Revisiting the Pressure Impulse in Australian Languages: Bininj Gun-wok

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Abstract

This study is an aerodynamic analysis of medial stop articulation in Bininj Gun-wok (BGW). Like many northern Australian languages, BGW has two stop series found in word medial, intervocalic position, at all places of articulation with no contrast for voicing or voice onset time. Acoustic and aerodynamic recordings of four speakers of the Kunwinjku dialect of BGW were recorded under field conditions in a remote community of Arnhem Land. Three repetitions of real Kunwinjku words were recorded within a carrier phrase. The analysis includes the measurement of peak intra-oral pressure (P_o) over time which is termed the Pressure Impulse (PI) after Malécot. Results show that peak pressure and consonant duration are independent parameters and that while lenis and fortis stops differ in terms of duration and peak intra-oral pressure, they attain the maximum pressure peak at a similar time after closure. Pressure Impulse measurements also differentiate the stop types and furthermore, results show that there may be differences within the long stop category contrasting fortis stops with geminates (homorganic clusters).

Index Terms: Australian languages, fortis, lenis, geminate, aerodynamics, intra-oral pressure, Pressure Impulse

1. Introduction

In Australian languages voicing does not reliably cue the differences between stops types although they are generally voiced word initially and devoiced word finally. There are a number of Australian languages, including BGW, which have two stop series matched at each place of articulation and found morpheme internally in disyllabic words (see Table 1). Observed differences between medial stop types in Bininj Gun-wok have resulted in the application of the phonological descriptors lenis and fortis. This implies that there could be a difference in articulatory strength between them and follows similar categorisation in related Australian languages such as Burrara and Yolngu Matha. There has been debate as to whether these are are appropriate cross-linguistic labels for contrasting stop series, both within Australia and Worldwide as there are not a single set of phonetic cues that signal a contrast [3, 4, 5, 6]. European languages, for example, contrast stop series either by the presence or absence of glottal pulsing or in terms of voice onset time (VOT) differences that lead to a contrast between aspirated and unaspirated consonants.

2. Background

Bininj Gun-wok has medial stops that differ phonetically in a number of ways. Duration is the primary difference but voicing (glottal pulsing) and voice onset time differences have not shown to be reliable phonetic cues to a difference. The lenis series is generally but not exclusively voiced, with a short duration and the fortis series is invariably devoiced with a longer duration and VOT varies by place of articulation [8]. Bininj Gun-wok has many heterorganic clusters—clusters of two lenis stops with different places of articulation—the language also allows for the formation of homorganic geminate clusters sometimes termed false geminates [7]. These geminate clusters span a morpheme boundary—inter-morphemic—and are lexically frequent due to the polysynthetic, agglutinative nature of the language (See list C in Table 2 below). A contrast between fortis stops and geminates clusters has been posited for a number of Yolngu Matha (YM) varieties such as Galpu and Gupapuyngu [13, 9]. The phonetic differences between the BGW and YM are yet to be tested instrumentally, however. The current study investigates these differences in BGW between the stop categories and also between fortis stops and geminate clusters as there is a reported phonetic contrast between geminate clusters spanning a morpheme boundary and fortis stops that are morpheme internal [1].

Table 1: *The phoneme inventory of Bininj Gun-wok. (after Evans, 2003)*

		PLACE OF ARTICULATION					
		bilabial	apico-alveolar	apico-retroflex	lamino-palatal	velar	glottal
MANNER	LENIS	p	t	ʈ	c	k	ʔ
	FORTIS	pː	tː	ʈː	cː	kː	
	NASAL	m	n	ɳ	ɲ	ŋ	
	LATERAL		l	ɭ			
	APPROX.	w			j		
	RHOTIC		r	ɻ			

Jaeger [11] has argued that in Jawoyn (Jarwoñ), a language related to BGW, pressure differences in medial stops are not independent of the duration, suggesting that there is no difference between them in terms of force of articulation. Any observed pressure differences would therefore be due to the pressure being able to rise until the stop is released and the time from stop closure, until the maximum peak pressure would therefore be much longer in fortis stops. Jaeger [11, p. 188] also suggests that the fortis consonants have developed diachronically from consonant clusters and although it is not possible to test this using synchronic data, Evans [1, p. 85] suggests that this is not the case for many medial long stops in BGW.

Jaeger's hypothesis has been tested by Butcher for a selection of languages including English, French, Italian, Javanese, LuGanda and the Australian languages Murrinh Patha and Burarra, [12, 5]. When the results from the Australian languages are considered, these studies find a difference between the rise rates in the intra-oral pressure between the stop categories. Fortis stops showing a much more rapid rise in the intra-oral pressure than lenis stops [12, 5]. This would indicate that the differences in intra-oral pressure measured are not simply a function of a greater duration. This may be achieved by measuring the peak pressure over time [12, 5].

2.1. Pressure as a function of time

Malécot [14, 15], while investigating plosives in American English, introduced a measurement that he termed the Pressure Impulse (PI). This is defined as the integral of the peak pressure curve measured as a function of time with limits at the onset and offset of oral closure in a plosive consonant. This can be expressed as,

$$\mathbf{PI} = \int_{T1}^{T2} \mathbf{P_o} dt, \tag{1}$$

The limits, T1 and T2 (as shown in Equation 1) are measured as the points between the onset (T1) and offset (T2) of a medial consonant with reference to the acoustic signal. Figure 1 shows the limits of the integral and also the point in which the maximum intra-oral pressure (P_oMAX) is attained.

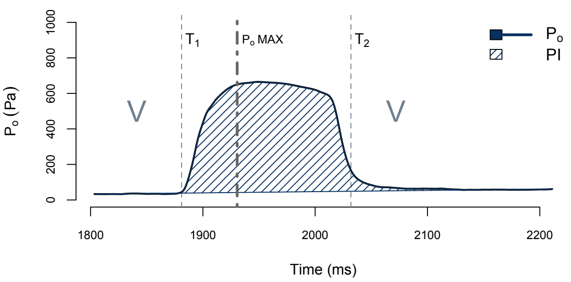

Figure 1: *An intervocalic medial bilabial stop in Bininj Gunwok showing the peak intra-oral pressure (P_o), the Pressure Impulse (PI) - shaded, and the Maximum oral-pressure (P_oMAX)*

The integral of peak oral-pressure over time can be approximated using *Simpson's Rule* [16] [1] The resulting Pressure Impulse is reported as a derived unit, Pascal seconds (Pa.s).

3. Research Questions

This study examines word-medial intervocalic bilabial consonants in the language to investigate phonetic differences and whether these are sufficient to cue the phonological difference between them. Additionally, is this difference directly related to their prosodic position as they are restricted word medial, intervocalic positions, except after a nasal? Jaeger's assumption that maximum peak pressure is dependent on duration is tested in Bininj Gun-wok and it will be investigated whether the Pressure Impulse reliably differentiates the two classes of stop. Additionally any observable difference between long fortis stops and long geminate clusters will also be tested.

[1] This formula is used in favour of other Newton-Cotes approximation methods for example the *Trapezoidal rule* or *Gaussian quadrature*.

4. Methods and Materials

4.1. Speakers and Stimuli

In this study, four—two female (BN, RN) and two male (CM, DJ)—first language speakers of the Kunwinjku variety of Bininj Gun-wok were recorded under field conditions in a remote community in Western Arnhem Land, Australia. This study presents both acoustic and aerodynamic recordings of intra-oral pressure (P_o) using a PCQuirer system (manufactured by Scicon R&D) and analysed using standard aerometric techniques [17]. All intra-oral pressure measurements are measured in intervocalic bilabial stops within real Kunwinjku words. A word list of 11 words were placed within a carrier phrase with the target word in focussed position and these were repeated three times (see Table 2). List A are all lenis or short stops (4 words), list B are all fortis or long stops (4 words) and words in list C all contain clusters that cross a morpheme boundary (geminate). There are recordings of 132 tokens and 122 tokens were included in the analysis with 10 tokens excluded due to zero values in the pressure record.

Table 2: *Bininj Gun-wok words included in this study.*

ID	Word	Struc.	Gloss
A01	kabbal	VC:V	*flood plain*
A02	ngabbard	VC:V	*kinship term (F)*
A03	kubbunj	VC:V	*canoe*
A04	djobbo	VC:V	*butcher bird*
B01	aba	VCV	*interjection*
B02	kabo	VCV	*green ant*
B03	bobo	VCV	*goodbye*
B04	bibom	VCV	*hit*
C01	k**ebbal**djurri	VCCV	*royal spoon bill*
C02	k**ebbal**hmeng	VCCV	*close your nose*
C03	k**ebbe**rrelh	VCCV	*flat nose*

The words tested are all between two vowels although long stops can be found syllable finally after continuants such as laterals [l] and alveolar trills [r]. These complex cluster type are not included in the current study. Calibration of the pressure transducers was done at the start and end of fieldwork at the University of Melbourne and also in the field at the start of each session, using a U-tube manometer [17, p. 63].

4.2. Analysis and Statistical Methods

The acoustic signals were phonetically hand labelled within the Emu Speech Database and the onset (T1), burst (H) and offset (T2) of the intervocalic consonants were marked. The maximum Intra-oral pressure (P_oMAX) was calculated by computer script from the P_o. The subsequent statistical analysis included a general linear mixed effects (GLME) model within the R statistical environment [18] using the *lme4* package [19]. *Speaker* and *word* were included as random factors and three main effects were tested. A number of main effects were tested as a function of the stop category. The stop category is a three levelled factor (lenis, geminate, fortis) The main effect of the Pressure impulse as a function of stop category was tested.

5. Results

Results show that there is a clear durational difference between lenis and fortis stops in the sample consisting of Bininj Gunwok bilabial medial stops. When a General Linear Mixed Effects model testing a main effect of stop category on consonant duration ($\chi^2(6,N{=}128)= 52.8$, $p < .001$), fortis stops are found to be 82 ms longer than lenis stops using a *post hoc* Tukey Honest Significant difference test ($p < .001$). Fortis stops have a mean duration of 170 ms with a sd. of 25 ms and lenis stops have a mean duration of 88 ms with a sd. of 17 ms. The mean duration of geminates—also termed homorganic intermorphemic stop clusters—is 156 ms which is not found to be significantly different to the duration of the fortis stops.

Figure 2 shows the plot of consonant duration (measured in milliseconds) when compared with peak intra-oral pressure (measured in Pascals). The results of a logistic regression are superimposed as trend-lines on the figure with the standard error at a 95% confidence interval plotted in grey. As the consonant duration increases, the intra-oral pressure increases for lenis stops and clusters but remains high for fortis stops. Although the clusters overlap for duration they have consistently lower pressure values.

When the analysis is restricted to the lenis and fortis stops, the results show that the peak pressure for fortis stops is just under twice that of lenis stops—450 Pa for fortis vs. 200 Pa for lenis, suggesting a difference between the peak pressure targets for these two stop categories. To test whether this difference is due to the fortis stop's longer duration the time after closure of the maximum peak pressure is measured. If pressure and duration are dependent on one another, the pressure peak in the fortis stops would be attained later in the closer period to allow for a linear rise in intra-oral pressure. This strongly suggests that maximum peak P_o (P_oMAX) is not correlated with duration when each stop category is considered separately and this assertion is tested in the following section (§ 5.1).

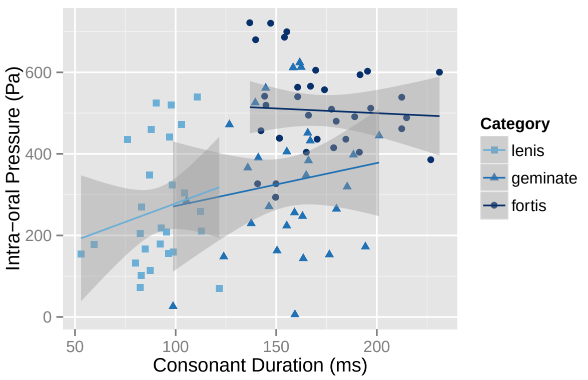

Figure 2: *Consonant duration (ms) by peak maximum intra-oral pressure (Pa) for all speakers separated by stop category*

5.1. Time to reach Maximum Pressure

As shown in Figure 2, duration is the primary difference between the stop categories lenis and fortis but when the homorganic clusters are considered the difference is not as clear as there is overlap between the geminate clusters and fortis categories. When speaker identity is included as a random factor in the GLME there is very little observable durational difference between fortis stops and geminate clusters. This may explain why it is difficult to differentiate them using acoustic methods. If the intra-oral pressure is indeed a function of the duration, as posited by Jaeger [11], then we would expect that the maximum peak oral pressure would occur later in fortis stops as there is greater time for the pressure peak to be achieved.

Figure 3 shows the time taken to reach the maximum pressure (P*o*MAX) for lenis, geminate clusters and fortis stops respectively in each of the four speakers. the peak pressure is reached at a similar time in both lenis and fortis stops—approximately 80 ms after closure— whereas the geminates have the peak oral pressure occurring later after the onset of closure (far later in the case of speaker CM) although the GLME model does not show a statistically significant difference between the categories.

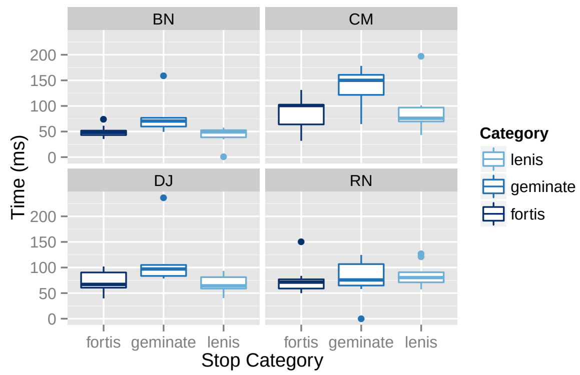

Figure 3: *The time to reach peak intra-oral pressure (ms) separated by stop category and speaker*

5.2. The Pressure Impulse

In order to collapse the variables into a single measure an approximation of the integral of the pressure curve was estimated. This combined measurement is termed the Pressure Impulse after Malécot (see § 2.1). The results show that there is a difference in the Pressure Impulse (PI) not only between lenis and fortis stops but between fortis and geminates.

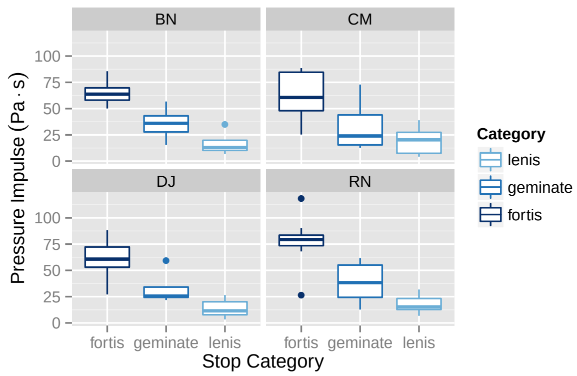

Figure 4: *Pressure impulse showing lenis stops, fortis stops and geminate clusters, separated by speaker*

A statistical analysis of the PIs of lenis, fortis and geminate stops input into the GLME model ($\chi^2(6,N{=}122)= 24.1$, p

<.001) confirms that there is a significant difference in the pressure impulse between the categories. Testing a main effect of stop category on PI shows a significant difference when the lenis category is compared with fortis ($p < .001$) and also a significant difference when fortis is compared with geminates ($p < .001$) but no difference when the lenis group is compared with geminates. This is confirmed between the categories using a *post hoc* Tukey HSD test and the mean difference between the PIs was compared. Fortis stops have a mean PI that is 49 Pa.s higher than the lenis stops (55 Pa.s compared with 6 Pa.s in absolute terms). Fortis stops have a mean PI of 30 Pa.s which is higher than that of geminate clusters a mean PI of 25 Pa.s. There is no significant difference between the mean PIs of the lenis and geminate categories, suggesting that geminates behave more in line with Jaeger's observations in Jarwoyn and Zapotec. The maximum pressure peak occurs later within the closure and consequently there is a lower associated PI than in the fortis stops.

6. Discussion

This study investigated whether there are consistent articulatory differences between lenis, fortis and geminate stops (i.e. homorganic stop clusters) in BGW. These results suggest that as well as a difference between lenis and fortis stops, there are two types of long stop, one in which pressure is dependant on duration and one in which the two parameters are independent. The fortis stop has shown to contrast with the lenis stops in terms of both timing and pressure, each having a different peak pressure target as previously shown by Butcher [12, 5]. The geminate does not have the associated early pressure rise although peak pressures and durations are comparable to fortis stops. This suggests that a geminate is more akin to a cluster of lenis stops than to a fortis stop.

Both the fortis and the lenis stops attain the maximum peak oral pressure at similar times after the onset of oral closure, yet the the maximum peak pressure value is far higher in fortis stops than in lenis stops. The PI measurement shows a clear difference between the lenis and fortis stops. It is hypothesised that a fortis stop has a more forceful articulatory closure—at the lips in the case of bilabials examined in this study—or greater tension in the cheeks to prevent cavity expansion behind the closure. When the geminates are included in the analysis they pattern with fortis stops in terms of duration but are placed between lenis and fortis stops in terms of the Pressure Impulse. This suggests that there is not the associated force of articulation in lenis stops or geminates and that there is a three-way distinction between word medial, intervocalic stops.

In this paper, we have shown that intra-oral pressure is an important articulatory cue to the lenis/fortis contrast in BGW. Furthermore the maximum peak intra-oral pressures are not dependent on longer acoustic closure duration as suggested by Jaeger for Jawoyn. In addition there are Pressure Impulse differences between long/fortis stops and long/geminate clusters which may be similar to those suggested by Lehiste et al. for Estonian [20]. Future work hopes to test this claim with a larger sample of words already recorded for Bininj Gun-wok and then extend the analysis to other Australian languages that also have a phonological contrast between stop series.

7. Acknowledgements

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