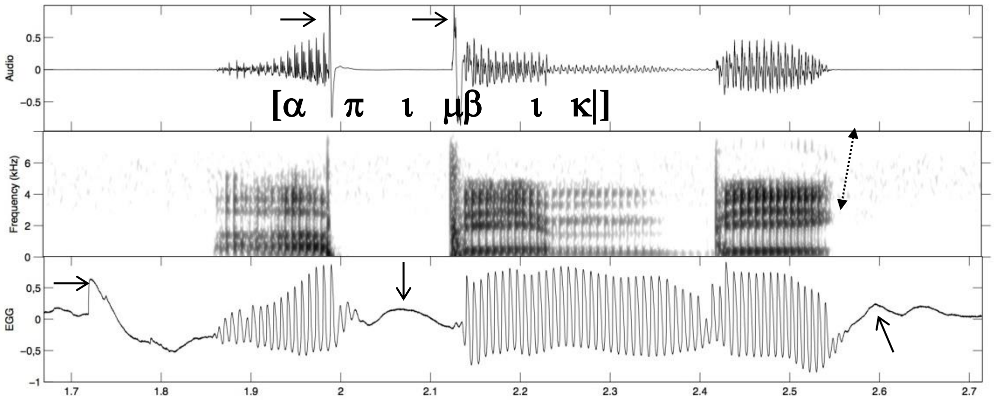

Figure 5. Audio waveform, wide band spectrogram and EGG signal of the word [απιβμβικ|] 'to push'. Arrows on the audio waveform indicate the vowel [α] ending with a burst and the initial burst of the following [π]. The final unreleased voiceless velar stop is identified by the F2/F3 approximation as indicated by the double arrow. Arrows on the EGG show the signal during : the initial glottal stop [?], the intervocalic voiceless bilabial stop [π] following the vowel with the final burst and the final voicless velar stop [κ|].

3.2 A glottal burst at the end of a vowel before a final unreleased voiceless stop.

Figure 1a shows that the word, [μβαπ|] 'lame' ends with an unreleased voiceless bilabial stop [π|]. The audio waveform and the EGG signal suggest that there is a contact between the vocal folds at this moment. The EGG oscillations end, at the moment where there is the burst on the audio waveform, and then rises gradually. Therefore it seems that the closing gestures of the lips and of the glottis are produced simultaneously. This results in the rise of acoustic pressure triggering the burst at the end of the vowel.

3.3 A glottal burst at the end of a vowel before a voiced nasal consonant

A number of vowels ending with closing bursts have been observed before the allophones of voiced nasal consonants that are described by Storto (1999) as pre-oralized [βμ, δν, γN] or final unreleased nasals [μ|] (see Figure 1.1 b), and for this reason we choose to illustrate one of these cases. In these data, again, the final cycle of the vowel is realized with a burst on the audio waveform as can be observed with the word [καβμ|] presented in Figure 6. Another example can be observed in Figure 1b. There is an increase in the amplitude of the EGG signal at the end of the vowel suggesting a greater contact and maybe tension of the vocal folds. This is followed by a ‘fall and rise’ movement of the EGG signal during the voiced segment which is due to a rising falling movement of the larynx.

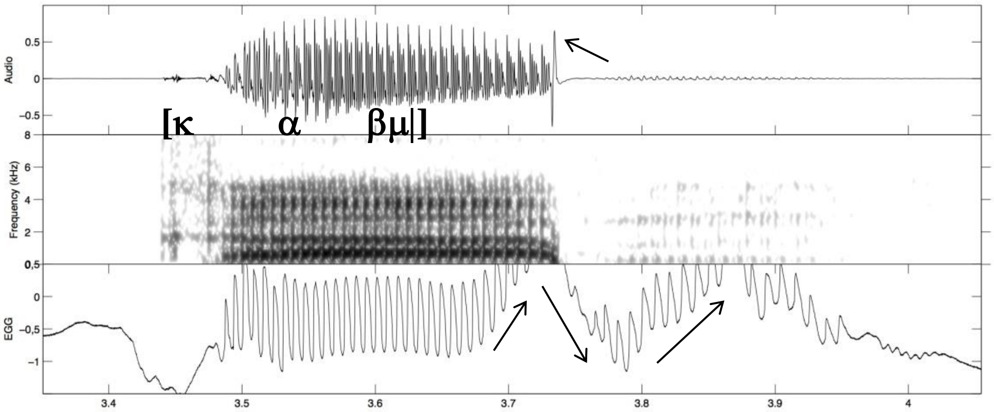

Figure 6. Audio waveform wide band spectrogram and EGG signal of the word the word [καβμ|] ‘now’. The arrow on the audio waveform indicates the burst at the end of the vowel preceding the pre-oralized stop [βμ|]. Arrows on the EGG show the increase and decrease of the signal at the end of the vowel [α] and during the final consonant [βμ|].

3.3 Sequences of oral and glottal gestures

The importance of the timing between glottalic and oral gestures is illustrated in Figure 7. in which we find sequences of oral and glottal gestures in consonants. An unreleased alveolar stop is followed by a glottal stop in the word [?oτ|?o⌉π|] ‘species of egret’. The interpretation of the EGG signal for the initial glottal stop is similar to what has been discussed for Figure 4. The consonant cluster [τ|?] constitutes a sequence of open to close glottalic gestures. The EGG signal of the initial vowel [t|] of the sequence shows a loss of contact between the vocal folds. There is then an increase in the EGG signal between the two [o] vowels. This shows an increase in contact between the vocal folds at the end of the voiceless alveolar stop. The acoustic signal does not display this event. The initial consonant [t|] is identified by its rising formant transition accounting for the locus of an alveolar consonant (Figure 7). This contrasts with the flat transition at the beginning of the following vowel which accounts for the transition between a glottal stop and a vowel.

The observation of the final consonant shows that the unreleased voiceless alveolar stop is produced with a superimposition of the oral and glottal closures. The audio waveform does not show a release burst. The EGG shows that there is vocal folds contact accompanying the oral closure as the signal gradually goes down and is maintained steady for a while. This example is particularly important to understand the difference between what happens in a *sequence* of open and close glottis versus the *superimposition* of oral and glottal gestures in word-final position when a stop is unreleased.

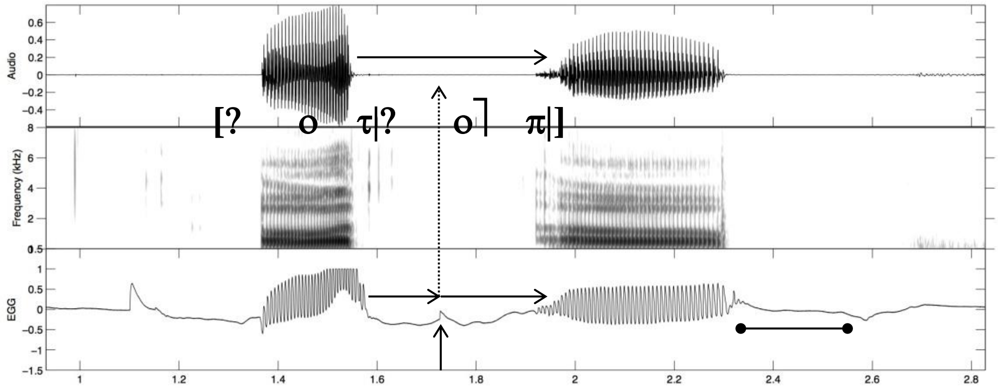

Figure 7. Audio waveform wide band spectrogram and EGG signal of the word [?oτ|?o⌉π|] 'species of egret'.The vertical arrow on the EGG indicates the glottal closure at the beginning of the second glottal stop [?] of the word. The two horizontal arrows show the sequence of the open and closed glottis accounting for the voicless alveolar stop [τ|] and the glottal stop [?]. The line between dots show the approximate timing of the glottal closure made during the final unreleased voiceless stop [π|]. The vertical arrow between the audio waveform and the EGG show that no burst accounts for the alveolar stop, suggesting that the alveolar closure is lasting during the glottal closure. The horizontal arrow shows the signal during the squence.

4 Why is there a burst at the end of some vowels?

The main factor involved in the vowels showing a final burst is a last final cycle with greater intensity. There is therefore a pulse with higher pressure on the acoustic waveform.

The explanation that we are proposing is that the burst at the end of the vowels (whether they precede voiceless stops or voiced segments) is the consequence of a greater or stiffer constriction of the glottis and vocal folds at the end of these vowels. This si produced almost simultaneously with an oral closure. Final voiceless stops are often produced with the oral closure gesture of the stop made with an adduction of the vocal folds. In this case, there is a partial or complete superimposition of the two gestures. This is contrary to the expected open glottis gesture of a voiceless stop. These settings likely favour the higher acoustic pressure accounting for the burst at the end of vowels.

The burst at the end of Figure 5 shows that at the moment of the oral closure (where voicing stops on the audio waveform) there is a sharp difference in amplitude between two consecutive oscillations of the vocal folds. They are followed by 2 weak amplitude oscillations. This is quite different from sequences where a vowel is followed by a voiceless stop where the EGG waveform gradually diminishes in amplitude. Again this suggests that the oral closure is accompanied by a closing gesture of the vocal folds. Before voiced segments, such as pre-oralized stops (e.g. [bm]), there is an increase of the glottis closure towards the end of the preceding vowel, suggesting a greater glottal resistance.

Although the explanation we are proposing should be confirmed on a better physical basis we believe that this phenomenon is important. The ‘abruptness’ of the phenomenon, i.e. the fact that it is observed on a single pulse, makes it difficult to explain. We initially thought that it was due to some contact of the speakers’ lips with the microphone or by a clipped signal. However this was gradually ruled out by the systematic presence of the phenomenon at the end of the vowels and not anywhere else in the signal of the recoded data. Recently we observed similar phenomena in Dâw and Pirahã suggesting that the phenomenon is not specific to Karitiana and might be a phonetic feature to be explained for these languages.

There is another important feature to note that deserves further investigation. Indeed Karitiana data observed here suggest that there is very little coarticulation between vowels and consonants in the contexts that we discussed. As it was mentioned above, sequences VC whether word internally or when the last is a final unreleased stop show that the timing of the oral and glottal closures makes the transition between the vowel (that can show a burst at the end) and the consonant well marked. There is little coarticulation between the vowel and the consonant. The same can be observed with nasal consonants that show no coarticulation, i.e. no nasalization, with oral vowels since there is always either some pre- or post-oralization when an oral precedes or follows a nasal consonant as can be seen on Figures 1b, 5 and 6. Even when a nasal vowel is in contact with a nasal consonant there is a well marked transition between the two segments. This feature might be specific to Karitiana but further investigations would be necessary to see if this feature is found in other Tupi languages.

5 Phonological consequences

The glottal closure or vocal folds adduction observed above at the end of voiceless stops explains why they are not exploded as shown in Figure 1b, 5 and 7 (Storto & Demolin 2002). Indeed there is no pressure (Ps) build up in the oral cavity if the glottis is closed from the start of the consonant . That is, with no airflow coming from the lungs into the oral cavity because of the glottal closure, the latter does not suffer a significant increase in pressure. A second possibility, illustrated in Figure 9 ([^{N}γαπ|] ‘’), shows that after an initial rise of Ps which is the consequence of the lips closure in the final consonant, Ps gradually diminishes without any apparent leaking at the lips of nostrils. This is due the expansion of oral cavity between the lips and the glottis with a lowering movement of the larynx. In the case of the nasals, there is no Ps because of the lowered velum, that lets the air escape through the nasal cavity. The unreleased stops found in Karitiana are not an isolated case in Tupi languages (Storto & Demolin 2012). This occurs in similar cases in English, i.e. with final voiceless stops which can alternate with glottal stops (Laver 1994). It would be interesting to check whether other Tupi languages also display an adduced or closed glottis simultaneous with the unreleased stop.

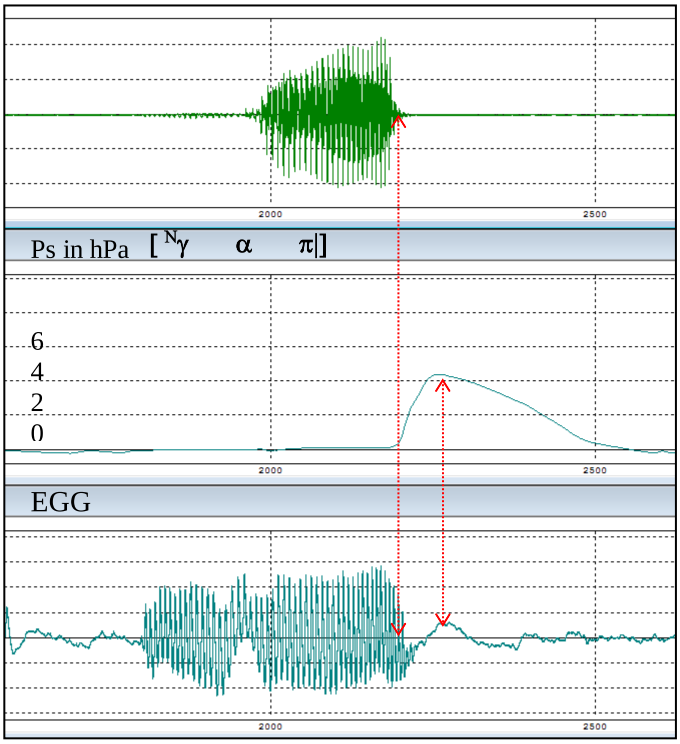

Figure 8. Audio weveform Ps, and EGG of the word [^{N}γαπ|] ‘’. Double arrows show (from left to right) the beginning of the bilabial closure, the maximum of Ps corresponding to slight a increase of the EGG signal. It can be be observed that Ps gradually falls after the maximum that is reached sightly after the beginning of the bilabial closure[1].

In Karitiana, there is a phonological process of lenition, in which a morpheme final voiceless consonant becomes a voiced approximant when a suffix starting with a vowel is added to the word. The same phenomenon occurs with nasal consonants. This phonological process has been described in the representation in table 2, adapted from Storto (1999)[2]:

Table 2. Voicing and lenition of stops and nasal

π →	ς	μ →	ς)
τ →	P	ν →	P)
κ →	Σ	N →	Σ)

[1] Data from this Figure were recorded using an EVA2 portable working station allowing to record simultaneously, the acoustic signal, oral airflow, intraoral pressure and the EGG signal (see Demolin 2011 for details on the method).

[2] Storto (1999:38) uses the IPA symbol of voiced bilabial and velar fricatives respectively to describe some of the sounds that result from lenition, whereas we use the symbol for a bilabial and velar approximant instead. The velar approximant symbol is used by Storto to indicate the sound resulting from lenition of bilabial stops and nasals in the environment of round vowels.

| → φ ⌡→ φ)

The following data illustrate the process:

(1) α + τακτακ + α → ατακταΣα

2-to swim-imperative ‘swim!’

(2) α + τατ + α → αταPα

2-to go-imperative ‘go!’

(3) α + ηι.ρ→π + α → αη→ρ→ωα

2-to cry-imperative 'cry'

The phenomenon of lenition is easily explained taking into account the articulatory setting of the final voiceless stops or nasals. Since the oral closure is made with none or almost no pressure (Ps) in the oral cavity due to the glottal closure or adduction, the stop is (acoustically) weakened as there is no burst. The adducted vocal folds found with these consonants favors voicing when in contact with a following voiced segment. Therefore, the glottis setting (closed or adducted) (i) prevents Ps build up in the oral cavity which favors lenition and (ii) also weakens the oral closure which becomes ‘looser’ and more like an approximant at the same place of articulation. Voicing assimilation by the stop is favored by the glottis setting (adducted) when a voiced segment follows, because glottal adduction it is a prerequisite for voicing.

6 Conclusion

The apparent random occurrence of vowels ending with bursts is related to a specific glottal setting following the vowel. The voicing and lenition processes found in Karitiana are naturally explained by the superimposition of two gestures (one glottal and one oral) having a variable timing and amplitude.

The co-occurrence of glottal stops and stress at the end of words indicates, as well, that the closing gesture of the glottis may have a prosodic function in the language, and should be subject of further investigation.

The fact that other Amazonian languages display similar phenomena suggests that it might be an important phonetic feature of these languages which on the other end have quite complex laryngeal features as laryngalization or glottalization of vowels and consonants (Storto & Demolin 2012).

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