An electro-palatographic study of consonant sequences in Iwaidja

Janet Flecher[1], Deborah Loakes[1], Andrew Butcher[2]

[1] School of Languages and Linguistics, University of Melbourne, Melbourne, Australia
[2] Department of Speech Pathology and Audiology, Flinders University, Australia
janetf@unimelb.edu.au, dloakes@unimelb.edu.au, andy.butcher@flinders.edu.au

Abstract

An EPG (electro-palatographic) corpus of Iwaidja consonant sequences was examined to investigate global consonant timing patterns and the extent of coarticulation and co-production in nasal+stop and lateral+stop clusters. As observed in other Australian languages (e.g. Warlpiri), there was limited anticipatory coarticulation in certain heterorganic sequences and evidence of coarticulatory resistance in others. Furthermore lateral clusters patterned differently from nasal clusters. In addition to biomechanical constraints implied by the DAC (Degree of Articulatory Constraint) model, phonological structures of the language including place and manner features clearly influence the extent of coproduction and subsequent spatial modification of consonant gestures in Iwaidja consonant sequences.

Index Terms: coproduction, consonants, Iwaidja

1. Introduction

Previous articulatory research on consonant $C_{1\#}C_2$ sequences in languages like English has shown that the first consonant is overlapped somewhat by C_2 particularly if the C_1 is alveolar, but there is less temporal overlap in syllable initial clusters (e.g. [1] [2]). It is well known that the alveolar nasal in English words like "pancake" assimilates to the following velar although there can be a high level of inter-speaker variability i.e. some people totally assimilate the /n/ to /ŋ/ whereas others show evidence of partial assimilation [3]. By contrast, Australian indigenous languages are said to show remarkable stability in hetero-syllabic C_1C_2 sequences where C_1 is alveolar and C_2 is velar as in /nk/ sequences.

This claim was borne out to a certain extent in a previous electropalatographic investigation of heterorganic consonant clusters in Warlpiri [4]. For most alveolar+velar sequences, the tongue dorsum raising gesture was delayed somewhat relative to the apical alveolar gesture. A degree of temporal overlap or coproduction of tongue tip and tongue dorsal gestures was however observed in apico-alveolar nasal + velar stop sequences. There was also some minor spatial modification to the alveolar gesture (i.e. there was slightly more palate coverage) but the apical gesture was clearly maintained in these sequences. A related set of findings emerged in recent pilot work on a Northern Australian language, Bininj Gun-wok. It was found that nasals in VNCV sequences are somewhat *longer* than in VNV contexts and that vowel transitions are also preserved to maintain clear place of articulation cues [5]. These results also concur with an earlier kinematic and acoustic study of Warlpiri where it was also found that post-tonic medial consonants tend to be strengthened and lengthened [6].

It is also important to note that not all place of articulation contrasts are preserved in clusters in languages like Warlpiri, however. In [4] it was also found that palatal nasals in /ɲC/ sequences exert strong spatial coarticulatory effects on following stop consonants. This is precisely what coarticulation models like the DAC ("degree of articulatory constraint") model would predict [e.g.7]. Among other things, this model predicts that there is a relationship between coarticulation dominance and coarticulatory resistance, i.e. segments that exert the greatest coarticulatory influence like palatals (or retroflex consonants), are also those that are most resistant to coarticulatory influences from surrounding segments. Another feature of DAC is that it makes clear predictions about different *degrees* of gestural overlap depending on manner of articulation of segments within clusters. For example, the model predicts that laterals in clusters are less prone to coarticulatory modification than nasals in clusters due to their higher DAC values. Research on German clusters [8] has found that syllable-initial /kl/ clusters show more temporal overlap than /kn/ clusters bearing out the prediction by the DAC model. The authors also discuss their findings in relation to a range of other principles and various prosodic affects like degree of accentual prominence that can influence the degree of temporal coordination and coproduction in different clusters.

In view of this background, the current study investigates aspects of spatio-temporal patterning in nasal+stop and lateral+stop medial clusters in the Australian language, Iwaidja, which is spoken by around 200 people in the Coburg Peninsula, Northern Territory, Australia. Like other Australian languages investigated so far, Iwaidja permits a wide range of heterorganic and homorganic nasal+stop and lateral+stop clusters. In this paper we examine spatio-temporal variation in a set of apico-alveolar and retroflex sonorants + stop clusters. We also hypothesis that as in Warlpiri, there may be minor spatial modification of alveolar sonorants due to following velar stops. Unlike English, but like German, Iwaidja does not have a velarised alveolar lateral so we further hypothesis there will be coarticulatory resistance in clusters containing high or intermediate DAC consonants like clear /l/. We also predict that retroflex /ɳ/ and /ɭ/ will also resist coarticulatory influences of a following consonant. They are likely to show a high degree of coarticulatory resistance given their known tendency to influence the articulation of surrounding segments in Australian languages (e.g. Arrernte [14]). Other studies of retroflexes in languages like Wubuy [15] and Kannada [16] have also shown that they are associated with a relatively stable posterior tongue position in order to facilitate the sub-apical retraction which contributes to their high DAC value.

In addition, medial post-tonic position has been claimed to be a "strong" environment in Australian languages so coda consonants may be somewhat strengthened relative to syllable onsets [9]. Consequently, only word medial hetero-syllabic $C_1.C_2$ clusters are examined in the current study with the focus on C_1, i.e., coda consonants. The behaviour of retroflex consonant clusters has not been examined for any Australian language to date.

2. Method and Materials

2.1. Speakers and Language Materials

Figure 1 shows the northern part of Arnhem Land, Northern Territory, Australia where Iwaidja is still spoken. Two speakers of Iwaidja participated in this experiment. They were recorded at Minjalang on Croker Island by the third author and Iwaidja language consultant Bruce Birch. The corpus was recorded as part of an ongoing investigation of coarticulation in Australian languages.

Figure 1. Map of Northern Australia showing where Iwaidja and other indigenous languages of the region are spoken.

Table 1 shows the consonant phoneme inventory of Iwaidja, after [10]. It is typical of many Australian languages in that there is a single stop series, no fricative series, a rich inventory of sonorants and place of articulation contrasts, and relatively few vowel contrasts. Some of the stop contrasts (e.g. amongst the coronal set) are neutralized word initially, but all are realized intervocalically. Iwaidja has an even richer sonorant inventory than the majority of Australian languages with 3 rhotics and 4-5 laterals (depending on the phonological status of the pre-lateralised coronal stops).

Table 1. Consonant Inventory for Iwaidja

		Peripheral		Coronal		
				Apical		Alveo-pal
		Labial	Velar	Alveol	Retro	
Stop		b	k	t	ʈ	c
Nasal		m	ŋ	n	ɳ	ɲ
Approximant		w	ɰ		ɻ	j
Liquid	Tap			r	ɽ	
	Lateral			l	ɭ	
Pre-lateralised stops				ˡd	ˡɖ	

The Iwaidja corpus consisted of 187 real words of between two to five syllables in duration. The words were read in citation form and in a carrier phrase. In all cases, the words were in prosodically prominent phrase-initial position. For the purposes of this study, only those tokens that contained the following heterorganic and homorganic clusters in word-medial position were analysed:

•Son + stop /lk/ /ɭk /nt/ /nc/ /nk/ /ɳʈ/ /ɳc/ /ɳk/

There were no instances of /ɭc/ in this corpus.

2.2. Recording and Analysis procedure

Electropalatographic data were recorded using the Reading Electropalatograph (version 3) and the Articulate Assistant (version 2) software package. The speakers were required to wear a speaker-specific artificial palate. Once the speakers felt comfortable with the palate, the recordings took place. Acoustic data were recorded simultaneously at 22Khz. The EPG data were recorded at a sampling rate of 100 Hz. There were between 10 and 20 instances for each nasal+stop and lateral+stop heterorganic sequences per speaker. Segmental labelling was carried out using the acoustic waveform, spectrogram and EPG window in the EMU Speech Database System [11]. The onset and offset of nasal and lateral segments were used to locate the boundary of these segments (i.e. at the onset and offset of central contact on the palate). A range of data reduction procedures was performed within EMU-R. For each nasal/lateral stop cluster, the COG (centre of gravity: the main concentration of electrode activation on the artificial palate), AI (Anteriority Index – degree of contact in the first five rows), and DI (Dorsal Index – degree of contact in the last three rows) were calculated for nasals, laterals and for following stops. Figure 2 shows the relationship of EPG indices to place of articulation. The EPG indices were derived for the entire segment, cluster, and also at the .5 midpoint for each member of the cluster. Higher COG values (i.e. up to 7.5) are interpreted as a more anterior place of articulation; lower values are interpreted as more back. Similarly, higher values (up to 1) are interpreted as more anterior or posterior for the AI and DI indices respectively.

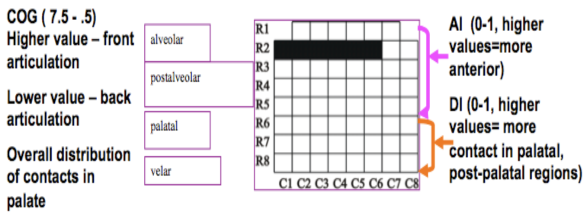

Figure 2. EPG indices: COG, AI and DI relative to palatogram. Higher values for COG and AI indicate a more fronted articulation. Higher DI values indicate a more posterior place of articulation.

3. Results

3.1. Centre of Gravity and acoustic duration – Homorganic and Heterorganic clusters

Figure 3 shows a simplified distribution, median values and outliers of the COG (Centre of Gravity) index derived from the midpoint of the initial nasal for a series of nasal+stop sequences where the initial nasal is apico-alveolar or retroflex and the following stop is /t/ /c/ or /k/. There is the predictable strong effect of place of articulation on the COG value of the initial consonant for both speakers (F: df(1,47)F=68.78, $p<0.0001$; M. df(1,65) F=77.15, $p<0.0001$). /n/ has a higher mean COG value suggesting a more anterior point of palate contact than /ɳ/. However this is not consistent across all clusters. There is also a strong interaction between the nasal and following consonant (F: df(4,47)F=9.08, $p<0.0001$; M. df(4,65) F=13.54, $p<0.0001$). For example, both speakers show a significant but small spatial effect of place of articulation of the following C on the COG value of the alveolar nasal. Alveolar nasals in homorganic /nt/ clusters have the highest COG values (5.02, and 5.22, for the female and male speaker respectively). The alveolar nasal in /nk/ clusters has a marginally lower COG value for both speakers(4.08, 4.17 respectively). There were no instances of complete assimilation of alveolar nasals in anticipation of the following velar stop consonant. Nasals in alveolar+palatal sequences have intermediate values to those for homorganic alveolar and alveolar+velar sequences. Although not plotted here, the mean COG value of velar nasals in homorganic velar clusters is a very low .89 for both speakers.

In general, there is higher degree of variation in the COG values for alveolar nasals in velar environments compared to the other two contexts. In the retroflex+stop sequences, the COG of /ɳ/ is even more variable but notably higher when followed by palatal /c/ compared to /t/ or /k/ for both speakers. For the female speaker, retroflex COG values are lowest in /ɳk/ clusters and for the male COG values are lowest in /ɳʈ/ clusters.

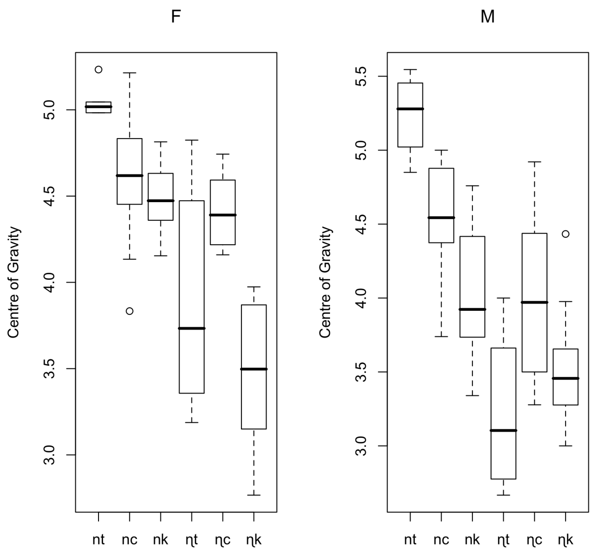

Figure 3: Box plots showing the distribution of EPG Centre of Gravity (COG) values for alveolar nasals in homorganic /nt/ and heterorganic nasal stop clusters in Iwaidja for the male and female speakers.

Figure 4 plots the simplified distribution of acoustic duration values for the nasals in clusters. The male speaker shows a significant effect of place of articulation of following consonant on nasal duration (df(2,29)F=17.48; p<0.0001). Nasals are significantly longer in /nk/ compared to the other two /n/ clusters. Similarly /ɳ/ is longer in /ɳc/ and /ɳk compared to homorganic / ɳʈ /. The female speaker showed a high level of durational variability across all places of articulation.

Figure 5 plots the COG (Centre of Gravity) results for both speakers for alveolar and retroflex lateral+stop sequences: /lt/ /lk/, /ɭʈ/ and /ɭk/. There is a predictable effect of place of articulation on COG value of the two laterals (F: df(1,67)F=42.92,p<0.0001;M:df(1,86)F=227.85,p<0.0001). Alveolar laterals have higher mean COG values than retroflex laterals. Both speakers also show a significant effect of following consonant on the COG values of retroflex laterals, in particular (F: df(2,67)F=4.29, M:df(2,86)F=13.01, p<0.0001). The COG at the midpoint of the retroflex has a higher value before velars than in the homorganic context of /ɭʈ/. There is no significant difference between COG values of /l/ in either homorganic or heterorganic clusters for either speaker.

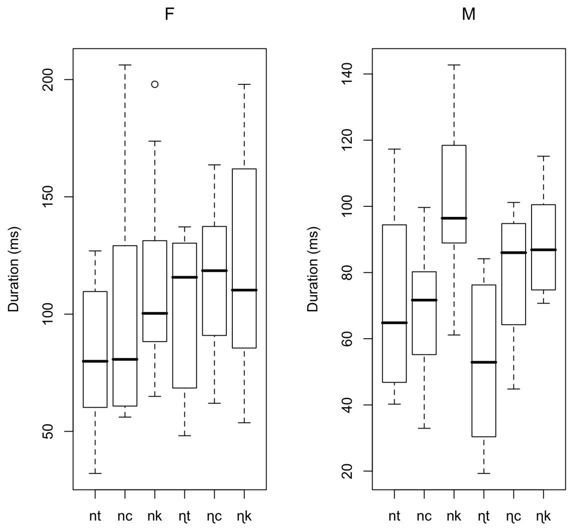

Figure 4: Box plots showing the acoustic duration of nasals in various nasal+stop clusters for the two speakers

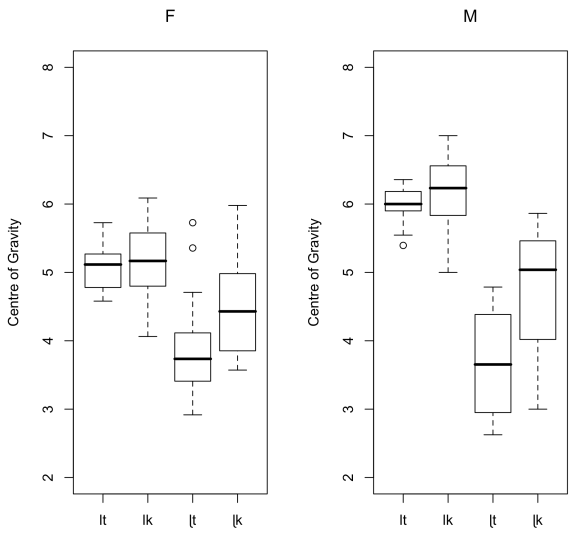

Figure 5: Box plots showing the distribution of EPG Centre of Gravity values for alveolar laterals in a homorganic and two heterorganic lateral stop clusters in Iwaidja for the male and female speakers.

An analysis of the acoustic duration of laterals in clusters showed no effect of following consonant on lateral duration for the male speaker, and a small but significant effect for the female speaker (df(2,70)F=4.6, p<0.05). The mean duration of /l/ is 91 ms compared to 112 ms for /ɭ/. The duration difference is clearest in homorganic retroflex clusters.

3.2. Temporal sequencing of Apical and Dorsal Gestures

Figure 6 plots the averaged apical (black) and dorsal (gray) trajectories of eight clusters analysed in section 3.1. The male speaker's productions are shown here (the female speaker produced similar patterns). Alveolar /nk/ and /lk/, as well as retroflex /ɳk/ and /ɭk/ clusters are shown (note that the practical orthography representation of the retroflex consonants: /rn/ and /rl/ is used in the second row of plots).

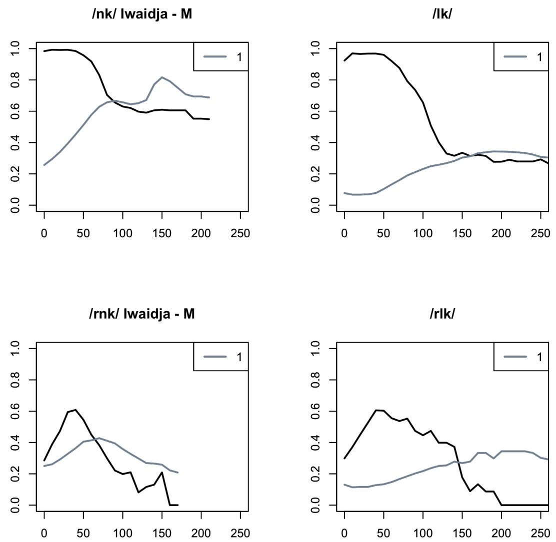

Figure 6. Averaged Anteriority Index (black) and Dorsal Index (gray) trajectories across the entire cluster for apico-alveolar (/n/, /l/ +/k/ and retroflex(/ɲ/, /rl/)+/k/ clusters.

A high sustained plateau in AI values is observed for cluster-initial /l/ and /n/ with values approaching 1.0 which indicates the highest level of palate coverage in the anterior zone. This accords well with the relatively long acoustic duration of these nasals. A lower peak-like pattern is observed for AI values in retroflexes with palate coverage in the post-alveolar zone (AI=6.0). The onset of dorsal contact (the gray signal) begins almost immediately at the start of the N+k clusters showing anticipation of the following velar. The DI peak is reached after the plateau (or peak, in the case of the retroflex) in AI values. In L+k clusters, by contrast the rise in dorsal contact is somewhat delayed (usually approximately 40 – 50 ms into the lateral). These results suggest that patterns of temporal coordination are indeed different in N+k and L+k clusters as noted in a range of other languages [8].

4. Discussion and Conclusion

The results presented in this paper suggest that there is a degree of anticipatory coarticulation and temporal coproduction in some hetero-syllabic apical+dorsal clusters in Iwaidja. Centre of Gravity values at the C_1 consonant midpoint in apico-alveolar nasals are lower in heterorganic compared to homorganic sequences consonant clusters. In retroflex nasal+stop clusters, the COG value at the consonant midpoint is higher when the following consonant is laminal palatal, which also suggests an anticipatory coarticulatory effect of fronting. Lateral clusters, by contrast, do not show any consistent spatial modification except for retroflex+k clusters (recall there were no /ɭc/ clusters in this corpus). However in these cases the COG value for /ɭ/ shifts forward suggesting *strengthening* of the place cue coupled with a later onset of the dorsal raising gesture for /k/. These results support the view that Iwaidja laterals (and in particular retroflex laterals) have high DAC values and are more resistant than nasals to articulatory modification due to an upcoming consonant. Furthermore, the later temporal sequencing of dorsal gestures in L+k clusters provides further support for DAC model predictions that nasal and lateral clusters behave differently, in keeping with a range of other studies e.g. [8]. Recent research on clusters in English and Romanian suggests that /lC/ clusters show distinct timing patterns depending on their phonotactic composition [12, 13] so these factors need to be examined further in Iwaidja. Nevertheless, as in Warlpiri and other Australian languages, there are a range of biomechanical as well as phonological constraints that influence the spatio-temporal patterning of hetero-syllabic clusters in Iwaidja.

5. Acknowledgements

This research was supported by Australian Research Council Discovery Grant DP0557540 awarded to the first and third authors.

6. References

[1] Hardcastle, W.J. "Some phonetic and syntactic constraints on lingual coarticulation during /kl/". *Speech Communication*, 4, 247-263. 1985.
[2] Byrd, D., "Influences on articulatory timing in consonant sequences", *JPhon*, 24, 209-244. 1996
[3] Ellis, L. & Hardcastle, W.J. Categorical and gradient properties of assimilation in alveolar to velar sequences. *JPhon* 30,373-96. 2002
[4] Fletcher J. et al. "Coarticulation in nasal and lateral clusters in Warlpiri'. *Proceedings of Interspeech 2008*, Brisbane. 2008
[5] Fletcher J et al. "Aspects of nasal realization and the place of articulation imperative in Bininj Gun-wok.". *Proceedings of SST2010*, Melbourne. 78-81. 2010
[6] Fletcher J. et al. An instrumental analysis of focus and juncture in Warlpiri. *Proceedings of ICPHS 2003*, 321-5. 2003
[7] Recasens, D., Pallarès, M. D., and Fontdevila, J. 1997. "A model of lingual coarticulation based on articulatory constraints," J. Acoust. Soc. Am. 102, 544–561
[8] Bombien, L. et al. Prosodic and segmental effects on EPG contact patterns of word-initial German clusters. *JPhon* 38, 388-403. 2010.
[9] Butcher, A. "Australian Aboriginal languages: consonant-salient phonologies and the 'place-of-articulation imperative' ". In Harrington, JM and Tabain, M. (eds) *Speech Production: Models, Phonetic Processes and Techniques*. Psychology Press, New York, 2006
[10] Birch, B. (in preparation). "The phonetics and phonology of Iwaidja". PhD thesis. University of Melbourne
[11] Harrington, J. *The Phonetic Analysis of Speech Corpora*. Oxford: Blackwell, 2010.
[12] Marin, S. & Pouplier, M. "Temporal organization of complex onsets and codas in American English: Testing the predictions of a gestural coupling model. *Motor Control*, 15, 380-407. 2010.
[13] Marin, S. "The temporal organization of complex onsets and codas in Romanian: A gestural approach. *JPhon*, 41, 211-227. 2013
[14] Tabain, M. An EPG study of alveolar vs. retroflex apical contrast in Central Arrernte. JPhon 37, 486-501. 2009
[15] Kroos, C., Bundgaard-Nielsen, R., Goldstein, L. and Best, C. (2010), 'Tongue body position differences in the coronal stop consonants of Wubuy', *SST2010*,
[16] Kochetov A. et al. "Spatial and dynamic aspects of retroflex production: An ultrasound and EMA study of Kannada geminate stops". *JPhon* 46, 168-184. 2014