An Acoustic Study of Coarticulation: Consonant-Vowel and Vowel-to-Vowel Coarticulation in Four Australian Languages

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Abstract

Acoustic phonetic experiments were conducted with the aim of describing spatial coarticulation in consonants and vowels in four Australian languages: Arrernte, Burarra, Gupapuyngu and Warlpiri. Interactions were examined between coarticulation and factors such as consonant place of articulation (the location of the point of maximal consonantal constriction in the vocal tract), the position of the consonant relative to the vowel (preceding or following), prosodic prominence and language. The principal motivation was to contribute to the experimental literature on coarticulation in Australian languages, given their unusual phonological characteristics.

The results of acoustic measurements show that in stop consonant and vowel production, there are systematic contrasts between consonant places of articulation, especially between peripheral (*i.e.*, bilabial and dorso-velar) and non-peripheral categories, and there are clearly discernible consonant place-dependent differences in the degree of vowel-to-consonant and consonant-to-vowel coarticulation. Additionally, consonant place of articulation is seen to strongly modulate vowel-to-vowel coarticulation. As observed in other languages, such as Catalan, Italian and German, the degree of vowel-to-consonant coarticulation is seen to vary inversely with the degree of consonantal articulatory constraint (*i.e.*, degree of tongue dorsum raising), as does the degree of segmental context-sensitivity. However, findings reported in this dissertation suggest that, unlike results reported previously for European languages such as English, anticipatory vowel-to-consonant coarticulation tends to exceed carryover coarticulation in these languages. With regard to prosodic effects on coarticulation, it appears that prominent vowels do not typically undergo localised hyper-articulation or acoustical expansion as in English, Dutch and German.

It is concluded that these results support the view that the maintenance of consonant place of articulation distinctions is pre-eminent in Australian languages. The analyses that are presented contribute to an understanding of the role of consonant place of articulation in coarticulation and, more generally, of the relationship between the acoustics and the biomechanics of speech.

Declaration

This is to certify that

(i) the thesis comprises only my original work towards the PhD except where indicated in the Preface,

(ii) due acknowledgement has been made in the text to all other material used,

(iii) the thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Signed

N. SIMONE GRAETZER
(13 September, 2012)

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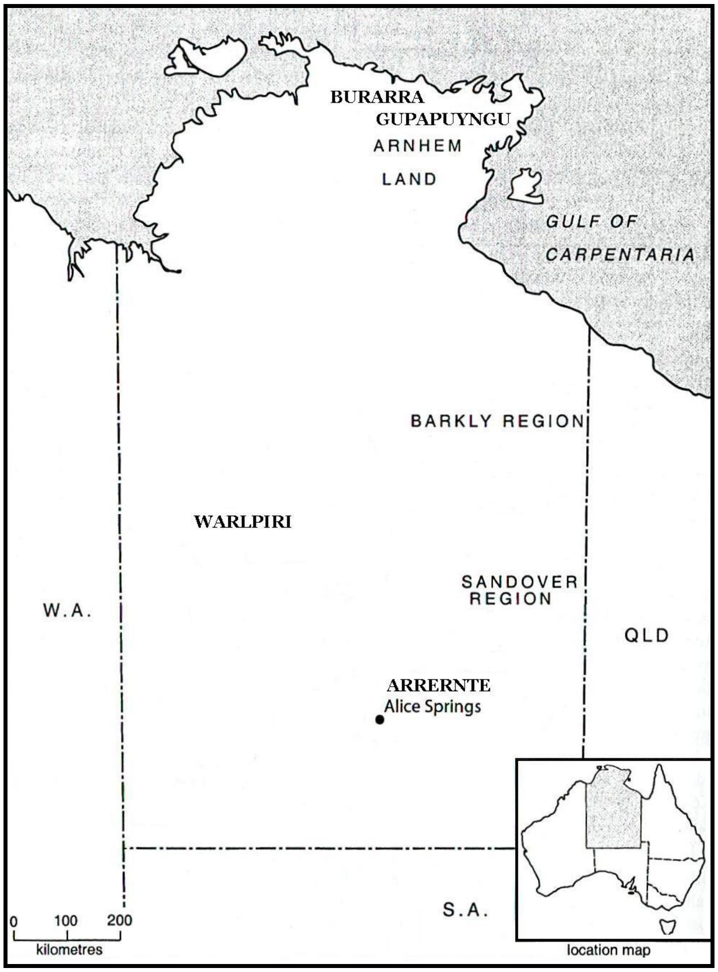

Map. Locations of the Arrernte, Burarra, Gupapuyngu and Warlpiri languages (based on a map prepared by Jenny Green).

1 Introduction

Contextual variability in the acoustics of successive consonants and vowels has been studied for many years (see, e.g., English: Joos, 1948; Lindblom, Agwuele, Sussman, & Eir Cortes, 2007; Swedish, English and Russian: Öhman, 1966; Catalan: Recasens, 1984a,b; 1987). It has been shown that speech sounds are both influenced by the context in which they occur and are produced in an overlapping way; these processes are referred to by the term 'coarticulation' (Menzerath & de Lacerda, 1933). Coarticulation can be characterised articulatorily by patterns of coordination 'between the articulatory gestures of neighbouring segments, which result in the vocal tract responding at any one time to commands for more than one segment.' (Manuel, 1999, p. 182; see also Fowler & Saltzman, 1993, p. 173) These articulatory gestures are 'inherently context-sensitive' (Recasens, 1984a, p. 61). The effects of coarticulation include changes in place and manner features in consonants and changes in quality in vowels.

Acoustically, coarticulation is characterised by deviation from 'an ideal canonical form or articulatory target' (Bladon & Al-Bamerni, 1976, p. 139) and by formant frequency transitions between adjacent segments or segmental targets.[1] Typically, a 'transition' is a movement of the vocal organs from one position to another, and any acoustical effect of such a movement, e.g., an increase in F2 as the constriction location is moved forward. Vowel formant transitions, especially F2 and F3 transitions, are known to contain information concerning place of articulation in nearby consonants and concerning the spectral properties of nearby vowels (Delattre, Liberman, & Cooper, 1955).

Coarticulation can be described in terms of segmental effects, directionality and the major articulators involved: the tongue, jaw, velum and lips. With regard to segmental effects, 'C-to-V coarticulatory effects' are the coarticulatory effects of the consonant on the vowel, also termed 'consonant-dependent' vowel coarticulation, and 'V-to-C coarticulatory effects' are the effects of a vowel on a consonant, also termed 'vowel-dependent' consonant coarticulation. 'V-to-V effects' are the effects of one vowel on another, typically across one or more consonants. Coarticulation can be anticipatory (right-to-left) or carryover (left-to-right) (see §2.1). It is generally believed that anticipatory coarticulation arises from the interaction between articulatory planning and production, whereas carryover coarticulation may arise from the biomechanics of production (that is, the motions of the articulators) and a feedback assisted strategy for accommodating speech segments

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[1] The term 'target' refers to the section of the segment that is least affected by context, thus, a target or rest value for location and degree of constriction (Browman & Goldstein, 1990, pp. 306-207).

to one another (Daniloff & Hammarberg, 1973; Recasens, 1984a,b; Recasens, Pallarès, & Fontdevila, 1997; but *cf.* Krakow, Bell-Berti, & Wang, 1995).

The relative salience of carryover to anticipatory coarticulation or *vice versa* appears to depend on the strength of biomechanical constraints associated with the consonantal gesture and on differences in gestural compatibility between adjacent consonants in a consonant cluster (Recasens, 1999; see §2.1). It also depends on the manner and other inherent properties of the particular segments involved (see, e.g., Byrd, 1996). Typically, the stronger the biomechanical constraints on a gesture, the greater that gesture's resistance to coarticulation. Coarticulation resistance is therefore '[t]he ability of a given gesture to resist potentially disruptive encroachments by nearby gestures' (Fowler & Saltzman, 1993, p. 179).

Coarticulation interacts with cognitive processes, biomechanical constraints (§2.2), perceptual distinctions (see, e.g., §2.1.2.3 and §2.3), language-specific phonological processes (e.g., §2.1.2), prosodic and timing factors (§2.4), articulatory economy (e.g., §2.1.1) and individual speaker variability. Coarticulation allows certain advantages to the speaker and hearer, such as economy of articulatory gesture, and more rapid perceptual processing, because the articulation of a phoneme 'yet to come' is anticipated, and this anticipation provides information about that phoneme's identity (Ladefoged, 1993, p. 56). Coarticulation is the basis of many well known phonological processes, such as assimilation and vowel harmony. It is an important subject in speech science because of what it means for the relationship between the biomechanics and the acoustics of speech, for linguistic representation, and, relatedly, because of its relevance to the relationship between phonetics (concerned with varying, non-discrete units) and phonology (concerned with invariant, discrete units). It is relevant to the relationship between these disciplines because the magnitude of coarticulation is, in part, restricted to ensure that meaningful perceptual, *i.e.*, phonological contrasts are maintained. When the maintenance of perceptual contrasts is less important, the drive towards economy of articulation may result in greater contextual variability (e.g., because articulatory targets may be 'undershot'; see §2.3).

It is clear that coarticulation is both universal (all languages display coarticulation), and language-specific (coarticulation is realised differently in different languages) (Öhman, 1966; Fowler, 1983; for reviews, see Farnetani, 1999; Farnetani & Recasens, 2010). There is evidence in coarticulation of not only language- but also speaker-specificity (e.g., Kuehn & Moll, 1976; Lubker & Gay, 1982; Nolan, 1983; Perkell & Matthies, 1992; Johnson, Ladefoged, & Lindau, 1993; van den Heuvel, Cranen, & Rietveld, 1996; Magen, 1997; Recasens & Pallarès, 2000; Robert, Wrobel-Dautcourt, Laprie, & Bonneau, 2005; Grosvald, 2010; but *cf.*

McDougall, 2005) and speakers exhibit variation beyond that due merely to anatomical differences (Ladefoged & Broadbent, 1957; Perkell & Matthies, 1992). For example, Mooshammer, Perrier and Fuchs (2008) found that speaker-specificity was also related to the interaction between vowel-specific variability and anatomical differences and speaker-specific perceptual constraints (see also Brunner, Fuchs, & Perrier, 2009). It is clear that speaker-specificity should be taken into account when developing and assessing coarticulation models (Kühnert & Nolan, 1999).

This dissertation is an acoustic phonetic study of spatial coarticulation in four Australian languages: Central/Eastern Arrernte (hereafter simply 'Arrernte'), Burarra, Gupapuyngu and Warlpiri. The primary purpose of this examination is to determine whether and in what manner consonant-vowel coarticulation varies according to such factors as consonant place of articulation in these Australian languages. A secondary purpose is to investigate vowel-to-vowel coarticulation in order to determine whether, as has been found for English, Swedish and Catalan, there is evidence of a gradual and (near) continuous diphthong-like vowel movement dependent on the close vowel, which is modulated or 'coloured' by the intervening consonant. A major focus of this investigation of vowel-to-vowel coarticulation is the effect of the place of articulation of the intervening consonant. A full discussion of the aims of this study follows in §1.3.

The structure of this introductory chapter is as follows. In §1.1, a brief summary of more recent models of coarticulation is given. §1.2 constitutes a summary of the relevant literature concerning the four languages, including inventories. The aims and implications of this dissertation are outlined in §1.3 and §1.4. Finally, the structure of the dissertation as a whole is summarised in §1.5. In the following chapter, Chapter 2, the literature will be reviewed.

1.1 Introduction to models of coarticulation

Several models have been proposed to account for coarticulation. The more comprehensive of these models attempt to 'predict the details of the process bridging the invariant and discrete units of representation to articulation and acoustics' (Farnetani & Recasens, 2010, p. 31). More recent models that address this process include a coproduction or 'temporal overlap' model, which was developed by Bell-Berti and Harris amongst others (e.g., Öhman, 1966; Bell-Berti & Harris, 1979; 1981; 1982; Fowler, 1980; Fowler & Saltzman, 1993), and is strongly associated with Articulatory Phonology and the Task Dynamics model (e.g. Browman & Goldstein, 1990). Other models developed during the last thirty years include the Hybrid model (Bladon & Al-Bamerni, 1982; Perkell & Chiang, 1986; Boyce, Krakow, Bell-Berti, & Gelfer, 1990) which draws from the look-ahead model

(Henke, 1966) and early coproduction or 'time-locked' models (Bell-Berti & Harris, 1979; 1981,; 1982). The hybrid, look ahead and coproduction models were typically compared on their capacity to predict the onset of the anticipation of lip rounding in V1C1(C2)V2 sequences, in which V1 is unrounded, C1 and C2 are unspecified for rounding and V2 is rounded. A more recent model is the Movement Expansion Model (MEM) (Abry & Lallouache, 1995), which claims that the rounding movement is anticipated when there is no phonological constraint on rounding.

Coproduction models[2] draw on the insight that gestures are coproduced (Fowler, 1980) and this coproduction can be specified in terms of the relative phasing of gestures (Browman & Goldstein, 1987; 1990).[3] Coarticulation therefore reflects the interaction between the coordinative constraints for temporally overlapping gestures (Fowler & Saltzman, 1993). In a coproduction account, the underlying linguistic features are defined context-independently, and context-sensitivity arises primarily from temporal and gestural overlap (1993, p. 173). See Figure 1.

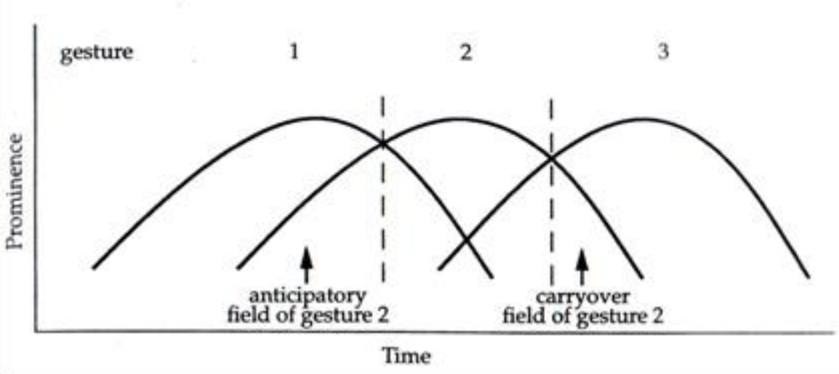

Figure 1. A representation of the overlapping or coproduction of three articulatory gestures (from Fowler & Saltzman, 1993). x-axis: time; y-axis: gestural prominence.

Coproduction models will be discussed in detail in §2.1.1. Within the framework of a coproduction model, the Degree of Articulatory Constraints (DAC) model of coarticulation resistance was developed primarily from Catalan articulatory and acoustic data by Recasens in a number of recent studies (e.g., Recasens, 1997; 2002; Recasens *et al*., 1997; Recasens & Espinosa, 2009a). The DAC model is

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[2] In this dissertation, the term 'coproduction model' or models refers specifically to a model of coproduction in the most general sense that has its roots in the early work of Fowler (e.g., 1980) and Browman and Goldstein (e.g., 1987; 1990).

[3] Here, a 'gesture' is a non-incidental articulatory movement pattern. Gestures can be specified in terms of 'speech tasks' such as the formation of a closure and the release for a consonant and secondly in terms of gestural dynamics that 'serve to characterise the motions' (Browman & Goldstein, 1990, p. 300).

based on an understanding of the relationship between coarticulation resistance and dorso-palatal constraint (see further, §2.2). Linguistic, *i.e.*, phonological, constraints are also factored in to any coproduction analysis of coarticulation; recall that coarticulatory patterns may be limited or modulated by such constraints.

The issues introduced in this brief overview will be discussed in greater detail in Chapter 2 with specific reference to the context of the present study. In the next section, details will be provided of the languages examined in this dissertation, commencing with general overview of relevant features of the phonological and phonetic systems of Australian languages.

1.2 Languages examined

The four Australian languages examined in this study are Arrernte, Burarra, Gupapuyngu and Warlpiri. Justification for the choice of these four languages is provided in §1.3. Australian languages are remarkably different from the majority of the world's languages. They are relatively homogeneous in their consonant inventories (see Capell, 1967, pp. 85-6; Dixon, 1980, p. 125), that is, they possess long and flat consonant inventories[4] compared to Indo-European languages such as English (e.g., Butcher, 1996; 2006). They typically possess two or more coronal classes - dental, alveolar, (typically sub-laminal) retroflex or postalveolar, (alveolo)palatal - which can be grouped into apical and laminal articulations, and two non-coronal, or 'peripheral' classes: bilabial and dorso-velar (Butcher, 2006).

According to Butcher (1995), approximately half of Australian languages have three distinct coronal categories and a further third have four categories (see also Evans, 1995, pp. 724-726). The maximal place of articulation inventory comprises six contrasts. Typically, only in *word-medial position* are all place categories in contrast; word-initially, the apical (alveolar and retroflex) opposition may be neutralised (the contrast is lost) and word-finally, the laminal opposition may be neutralised (Evans, 1995; Butcher, 1995). Consonants appear to be strengthened and lengthened in word-medial position (Butcher, 1990; 2006; 2010; see §2.4.3). While there is no standard voicing contrast, the Gunwinyguan, Burarran, Garaman and Dhuwal/Dhuwala language groups, amongst others, which include Burarra and Gupapuyngu, have a fortis/lenis distinction in their plosives (essentially, a length or articulatory effort distinction; see Butcher, 2003; 2004; see further, §1.2.2.1 and §1.2.3.1). Importantly, both in heterorganic consonant clusters such as /nk/ and in the context of nasal segments, perceptual contrasts tend to be maintained.

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[4] By 'long and flat' is meant that the languages involve a relatively large number of place of articulation categories and relatively few manner distinctions within the obstruent series.

In Australian languages, the number of vowel categories is small (e.g., there are as few as two vowel phonemes in some varieties of Arrernte) or very large, comprising up to 17 (phonetic) vowels (in Anguthimri; Evans, 1995). More than 50% of Australian languages possess phonemic inventories consisting of only three vowel qualities, /i a u/, in a triangular system (e.g., Gupapuyngu and Warlpiri; Butcher, 1994).

With regard to Australian language phonotactics and prosody, the typical word is disyllabic (or at least bi-moraic), although monosyllabic surface forms are possible in languages such as Arrernte and Gupapuyngu. The typical stem is also disyllabic (e.g., Evans, 1995, p. 742). The majority of Australian languages, including Burarra and Gupapuyngu, show predominantly word-initial stress (Goedemans, 2010). Further information on the standard inventories and phonotactics of Australian languages is provided in Evans (1995), Hamilton (1996) and Dixon (2002).

1.2.1 Arrernte

Arrernte is an Arandic language of the Upper Arrernte (Upper South Arandic) subgroup spoken near Alice Springs in the Northern Territory (Hale, 1962; Henderson & Dobson, 1994; Breen & Dobson, 2005). As shown in Figure 2, the Upper (South) Arandic group comprises varieties and dialects such as Eastern and Central Arrernte, Alyawarr, Anmatyerr and Antekerrepenh. The Arrernte speakers in this corpus are speakers of the Eastern and Central dialects (sometimes termed Mparntwe). The Arandic family is a member of the Pama-Nyungan family (Walsh & Wurm, 1981; *cf.* Dixon, 1980). Pama-Nyungan languages cover approximately 90% of the continent of Australia. There is a good deal of conflicting and complicated data relating to the Arrernte language, especially with regard to the size of the vowel inventory and the underlying syllable structure (see §1.2.1.2 and §1.2.1.5). Arrernte is one of the more studied of the four languages considered in this dissertation and hence these issues can be discussed in some depth.

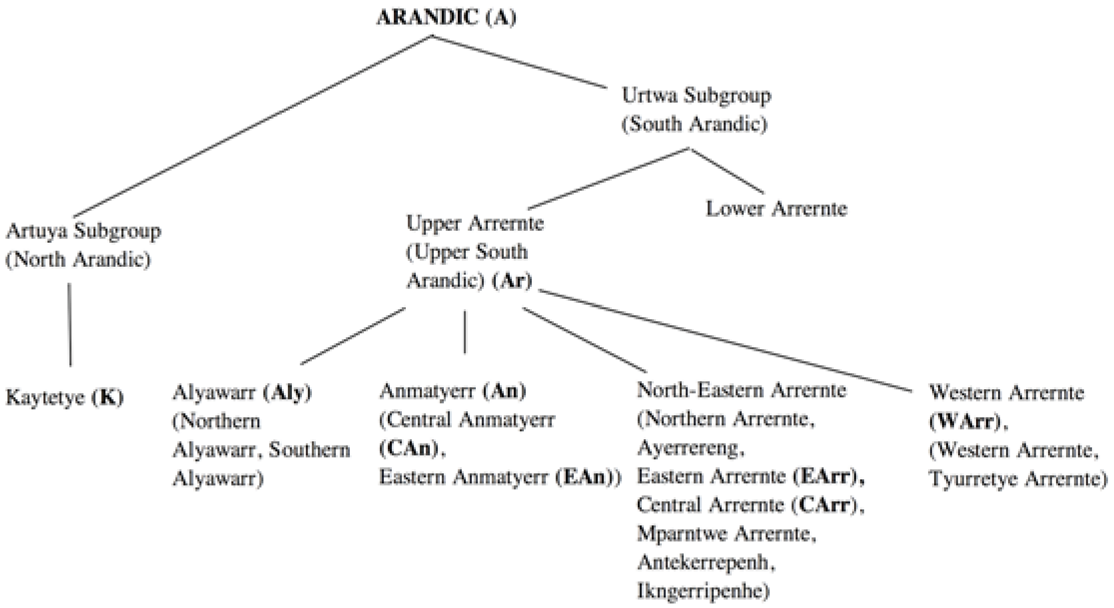

Figure 2. Arandic typology (Green, 2009, p. 8; used with permission).

1.2.1.1 Consonants

The Arrernte consonant inventory is shown in Table 1 (after Breen & Dobson, 2005). A practical orthography is given in brackets to the right of the phonemic representation. As can be seen in the table, there are six places of articulation for plosives. In the oral plosive, nasal, lateral, and pre-stopped nasal[5] series of coronals, Arrernte makes four apical/laminal contrasts, two of which are laminal (where the tongue-blade is the active articulator), and two apical (where the tongue-tip is the active articulator) phonemes. These are referred to as (lamino-)dental (or lamino-interdental), apico-alveolar, (sub)apico-postalveolar (or retroflex or sublaminal pre-palatal; Butcher, forthcoming a), and lamino-palatal (or lamino-alveolopalatal or laminal postalveolar), hereafter ‘palatal’ (Breen, 2001, p. 47; Butcher, 1995; 2010). There are also bilabial and velar (*i.e.*, peripheral) series. Phonemic labialisation of all consonants except /w/ and the velar fricative or approximant occurs, but this has been associated with a consonant position in a word rather than strictly with the consonant (Breen, 1991; Breen & Dobson, 2005). Unlike Burarra and Gupapuyngu, Arrernte has a lateral phoneme for each coronal articulation. It has no voicing distinction, and so there is potentially free variation between voiceless and voiced plosives; in reality, plosives tend to be voiceless unaspirated ‘but are voiced following a homorganic nasal in a cluster, or occasionally elsewhere for no clear reason’ (Breen & Dobson, 2005). Consonant neutralisation in Arrernte is discussed in §1.2.1.4.

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[5] The pre-stopped nasals have also been described as nasally-released stops (Anderson, 2000, p. 35).

Consonant clusters in Arrernte may be homorganic or heterorganic, typically comprising a nasal, lateral or rhotic as the first consonant and a stop or nasal plosive as the second, e.g., <ntuye> /ntuj/ 'wife's father', <awenke> /ɐwənk/ 'young woman', <inngerre> /inŋər/ 'face' (Butcher, forthcoming b; with the final, non-contrastive vowel unrepresented). Additionally, tri-consonantal clusters are possible, e.g., <akurrknge> /ɐkur^{k}ŋ/ 'brain' (Butcher, forthcoming b).

In an electropalatographic (EPG) study, it was found that the apico-postalveolar stop typically involves central (approximately mid way between the front of the hard palate and the velum) and lateral (side) contact (e.g., Tabain, 2009a) and there is a forward movement of the tongue during production (e.g., Henderson, 1998). According to Butcher (Ladefoged & Maddieson, 1996, pp. 28-29), the retroflex consonant of Eastern Arrernte is a sub-apical articulation in the postalveolar region but some tokens recorded by Butcher involve an articulation that is even further back than a true postalveolar. Apico-postalveolar consonants may be pre-palatalised (e.g., Henderson, 1998; see §1.2.1.3 for a discussion). The (lamino-)palatal series has also been described as alveolopalatal or palatalised alveolar (see, e.g., Breen & Pensalfini, 1999; (Tabain & Breen, 2011; Tabain, Fletcher, & Butcher, 2011). The palatal stop is often affricated in citation form speech and involves extensive lingual contact at the sides and front of the palate (e.g., Butcher, 1995; 2010; Tabain *et al.*, 2011). Older female speakers appear to produce palatal articulations with more extensive and more fronted linguo-palatal contact than younger speakers (Tabain *et al.*, 2011). Generally, there is more extensive contact for the Arrernte palatal consonants than in, for example, Yanyuwa (Butcher, 1995).

The velar plosive in Arrernte is a very backed articulation in the context of the low central vowel (Butcher & Tabain, 2004). In Arrernte, there is a velar approximant or glide, represented orthographically as <h>, which has also been analysed as a fricative (in Mpwarntwe: Wilkins, 1989; Evans, 1995), and has a limited distribution (e.g., Breen & Dobson, 2005).[6] In the present corpus, it appears only intervocalically after word-initial /a/, e.g., in <aherre> /ɐɰər/ 'kangaroo' and <ahekngerre> /ɐɰə^{k}ŋər/ 'dangerous' (with the final vowel unrepresented). According to Koch (1997), the original context in which the velar became an approximant was when following a long stressed vowel. More recent studies of consonant articulation in Arrernte include Tabain (2009a,b) and Tabain et al. (2011).

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[6] In fact, when fricatives appear in Australian languages, they tend to be peripheral consonants (Evans, 1995, p. 730).

Table 1. Arrernte consonants (adapted from Breen & Dobson, 2005, but excluding the labialised series and with the velar approximant/fricative in the glide series after Breen, 2001). 'P-S' refers to pre-stopped consonant. Here and elsewhere, where /w/ is a labio-velar. Items in brackets are orthographic representations.

		Lamino-	Apico-		Lamino-	Dorso-
	Bilabial	Dental	Alveolar	Retroflex	Palatal	Velar
Plosive	p	t̪ (th)	t	ʈ (rt)	c (ty)	k
Nasal	m	n̪ (nh)	n	ɳ (rn)	ɲ (ny)	ŋ (ng)
P-S Nasal	^{p}m (pm)	^{t}n̪ (thn)	^{t}n (tn)	^{ʈ}ɳ (rtn)	^{c}ɲ (tny)	^{k}ŋ (kng)
Lateral		l̪ (lh)	l	ɭ (rl)	ʎ (ly)	
Rhotic			r (rr)	ɹ (r)		
Glide	w				j (y)	ɰ (h)

1.2.1.2 Vowels

As has been mentioned, the analysis of the Arrernte vowel system is controversial, with disagreement primarily concerning the number of phonemic vowels. In this study, the number of Arrernte vowels is taken provisionally to comprise two non-marginal phonemes, /ɐ/ and /ə/,[7] and two marginal phonemes, /i/ and /u/ (shown in Table 2; after, e.g., Breen, 2001; Tabain, Breen, & Butcher, 2004, p. 176; Breen & Dobson, 2005; Tabain, 2009a,b; Tabain *et al.*, 2011), e.g., <iwenhe> /iwən̪/ 'what?' and <apurte> /(ɐ)puʈ/ 'clump' (based on Butcher, forthcoming b). /i/ is typically realised as a front close-mid vowel. /ɐ/ is described in the literature as a low central vowel (e.g., Henderson, 1998).

Arrernte vowels are highly restricted in terms of their position within the word; /ə/ (and /u/, on the four vowel analysis) cannot occur word-initially (except

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[7] Where the term 'marginal' refers to having a restricted distribution, low frequency and a low functional load. Schwa is the most common non-peripheral vowel across languages in primary systems, *i.e.*, systems without secondary articulations (Schwartz, Boe, Vallée & Abry, 1997a). Schwa appears to be relatively free to vary within the vowel space - van Bergem (1994) describes it as target-less - and it is in this way somewhat independent of the overall structure of the vowel system (Schwartz *et al.*, 1997a, p. 248; Schwartz, Boe, Vallée & Abry, 1997b, p. 260).

underlyingly for a word commencing with a consonant), and /i/ cannot occur word-finally (Anderson V. B., 2000). Tabain and Breen (2011) note that

> '[w]e are aware of only five minimal pairs involving /i/ and /ə/ in word-medial position (e.g., anteme /antəm/—'then/now' vs. antime /antim/—'again'), and only one involving /i/ and /ɐ/ (antyipere /ɐɲcipəɹ/—'smaller types of bats' vs. antyapere /ɐɲcɐpəɹ/—'the whole thing')—however, there are many more contrasts between /ɐ/ and /i/ in initial position'.
>
> (p. 70; italics in original)

Some near-minimal pairs containing the four vowels are as follows (after Butcher, forthcoming b, with the non-contrastive final vowel unrepresented):

a) /ə ɐ/: <(a)peke> /(ɐ)pək/ 'maybe', <(a)kaperte> /(ɐ)kɐpəʈ/ 'head' (between peripherals);

b) /ə u/: <antere> /ɐntəɹ/ 'fat', <arrutne> /ɐru^{t}n/ 'chin' (between an alveolar and a rhotic consonant);

c) /ə i/: <ntheme> /n̪t̪əm/ 'gives', <thipe> /t̪ip/ 'bird' (between a dental and a labial consonant).

Table 2. Arrernte vowels (where the two close vowels are marginal, after Breen and Dobson, 2005). Items in brackets are orthographic representations.

	Front	Central	Back
Close	i		u
Mid		ə (e)	
Open		ɐ (a)	

Two widely adopted vowel inventories are a two vowel analysis (/ɐ ə/; for some Arandic varieties but not, more recently, for Central Arrernte, according to Breen, 2001, p. 51) and a three or four vowel analysis, comprising /ɐ ə i/ with a marginal /u/ (see Breen, 2001, p. 53) or /ɐ ə u/ (Breen, 2001, p. 51). Recently, Breen argued that a two-vowel analysis is more plausible for other Arandic languages, such as Kaytetye and Western Anmatyerr (Tabain & Breen, 2011, p. 69). However, Arandic languages and varieties that have been analysed as possessing two-vowel systems include Eastern Arrernte (Ladefoged & Maddieson, 1996), Antekerrepenh (Breen, 1977, *cf.* Breen, 2001, p. 49), Western Anmatyerr (Breen, 2001, p. 62), Western Anmatjirra (Dixon, 2002) and Kaytetye (Hale, 1980,

p. 131; Koch, e.g., 1984; see Dixon, 2002, p. 550; *cf.* Breen, 2001, p. 61). Other Arandic languages and varieties appear to possess /i/ and /u/ but with a low functional load (Dixon, 2002, p. 634). It is clear that the two high vowels are phonetic vowels in Arrernte, regardless of their phonological status.

In recent studies by Tabain and colleagues (Butcher & Tabain, 2004; Tabain *et al.*, 2004; Tabain & Breen, 2011), at least three vowels are posited. On Butcher and Tabain's (2004) three-vowel analysis for Arrernte, the vowels are /ə ɐ ʷə/, where the third vowel is back, and realised as [ʊ]. Roundedness and frontedness features are associated with adjoining consonants and/or are situated on an autosegmental tier. These features associate to consonants on the skeletal tier but can spread to vowels unless a segment blocking such spreading intervenes (e.g., Evans, 1995, pp. 736-737).[8] On a further three vowel analysis (Breen, 1991; Anderson V. B., 2000, Tabain & Breen, 2011), /i/ is posited, but the rounding of the close-back vowel is associated with the syllable, rather than with the vowel. According to one source, unstressed vowels have been neutralised to /ə/, and the roundedness quality of an 'u' has been transferred to the preceding consonant, leaving the vowel as /ə/, the neutral vowel (Koch, 1997). Breen & Pensalfini (1999) give an example of the spreading of rounding rightwards onto the mid central vowel: /əkʷətəɹ/ [kʊtʊɹə] 'nulla-nulla (a weapon)' (based on their transcription, p. 23). Further examples are provided by Henderson (1998).

In the analysis adopted by Evans (1995) and Breen and Dobson (2005), there are two non-marginal (central) and two marginal (front and back) phonemic vowels (*cf.* Butcher & Tabain, 2004; Harrington, 2005): /i ə ɐ u/. This analysis is not without controversy. Breen (2001, p. 51) suggests that there are reasons related to phonemic distribution for preferring an analysis including /u/. However, in more recent work, he considers rounding to be a property of the consonant (Tabain & Breen, 2011). Henderson (1998) suggests that /u/ is marginal in the speech of younger speakers, and rounding is a property of the consonant for older speakers.

With regard to the status of the word-final vowel in Arrernte, Kempe (1891) argued that 'all words terminate in *a*, with the exception of the vocative of substantives and the imperative mood of verbs which terminate in *ai*' (p. 2). However, as Breen and Green point out (1995, p. 91; see also Evans, 1995; Tabain, 2009a; Tabain & Butcher, 2011), this vowel is not always pronounced;

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[8] Diachronically, there has been a rightwards migration of lip-rounding and also palatalisation (see §1.2.1.3) in Arrernte (Butcher, 1996).

> ‘it is usually heard in the citation form of short words, but less often for longer words or when the final consonant is *y* or *w* (in certain dialects). It is not normally pronounced in connected speech if the following word begins with a vowel. It is frequently omitted utterance finally.’
>
> (Breen & Green, 1995, p. 91)

Breen (2005) states that his choice of <e> rather than <a> word-finally for (Central, Eastern, Southern and Western) Arrernte orthography during the 1970s was based on the ‘mistaken’ idea that it would be better, if a final vowel was wanted, ‘because then it would not have to be changed when a suffix is added ... [However,] suffixes in this language group actually begin with a vowel’ (p. 97). This word-final vowel varies in quality between [ə], [ɐ] and [a] (Central Arrernte: Breen & Dobson, 2005). It is sometimes included in the orthographic representation of the word and sometimes in the phonological representation (Harvey, 2011). It is transcribed in the literature variously as <e> [ə ɐ], e.g., <atweme> /ɐt^{w}əm/ [ɐt^{w}əmə] ‘hits’ and <unte> /unˈd/ [ndwɐ] or [nd^{w}ɐ] ‘you’, <kwatye> /k^{w}ɐc/ [k^{w}ɐɟə] ‘water’ (examples from Breen, 2001; Butcher, 2006; Tabain & Breen, 2011; see also Tabain *et al.*, 2004), as <e> /ə/ (e.g., Butcher, 1995; Evans, 1995, p. 744; Breen & Dobson, 2005) or as <a> /ɐ/ (e.g., Davis, 1988, presumably after Strehlow, 1942, or Kempe, 1891), e.g., <kama> /kɐm(ɐ)/ ‘to cut’ (based on Davis, 1988). (See further, Breen & Green, 1995.) This non-contrastive final vowel is here transcribed provisionally as /a/ based on the phonetic analysis by, e.g., Butcher (1995) and Tabain *et al.* (2004).[9] The status of the word-initial vowel is discussed in §1.2.1.4.

1.2.1.3 Consonant-vowel effects

With regard to consonant-vowel coarticulation in Arrernte, a study by Ladefoged and Maddieson (1996) did not find evidence of systematic carryover consonant-to-vowel coarticulation in Eastern Arrernte at the midpoint of /ə/ in word-medial CVC syllables (pp. 286-287), although there was a high magnitude of variability in the vowel in both F1 and F2. Tabain and Breen (2011) suggest that this may be due to a predominance of anticipatory C-to-V coarticulation given Breen and Pensalfini’s (1999) claim that the syllable in Arrernte is of the VC type (implying that there

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[9] This transcription is also based on the analyses presented in Chapter 5 (in which the word-final vowel appears to be most frequently realised as [ɐ] and is more similar in height to /ɐ/ than /ə/ in non-word-final contexts). However, this is in the context of citation form words only. It is not the intention of the author to make any claims concerning the phonological status of this vowel or concerning its realisation in continuous speech.

should be minimal vowel-dependent VC coarticulation; Tabain & Breen, 2011, p. 71; the issue of phonotactics will be explored in §1.2.1.4).

Breen (2001) states that /ɐ/ 'is affected very little in quality by surrounding consonants', with the exception of the pre-palatalised apical and the palatal approximant (pp. 52 - 53). This pre-palatalised apical has been considered an 'allomorph' (and allophone) of the retroflex series (Breen & Pensalfini, 1999, p. 9*f.*). According to Evans (1995), the pre-palatalisation of apicals is found in the Arandic languages Kaytetye, Antekerepenh and Alyawarra, but it is also documented by, for example, Breen (2001) for Central and Eastern Arrernte and by Ladefoged and Maddieson (1996) for Eastern Arrernte. Butcher (*pers. comm.*) attributes this pre-palatalisation to 'the proximity of F2 and F3 for both the retroflex and palatal consonants, the spectral prominence being lower in the case of retroflexes and higher in the case of palatals' (Tabain & Breen, 2011, p. 70). For Evans (1995), pre-palatalisation represents on a two vowel analysis 'a transfer of frontness from vowel to consonant phonemes' (p. 728; see Henderson, 1998; Tabain & Rickard, 2007; Breen, 2007; see also Recasens, 1999; Koch, 1997). In Breen's (1977) analysis of Antekerepenh:

> 'while initial [i:] and [ɛj] are quite common before /t/, /n/ /tn/ and /l/, they are … virtually non-existent before any other consonant … This evidence strongly supports Hale's [*pers. comm.*] belief that "the palatalized onglides are clearly features of the consonants".'
>
> (p. 382)

Koch (1997) argues that Arandic apicals became pre-palatalised when preceded by a stressed vowel and followed by /i/ (where word-initial consonants have been elided), but Harvey (2011) argues that there is evidence for pre-palatals 'deriving from retroflexes, regardless of the nature of the following vowel.' (p. 94) According to Breen, in Eastern and Central Arrernte,

> 'pre[-]palatalisation may be heard after initial /a/ [*i.e.*, /ɐ/] as in artwe "man", after /a/ when a heterorganic cluster with first member retroflex follows, as in atnarnpeme "gets down", and after initial underlying schwa when a heterorganic cluster with postalveolar lateral as first member follows, as in rlke "wind"; it is obligatory after /i/ as in arrirlpe "sharp"'.
>
> (2007)

An example of pre-palatalisation associated with phonemic retroflexes given by Tabain and Breen (2011) is that of <artepe> /ɐʈəp/ 'back', pronounced [æjtəp] (p. 70), in which the consonant is heard as an alveolar when pre-palatalised (see also Breen, 2001, p. 52). Henderson (1998) and Breen (2001) suggest that the pre-palatalised stop does not constitute a third apical place of articulation distinct from the retroflex and alveolar stops (see also Harvey, 2011, p. 95*f.*);[10] Breen (2001) states that '[a]uditorily, at least in Arrernte, [the pre-palatals] seem to range between the two other apicals in point of constriction' (p. 60). Butcher (1990) describes 'so-called pre-palatalised post-alveolars' as *not always* having a sublaminal articulation (p. 422).

Work that remains to be done in Arrernte with regard to consonant-vowel coarticulation includes an exploration of CV and VC coarticulation patterns in other contexts and involving a range of consonant places of articulation. Additionally, further work is necessary to provide phonetic evidence to support the claim of an underlying VC syllable (§1.2.1.5).

1.2.1.4 Phonotactics

Arrernte words are minimally disyllabic (bisyllabic), although some surface forms are normally monosyllabic, e.g., <the> /t̪ə/ or /t̪(ɐ)/ 'I', <me> /mə/ or /m(ɐ)/ 'here it is' (Butcher, forthcoming b). These monosyllabic surface forms, and all those words beginning with a consonant, are analysed as being /ə/- or /ɐ/-initial underlying (Henderson, 1998), also e.g., <mpetyane> /(ə)mpəcɐn(ɐ)/ [əmpəcɐn] '(skin name)' (example after Butcher, forthcoming b; Tabain *et al.*, 2011). Notably, about half of the words in Arrernte begin with /ɐ/ (see Henderson & Dobson, 1994). Moreover, Breen and Pensalfini (1999) argue that the twenty-five percent of Arrernte words that are pronounced in isolation with an initial consonant have an underlying initial schwa. As has been mentioned, in word-final position, only a central vowel can be realised.

In Arrernte (and in the other languages considered here), only in vowel-consonant-vowel (VCV) context, or word-medially, are all consonants in contrast (see Capell, 1967; Dixon, 1980; Butcher, 1995; 1996; 2006). In absolute word-initial position, there is neutralisation of the apical contrast (Anderson V. B., 2005; Butcher & Harrington, 2003), e.g., <artepe> /ɐʈəp(ɐ)/ 'back' but <rterte> /Aəʈ(ɐ)/ 'wet ground' (where 'A' represents an apical stop; after Butcher, forthcoming b). There is speaker variability in the choice of alveolar or retroflex in this absolute word-initial position (*cf.* Anderson V. B., 2000). Tabain (2009a) demonstrated in an EPG study that the apicals are maximally contrastive when following the vowel in a

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[10] Harvey (2011) argues based on Henderson (1998) that the status of the pre-palatal sequence in Eastern and Central Arrernte is problematic. He argues for a separate lexical listing of pre-palatal clusters ('yC') and retroflexes after /ɐ/ (see further, Harvey, 2011, pp. 102-103).

metrically stressed syllable, but are highly variable elsewhere. The various rules governing apical realisation include the following:

a) the first apical in a word causes subsequent apicals to become retroflexed when a schwa intervenes, e.g., <atnerte> /ɐtnəʈ(ɐ)/ 'stomach' and <atyete> /ɐcət(ɐ)/ 'soft' but not *<atnete> (Butcher, forthcoming b), and suffix-initially, an apical is often retroflexed when preceded by an apical but is otherwise alveolar;
b) a retroflex later in the word can cause the constriction of preceding alveolar to retract or become retroflexed, e.g., <aternnge> /ɐtəɳŋə/ may be realised as [ɐʈəɳŋɐ] 'dirty' (Tabain & Rickard, 2007; Tabain, 2009a);
c) a dental earlier in the word can turn a later retroflex into an alveolar; and
d) a word-initial palatal may turn a later retroflex into an alveolar, e.g., <uyarne> /ujɐɳ(ɐ)/ [ʊjɐn] (example derived from Butcher, forthcoming b).

Word-initially, Arrernte also provides some instances of the weakening and deletion or elision (word-initial 'dropping') of certain types of consonants: peripherals, glides and nasals (Butcher, 2006). The lenition and deletion of word-initial consonants is common in Australian languages (e.g., Hale, 1976; see further, §2.1 and §2.4) An example of (diachronic) word-initial velar deletion is seen in Arrernte <atne> /ɐtnə/ 'guts' (Wilkins, 1989), which derives from the general Pama-Nyungan word, */kuna/ (p. 108). Hale (1964) attributes such word-initial consonant deletion to stress shift and lenition processes.

1.2.1.5 Prosody

In Arandic languages, stress is placed on the first syllable in a word commencing with a consonant and the second syllable otherwise, e.g., <kake> /'kɐk(ɐ)/ [ə'kɐkɐ] 'elder brother' or ['kɐkɐ] but <iperte> /i'pəʈ(ɐ)/ 'hole' (based on Butcher, forthcoming b). Strehlow (1942) claimed that primary stress falls on the first syllable if it has an onset and otherwise, on the second syllable. Secondary stress falls on alternate syllables after the primary stress.

Tabain (2009a) found that the most stable apicals occur in the phonologically stressed syllable of the word and apical production is more 'ambiguous' in weak (initial) syllables (p. 495). Further, Tabain and Breen (2011) found that stressed /ɐ/ can be higher in the vowel space than unstressed /ɐ/, but this effect was not present for the mid-central vowel, /ə/.

With regard to the status of the syllable, after Sommer's (1969, 1970) papers on the VC syllable in Kunjen, an Australian language of Cape York (Peninsula, in Queensland), Breen (1991) and Breen and Pensalfini (1999) argued on the basis of data from the Arandic languages for underlying VC(C) syllables in Arrernte. Evidence for the VC syllable in Arrernte derives primarily from prosody, reduplication patterns, and the verbal game 'Rabbit Talk'. On this view, in citation forms, primary (or 'non-distinctive'; Tabain & Breen, 2011) stress tends to fall on the second underlying syllable - on a VC(C) analysis - e.g., <iperte> /ip'əʈ(ɐ)/ 'hole', (Breen & Pensalfini, 1999; Anderson V. B., 2000, p. 41; Tabain & Breen, 2011). In other words, stress is assigned to the first nucleus that is preceded by a consonant but Tabain and Breen (2011) state that 'it is not clear whether this is truly lexical stress, or whether it is a post-lexical prominence marking.' (p. 69)

According to the 'initial-vowel hypothesis' (Breen & Pensalfini, 1999), this first consonant is assigned to a VC syllable, with a realised vowel preceding it, or with an underlying initial schwa. The 'initial-vowel hypothesis' is also applied to verbal plural and reciprocal morphology; there are different forms for monosyllabic and disyllabic stems, and the surface consonant-initial + nucleus words receive the disyllabic form. This suggests an underlying word-initial schwa preceding surface consonant-initial words. Evans (1995) argues that 'at the deepest level of representation the arguments for VC being the canonical syllable in Arrernte must now be considered very strong.' (p. 747; see further, Evans, 1995; Butcher, 2006; Blevins, 2007) Breen and Pensalfini (1999) appear to argue that Arrernte is more likely than (some) other Australian languages to have an underlying VC syllable because it has a series of pre-stopped nasal consonants;

> 'It becomes clear that these two facts are not unrelated when one considers that the acoustically significant edge of a prestopped nasal, which allows it to be distinguished from a simple nasal, is the left edge (or closure). Since Arrernte lacks phonemic fricatives and affricates, the right edge of consonants may not be quite as important in this language as in others, whereas the left edge is considerably more important.'
>
> (p. 20).

However, as Butcher (1999) notes, 'the pre-stopping of nasal consonants is a widespread phenomenon at the synchronic phonetic level in many Australian languages, and is certainly not restricted to Central Australia.' (p. 480) Pre-stopping in Gupapuyngu is discussed in §1.2.3.1. The pre-stopping of nasals and laterals has been described as an areal feature of south eastern Central Australia (Evans, 1995, p. 734), but phonetically pre-stopped laterals have been found recently in Warlpiri (Loakes, Butcher, Fletcher, & Stoakes, 2008).

1.2.2 Burarra

The second language to be examined in this dissertation, Burarra (also known as Anbarra or Barera), is a language of the Burarran sub-group of the Maningrida family spoken in Central Arnhem Land, which is non-Pama-Nyungan (Green, 2003). It has been classified as a member of the Burarran family (Walsh & Wurm, 1981). Burarra and Gupapuyngu are spoken near each other and many individuals speak both languages. Burarra has twenty-one phonemic consonants and five vowels (Glasgow, 1981, p. 65).

Table 3. Burarra consonants (after Glasgow, 1981). Items in brackets are orthographic representations.

		Apico-		Lamino-	Dorso-
	Bilabial	Alveolar	Retroflex	Palatal	Velar
Plosive fortis	p	t	ʈ (rt)	c (ch)	k
Plosive lenis	b	d	ɖ (rd)	ɟ (j)	g
Nasal	m	n	ɳ (rn)	ɲ (ny)	ŋ (ng)
Lateral		l	ɭ (rl)		
Rhotic		r (rr)	ɽ/ɹ (r)		
Glide	w			j (y)	

1.2.2.1 Consonants

The Burarra consonant inventory is given in Table 3. As can be seen, there is a fortis/lenis distinction in the plosives, e.g., /p t k/ *vs.* /b d g/ (Capell, 1942); the plosive series is distinguished by means of intra-oral peak pressure and stricture duration rather than voicing (Butcher, 2004), that is, fortis consonants typically involve greater intra-oral pressure and are longer in duration. Lenis /b/ and /g/ are frequently lenited intervocalically and can be pronounced as a fricative or, more frequently, an approximant (Butcher & Tabain, 2004).

Burarra allows homorganic clusters, e.g., nasal + stop in <mingka> /miŋka/ 'sandfly' (Butcher, forthcoming b), and heterorganic clusters, e.g., nasal + stop in <gomkaka> /gomkaka/ 'middle-aged person' (forthcoming b). It also allows approximant + peripheral (non-coronal) /jk/ clusters, e.g., <waykin> /wajkin/ 'high, on top of' (forthcoming b). Clusters may include up to three consonants, e.g., <balngga> /balŋga/ 'afternoon' (forthcoming b).

1.2.2.2 Vowels

Burarra possesses a five vowel system, comprising /i/, /e/ or /ɛ/, /a/ or /ɐ/, /o/ (or /ɔ/) and /u/ as shown in Table 4, e.g., <delipa> /dɛlipɐ/ 'baby, child' and <gu-lotok> /gulotok/ 'little brown dove' (Butcher, forthcoming b). Trefry (1983) identified very extensive vowel overlap in Burarra involving all vowels, and showed every vowel affecting every other vowel. The anchor of the vowel space appeared to be the low central vowel (Trefry, 1983, p. 26).

/i/ can be realised as an close-mid front vowel, [e], or [ɪ], /a/ is generally realised as a low central vowel or schwa, /ɛ/ can be realised as [ɛ] or [e], /o/ is typically realised as a rounded open-mid vowel [ɔ], or as [o], and /u/ can be realised as schwa, [ʊ], or a lowered open-mid back rounded vowel, a lowered [ö] [*sic*] (Butcher, 2006). Additionally, unstressed vowels may be reduced to schwa or elided completely in certain environments, e.g., between a stop and a liquid (such as /l/ or /r/), or when preceded by a nasal (Butcher, 1996; 2006). For example, /a/ can be elided in <kunmenama kupara> /kun'menama ku'para/ [kən'mɛnmə gə'bɐɾə] (Butcher, 2006).

Table 4. Burarra vowels (after Glasgow, 1981). Items in brackets are orthographic representations.

	Front	Central	Back
Close	i		u
Open-Mid	ɛ (e)		o
Open		ɐ (a)	

1.2.2.3 Consonant-vowel effects

Trefry (1983) provides evidence that neighbouring consonants in Burarra 'have an effect on the movement of the vowel target, and if similar consonants occur each [*sic*] side of the vowel the effect tends to be more pronounced' (p. 45). Trefry notes that 'the velars have a tendency to reduce the frequencies of both formants [F1 and F2], and bilabials reduce the frequency of formant two' in the vowel target (1983, p. 45) Alveolars are seen to affect vowels least, and Trefry explains this with reference to the small amount of 'horizontal shift of the tongue as it moves between alveolar consonants and various vowels' (p. 45). He found no evidence of greater C-to-V carryover than anticipatory variation, or vice versa (p. 50).

Work remaining to be done on coarticulation in Burarra includes a more systematic analysis of CV and VC coarticulation incorporating a greater number of place of contrasts and considering the entire trajectory of the vowel rather than merely the vowel 'target' and at least in part, controlling for word length (as was originally intended by Trefry, 1983; see p. 21).

1.2.2.4 Phonotactics and Prosody

Burarra words are typically disyllabic, e.g., <bala> /bɐlɐ/ 'house' (Butcher, forthcoming b). However, tri-syllabic words, such as <diwija> /diwiɟɐ/ 'be open', are also common (example from Butcher, forthcoming b; Trefry, 1983, p. 21). When a retroflex consonant occurs as the first consonant in the word, there may be neutralisation of the apical contrast, as in Arrernte, e.g., <darrngap> /Aɐrŋɐp/ 'last one, only child' (recall that 'A' represents an apical stop; example based on Butcher, forthcoming b; Anderson V. B., 2000).

Very little work has been done on Burarra prosody. It is known that primary stress in Burarra is assigned to the first syllable of the first root of the word, e.g., <gacha> /'gɐcɐ/ 'to dry up', <gardabal> /'gɐɖɐbɐl/ 'garfish' (Butcher, forthcoming b). While there is no apparent consensus on secondary stress in this language, according to Goedemans (2010) in a recent (but perhaps not up-to-date) survey, if prefixation occurs, secondary stress is assigned to the prefix, e.g., <ama> /ɐ-'mɐ/ [ɐ'mɐ] 'will get him' (van der Hulst, Goedemans & Zanten, 2010, p. 670). Butcher (1996) provides examples of vowel reduction of all five vowel qualities when unstressed to a single mid central vowel, e.g., <lika> /'likɐ/ 'then' is realised as ['ləkə]. See also §2.4.3.

1.2.3 Gupapuyngu

Gupapuyngu (also known as Gobabingo) is a western dialect of Dhuwal-Dhuwala in the (Southern) Yolngu subgroup of the Pama-Nyungan family, which is spoken in north-eastern Arnhem Land in the Northern Territory (Lowe, 1975; Morphy, 1983,

p. 14). The speakers are members of the Yirritja moiety. Gupapuyngu has twenty-three phonemic consonants and three vowels with a length distinction. As Gupapuyngu lands surround Djinang traditional lands, speakers of the related Yolngu language, Djinang, frequently also speak Gupapuyngu, or have family members or spouses who speak Gupapuyngu (Waters, 1979; Hywel Stoakes, *pers. comm.*). There is no published experimental phonetic work on coarticulation in Gupapuyngu.

1.2.3.1 Consonants

As shown in Table 5, Gupapuyngu has seven places of articulation: bilabial, (alveo-)dental, apico-alveolar, apico-retroflex, lamino-(alveolo)palatal, dorso-velar and glottal (Lowe, 1975; Baker, 1999). The stop contrast can be described as fortis/lenis, as in Burarra (Lowe, 1975; Waters, 1979; 1980). Fortis stops are on average three times the duration of lenis stops, and voicing into the closure is curtailed, whereas lenis stops show prolonged glottal vibration (Butcher, 1995). Morphy (1983) states that ‘there is a potential contrast between [these] two types of stop [only] if the preceding segment is a vowel or liquid and the following segment is a vowel’ (p. 14), e.g., <bäpa> /bɐ:pɐ/ ‘father’ <bäba> /bɐ:bɐ/ ‘gum nut’ (Butcher, forthcoming b; see Table 5 and Table 6 for correspondences between orthographical symbols and phonemes).

With regard to the coronals, the dental either involves only laminal contact, or both apical and laminal contact (Butcher, forthcoming a; reported in Anderson V. B., 2000, pp. 44-45). The alveolar is said to be articulated similarly to the equivalent in English (Lowe, 1975, p. 4; Butcher, 1995). It may be marked relative to the dental and retroflex in Gupapuyngu (Hywel Stoakes, *pers. comm.*). Lowe (1975) remarks that /d/, as in <detung> /di:tuŋ/ ‘buffalo’ is not common; ‘[i]t usually occurs only when following the alveolar nasal /n/’. However, it also occurs in borrowed words and proper names (p. 15). The postalveolar involves a sub-apical or -laminal retroflex articulation (p. 19).

Table 5. Gupapuyngu consonants (after Lowe, 1975; Baker, 1999). Items in brackets are orthographic representations.

		Lamino-	Apico-		Lamino-	Dorso-	
	Bilabial	Dental	Alveolar	Retroflex	Palatal	Velar	Glottal
Plosive fortis	p	t̪ (th)	t	ʈ (t̲)	c (tj)	k	ʔ (')
Plosive lenis	b	d̪ (dh)	d	ɖ (d̲)	ɟ (dj)	g	
Nasal	m	n̪ (nh)	n	ɳ (n̲)	ɲ (ny)	ŋ (ng)	
Lateral			l	ɭ (l̲)			
Rhotic			ɹ (r) r (rr)				
Glide	w				j		

The (lamino-alveolo)palatal involves an articulation where the tip is down, making contact with the back of the lower teeth and can be realised as an affricate, [tɕ] (Lowe, 1975, p. 7; Butcher, 1995; Tabain *et al.*, 2011).

With regard to non-coronal consonants, the dorso-velar in Gupapuyngu involves a more backed constriction than is the case in English (Lowe, 1975, p. 13). The glottal stop is a characteristic of some Northern (Cape York and Arnhem Land) languages and is restricted in Gupapuyngu to syllable-final position (Evans, 1995) e.g., <bala'> /bɐlɐʔ/ 'house' (Butcher, forthcoming b).

Gupapuyngu also displays phonetic pre-stopping of nasals intervocalically, e.g., <cinaka> /cinaka/ [tɕɪᵈnɐkʰɐ] 'inside, underneath' (where the word initial consonant is a palatal affricate; Butcher, 2006).[11] Pre-stopped nasals are in free variation with plain nasals. This phonetic pre-stopping, which reflects a delay in the lowering of the velum until the last instant, may be associated with a general resistance to anticipatory nasal coarticulation (Butcher, 1996; 2006).

1.2.3.2 Vowels

Gupapuyngu possesses three contrastive vowels with a length distinction - /i ɐ u/ - as shown in Table 6, e.g., <wäkngani> /wɐ:kŋɐni/ 'fruit sp.', <yothu> /ju:t̪u/ 'child', <djeda> /ɟi:ɖɐ/ 'midnight' (Butcher, forthcoming b). This triangular vowel system is common in Australian languages. According to Lowe (1975), long vowels are approximately twice the duration of the corresponding short vowels. Lowe describes /i/ as having a quality approximating [ɪ], while /u/ is similar to [ʊ] (1975, p. 5).

Table 6. Gupapuyngu vowels (after Lowe, 1975; Baker, 1999; long vowels placed to the right of corresponding short vowels). Items in brackets are orthographic representations.

	Front	Central	Back
Close	i i: (i e)		u u: (u o)
Open		ɐ: ɐ: (a ä)	

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[11] Pre-stopping is not, however, considered in this dissertation.

1.2.3.3 Consonant-vowel effects, phonotactics and prosody

According to Lowe (1975), a retroflex consonant gives an ‘r’ like quality to the preceding vowel, e.g., in <wartja> /wɐʈɟɐ/ ‘shellfish sp.’ (Butcher, forthcoming b), while a lamino-alveolar consonant ‘pushes the preceding vowel forward, slightly distorting it. To our ears, it sounds as though ‘i’ has been inserted’ (Lowe, 1975, p. 18), e.g., in <gumatj> /gumɐc/ [gʊmɐⁱc] (clan) (based on Butcher, forthcoming b). It is clear that such consonant-vowel effects should be investigated experimentally in order to confirm these impressionistic observations.

Gupapuyngu words typically comprise two or three syllables but monosyllabic surface forms are possible, e.g., <dha> /d̪ɐ/ ‘tongue’, <dhäk> /d̪ɐ:k/ ‘hip’ (Butcher, forthcoming b). Words are predominantly vowel-final. Underlyingly, the word-initial segment is normally a consonant (Lowe, 1975). With regard to consonants, when a retroflex consonant occurs as the first consonant in the word, there is neutralisation of the apical contrast, as in Arrernte and Burarra (Laughren, 1984, pp. 74-75; Anderson V. B., 2000; Butcher & Harrington, 2003; but *cf.* Alpher, 2004, p. 115). With regard to lexical prosody, an early analysis by Lowe (1975) suggests that primary stress is on the first syllable of the word and secondary stress is on alternate syllables thereafter with the exception of the final syllable, e.g., <burgu> /'buɹgu/ ‘flower’ (Butcher, forthcoming b). Long vowels occur only in the word-initial syllable, e.g., <bäpa> /bɐ:pɐ/ ‘father’ but not *<bapä> (Lowe, 1975). See also §2.4.3.

1.2.4 Warlpiri

Warlpiri (also known as Waljbiri, Wailbri or Warlbiri) is a member of the Ngarrkic subgroup of the Pama-Nyungan family spoken in Yuendemu, to the North-West of Alice Springs. The phonology is marked by both regressive and progressive vowel harmony in high vowels, progressive harmony being the more productive process (Nash, 1986, p. 84; see §1.2.4.6). Warlpiri is one of the better documented Australian languages, as is Arrernte.

1.2.4.1 Consonants

As shown in Table 7, Warlpiri has five place contrasts in the oral (voiceless) plosive series: bilabial, apico-alveolar, apico-postalveolar/apico-retroflex or apico-domal,[12] lamino-palatal and dorso-velar (Nash, 1986). There is no voicing distinction, hence there is potentially free variation between voiceless and voiced plosives, although

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[12] Produced with the tip of the tongue against the dome of the hard palate; a term used by Jagst (1975).

intervocalic consonants are more likely to be voiced in spontaneous speech. As in Gupapuyngu, (phonetically) pre-stopped nasals in Warlpiri are in free variation with plain nasals (e.g., Butcher, 1999; 2006; Loakes *et al*., 2008; Fletcher, Butcher, Loakes, & Stoakes, 2010). Pre-stopped laterals are also known to occur (Loakes *et al*., 2008). See also Laughren, Hoogenraad, Hale and Granites (1996).

Warlpiri is uncommon amongst Australian languages in possessing three rhotic consonants (Busby, 1980, p. 90; Ladefoged & Maddieson, 1996, pp. 238-239): an alveolar tap/trill, /ɾ/, a retroflex continuant, /ɹ/ and a retroflex tap or flap, /ɽ/. Butcher (1996) points out that the third, flapped, rhotic is the lenited form of an original */ʈ/.

Table 7. Consonant inventory of Warlpiri (Nash, 1986). Items in brackets are orthographic representations.

		Apico-		Lamino-	Dorso-
	Bilabial	Alveolar	Retroflex	Palatal	Velar
Plosive	p	t	ʈ (rt)	c (j)	k
Nasal	m	n	ɳ (rn)	ɲ (ny)	ŋ (ng)
Lateral		l	ɭ (rl)	ʎ (ly)	
Tap/flap/trill		ɾ (rr)	ɽ (rd)		
Continuant	w		ɹ (r)	j (y)	

Finally, the velar stop is realised with a backed constriction, especially in the context of non-front vowels (Butcher & Tabain, 2004), which can be lenited to an approximant intervocalically, e.g., /'waca kanpa/ ['wɐɟɐɰɐb] ‘are you going?’ (Butcher, 2006). Attested homorganic and heterorganic consonant clusters include nasal, lateral and rhotics + stop forms and also nasal + nasal and /lw/ and /ɭw/ forms (Jagst, 1975; Nash, 1986).

1.2.4.2 Vowels

As in Gupapuyngu, the Warlpiri vowel series has three qualities and a length distinction, shown in Table 8: /i i: ɐ ɐ: u u:/, e.g., <purdangirli> /puɖɐŋiɭi/

‘straggling’ and <juurlpungu> /juːɭpuŋu/ ‘hopped’ (Butcher, forthcoming b). Butcher and Harrington (2003) describe the ‘close’ vowels as phonetically close-mid; /u/ can be realised phonetically as [ə], [o], or [ɵ], e.g., <jalangurluju> /cɐlɐŋuɭucu/ [ˈcɐlɐŋəɭəɟə] ‘today’.

Table 8. Warlpiri vowels (Nash, 1986; long vowels placed to the right of corresponding short vowels). Items in brackets are orthographic representations.

	Front	Central	Back
Close	i iː (i ii)		u uː (u uu)
Open		ɐ ɐː (a aa)	

As in Gupapuyngu, the vowel length distinction appears to be restricted to the word-initial syllable (Butcher & Harrington, 2003), except in cases of reduplication, e.g., <mimi> /mimi/ ‘forehead’, <miimiiyanyi> /miːmiːjaɲi/ ‘scrutinises’ (Jagst, 1975, p. 31; Butcher, forthcoming b). Pentland (2004) showed that phonemically long vowels are significantly (phonetically) longer than short vowels in word-initial and utterance/phrase-initial position, but not in non-word- and non-phrase-initial position (see also Pentland & Laughren, 2004). Stressed short vowel qualities are well separated in the F1 x F2 vowel space (Butcher, 2004) despite the vowel space typically being crowded. The issue of vowel space crowding will be addressed in Chapter 5 of this dissertation.

1.2.4.3 Consonant-vowel effects

There is evidence of consonant-vowel effects in Warlpiri relating to palatal, retroflex and velar consonants. Butcher and Harrington (2003) provided evidence of strong palatal consonant-dependent coarticulation in /uju/ sequences; the consonant target was associated with higher F2 frequencies in the /u/ vowels in a focussed context. Fletcher, Loakes, Butcher and Harrington (2007a) found anticipatory and carryover palatal-dependent coarticulation in an EPG analysis of /nc/ and /ɲk/ clusters (the latter in front vowel contexts). These results suggest that palatal stops in Warlpiri are more resistant to coarticulation than alveolar and velar stops. The authors found that velars were associated with a very back articulation in the low central vowel environment, e.g., in <wanka> /wɐnkɐ/ ‘raw’ [*sic*], but not in the close front environment, e.g., in <kinki> /kinki/ ‘devil’, consistent with the view that the velar involves a very retracted articulation except when adjacent to the close front vowel. With regard to retroflex-vowel effects, Jagst (1975) suggests that the degree of retroflexion in the retroflex series is greater following /a/ (/ɐ/) and lesser following /i/, while it is intermediate following /u/ (p. 26), while all vowels are retroflexed when adjacent to retroflex consonants (p. 31).[13]

With regard to consonant-dependent coarticulation on Warlpiri vowels, the front vowel, /i/, is realised as a close front vowel when adjacent to a palatal or palatalised consonant or word-finally (Jagst, 1975, p. 32), e.g., <yiri> /jiɹi/ [jiɹi] 'sharp point'. When the front vowel follows the /uw/ sequence word-finally, it is realised as a mid close front vowel (p. 32). Fletcher *et al.* (2007a) found front vowel effects that suggest that this vowel is somewhat resistant to coarticulation (consistent with a qualitative analysis by Jagst, 1975). The back vowel is realised as a high back vowel only when adjacent to a labio-velar or word-finally (p. 32), e.g., <puka> /pukɐ/ [pukɐ] 'rotten' (Butcher, forthcoming b). The back vowel is elsewhere realised as [ʊ] (Jagst, 1975, pp. 31-32). (See also §1.2.4.6 on Warlpiri Vowel Harmony.)

There is a particular need for further examination of CV and VC coarticulation in Warlpiri involving multiple places of articulation and not merely the palatal and retroflex, and also of an experimental study of consonant-dependent vowel and vowel-to-vowel coarticulation.

1.2.4.4 Phonotactics

The minimal word in Warlpiri is disyllabic (bisyllabic), consisting of a bimoraic foot (e.g., Anderson S. R., 2005), e.g., <yapa> /'japa/ 'person' (Butcher, forthcoming b). The syllable is typically CV(C), or CV(V)(C) word-initially (Nash, 1986, p. 78), e.g., /pi.na/ 'knowing', /kin.ki/ 'devil' (Jagst, 1975, p. 40). Most words start with a consonant and end in a vowel (Jagst, 1975, p. 33; Evans, 1995; Butcher & Harrington, 2003) but root-finally in verbs, /u/ does not occur underlyingly (Nash, 1986, p. 74). Consonant clusters are permitted only word-medially, e.g., <parlja> /pɐɭcɐ/ 'full' but not *<rljapa> (Butcher, forthcoming b), while consonants are not permitted word-finally (Nash, 1986). Medial consonant clusters can be homorganic or heterorganic, e.g., /ɳʈ/, /lk/.

As in the other languages considered in this dissertation, word-initially, there is neutralisation of the apical contrast (Nash, 1986, p. 71*f*; Butcher & Harrington, 2003); the sound equivalent to the postalveolar occurs in this position (Jagst, 1975,

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[13] Incidentally, there is some evidence that the series of pre-stopped nasals and laterals derive from a strategy to reduce carryover vowel-to-consonant coarticulation in order to preserve the left-edge of the sonorant (e.g., Loakes *et al.*, 2008).

p 26; Laughren, 1984; Butcher, 1995), e.g., <tari> /Aari/ [ʈɐɾɪ] ‘ankle’ and e.g., <tururru> /Auɹuru/ ‘clapsticks’ (where ‘A’ is as before; example based on Butcher, forthcoming b). The degree of retroflexion is said to vary intervocalically (Jagst, 1975, p. 26) although this remains to be investigated quantitatively.

1.2.4.5 Prosody

Warlpiri has recently been described as an accent language with pitch-marking on left prosodic edges (Pentland, 2004; Tabain & Breen, 2011; Pentland & Ingram, forthcoming). According to Nash (1986), the stress domain in Warlpiri is the phonological word. Feet are left-headed and primary stress is on morpheme-initial syllables, e.g., <watiya> /ˈwɐtijɐ/ ‘tree’, and secondary stress is on subsequent odd-numbered syllables except the morpheme-final syllable (e.g., Jagst, 1975, p. 41; Nash, 1986; Butcher & Harrington, 2003), e.g., <karlarnjirri> /ˈkɐɭɐɳciri/ ‘lizard’ (Butcher, forthcoming b). Jagst (1975) argues that primary stress in Warlpiri is ‘perceived as increased intensity of loudness, raised pitch, and sometimes length’ (p. 41, but *cf.* Harrington, Butcher, & Palethorpe, 2000a). The intonation contour in declarative sentences appears to involve a flat hat pattern with a fall to a low boundary tone (L%) (Butcher & Harrington, 2003). Phrasal stress is not said to be dependent on pragmatic interpretation (2003). With regard to focus, pitch accent in focussed words may be realised as a clear F0 peak (2003). In general, the focussed context is accompanied by greater supralaryngeal/spectral change than the unfocussed one (2003, p. 22).

It is well established that word-medial consonants in Warlpiri undergo articulatory strengthening and lengthening, and mark prosodic distinctions, such as focus, and word boundaries (Pentland, 2004; also Tabain *et al*., 2011 on word-medial strengthening). Overall, prosodic boundaries appear to be signalled more by rhythmic or durational differences (lengthening) than supralaryngeal or spectral ones (strengthening), for example, the oral bilabial closure is longer in word-initial than in morpheme-initial position (Butcher & Harrington, 2003, p. 23). An early study of word stress conducted by Harrington *et al.* (2000a) showed that stressed word-initial syllables were shorter in duration than unstressed word-medial and –final syllables in tri-syllabic words, rather than longer, as would normally be predicted in Indo-European languages such as English (e.g., Fry, 1955; Lindblom, 1963; Lehiste, 1970; Beckman, 1986; de Jong, 1995; see Fletcher, 2010, for a review); it has been hypothesised that stress in Warlpiri is marked by consonant rather than vowel lengthening (Harrington *et al.,* 2000a; Butcher & Harrington, 2003; Pentland & Laughren, 2004).

Consonant lengthening is most likely to occur in utterance- and phrase-initial rhymes, in post-tonic position (*i.e.*, occurring after the major word prominence) and phrase-finally, especially in the non-focussed context. Pentland (2004) found that consonant lengthening occurred in utterance-initial words only; this lengthening might then be 'a higher-level prosodic cue associated with phrasal or utterance-level prominence'. Pentland and colleagues (e.g., Pentland, 2004; Pentland & Laughren, 2004) provide some evidence of relatively long stop closures and release durations post-tonically when the stop is in syllable-onset following an utterance-initial primary stressed syllable. (See also Ingram, Laughren & Chapman, 2008.) In phrase-initial rhymes with pitch-accent, Butcher and Harrington (2003) found that consonantal spectral targets were more extreme. They also found that Warlpiri marks focus and distinguishes grammatical boundaries by means of fundamental frequency, supra-glottal expansion (see §2.3) and duration, but most of the duration differences and all of the F0 peaks and supra-glottal expansion are associated with the consonants in the rhyme rather than in the vowels. In fact, Nash (1986) states that the factor of stress does not much affect vowel quality in Warlpiri (p. 99). The literature on prosodic factors in coarticulation is discussed further in §2.4.

1.2.4.6 Vowel harmony

As mentioned above, bidirectional roundness (vowel) harmony occurs in Warlpiri. Laughren (2000) argues that Warlpiri vowel harmony operates over a syntactic domain whereas Nash (1986) argues that the domain of harmony is the phonological word (*cf.* Pentland & Laughren, 2004). For Dixon and Aikhenvald (2002), this harmony is a matter of prosodic constituency, *i.e.*, it serves to denote the prosodic domain. (See also Simpson, 1991).

Nash (1986) provides a morphosyntactic analysis of Warlpiri in which he addresses vowel harmony. On his account, a large proportion of nominal suffixes undergo progressive vowel harmony, while regressive harmony is confined to the past tense suffix -Nu (where N represents any nasal phoneme), which propagates regressive harmony of /i/ to /u/ throughout the verb root (see also Evans, 1995). Regressive harmonisation will spread to a previous vowel within the word unless blocked by an intervening low vowel. It also propagates through the inceptive (*i.e.*, relating to the beginning of the action) derivational suffix (Nash, 1986). Progressive harmonisation of /u/ to /i/ is spread by any positionally appropriate high vowel. The vowel harmony process is blocked in progressive harmony by a low vowel (*i.e.*, /ɐ/, hereafter /a/) or a labial consonant root internally, and when immediately preceded by /u/, e.g., in <ngamirni-puraji> 'your mother's brother' and <milpirri-puru>

‘during cloud’ (Nash, 1986, p. 88; Berry, 1998, p. 149). The process does not spread from a preverb to a verb stem or preverb, or beyond the second word in a compound word. According to Ohala’s account of sound change (e.g., 1981; 1993), this pattern of harmony blocking by a labial consonant indicates a phonologisation of consonant-to-vowel coarticulation. Given this account, it is clear that insights into coarticulation can be gained from a comparison of languages with Vowel Harmony and languages with merely ‘incipient Vowel Harmony’, or vowel-to-vowel coarticulation. However, it is beyond the scope of this particular study to examine differences in V-to-V coarticulation between Warlpiri and the other three languages in the manner of, e.g., Przezdziecki (2005), because the corpus was not specifically designed for such a purpose.

1.3 Aims of the study

The primary goal of this dissertation is to investigate and describe consonant-to-vowel, vowel-to-consonant and vowel-to-vowel coarticulation in Australian languages, specifically, in Arrernte, Burarra, Gupapuyngu and Warlpiri. A more general goal is to add to the literature on the influence of language-particular phonological structure on coarticulation and, more broadly, to the literature on distinguishing language-specific speech behaviour from universals of speech behaviour. The focus is restricted to spatial (non-temporal) coarticulation. Additionally, following Fowler and Brancazio (2000), speaker-specific coarticulatory patterns are identified. This study is the first to carry out a comprehensive cross-linguistic survey of coarticulation in Australian languages and the first to address vowel-to-vowel coarticulation in Australian indigenous languages.

The first aim is to identify the effects on consonant-vowel coarticulation of consonant place of articulation while taking into account the speaker and language, prosodic prominence in the vowel, and the position of the vowel relative to the consonant (VC or CV, the two possible types of ‘trajectory period’ in Recasens’ terms). The second aim is to identify and describe, in a preliminary manner, patterns in vowel-to-vowel coarticulation. This is done in order to analyse whether, as has been found for English, Catalan and Swedish, there is V-to-V coarticulation that is modulated by the place of articulation of the intervening consonant and by the quality of the flanking vowel. The third, minor, aim is to quantify the spectral patterns and variability (in F1 and F2) of vowels in these languages - and to gain a general picture of the acoustical vowel space, in particular the extent of crowding - to determine whether vowels tend to differ spectrally according to prosodic prominence and word position in disyllabic words. These results will inform the subsequent examination of trans-consonantal coarticulation between vowels in the same, controlled, word context. The matter of vowel acoustics is fundamental to vowel-dependent and, specifically, V-to-V coarticulation.

This study will address the preceding literature, in particular, the DAC model (see §2.2.1) and the work of Öhman (1966) and others on V-to-V coarticulation and coproduction models (see §1.1 and §2.1.1). Öhman's study is discussed in full in §2.1.1.

These particular four languages were chosen for examination for several reasons. Firstly, it was desirable to include languages varying in their vowel and consonant inventories as the previous literature identifies segmental characteristics as factors in coarticulation. Secondly, when considering the relationship between prosody and coarticulation, the inclusion of Arrernte was necessary given the previous literature on the relationship between syllabification and consonant-vowel coarticulation (e.g., Tabain *et al.*, 2011; see §1.2.1.5). Thirdly, given the complexities of the task of collecting data, having access to corpus materials in these languages was of considerable benefit in conducting the analyses.

1.4 Implications of the study

The aims outlined in the preceding section are important with regard to Australian languages for three main reasons. Firstly, relatively little experimental work has been conducted on Australian languages. Secondly, this work will inform the debate on phonemic inventories for these languages, in particular, for Arrernte (§1.2.1). Thirdly, previous experimental studies and impressionistic field work analyses of Australian languages have made a number of claims about coarticulatory processes in these languages that should be investigated further. The principal claims are summarised in (i) to (v).

(i) There is a great deal of evidence for a 'place of articulation imperative', *i.e.*, an imperative to protect perceptual contrasts involving consonant place of articulation, which may impose limits on coarticulation (e.g., Butcher, 1995; 2006; Cho, 2004; see §2.1.2.3).

(ii) Relatedly, there appears to be an avoidance of (synchronic) anticipatory coarticulation in Australian languages such that, for example, heterorganic consonant clusters remain heterorganic phonetically (see §2.1.2.3 and §2.1.2.4).

(iii) Moreover, there is evidence of word-medial consonant strengthening and lengthening in Arrernte, Warlpiri and elsewhere (e.g., Butcher & Harrington, 2003; Tabain *et al*., 2011) and little evidence of (syllabic and prosodic) domain-initial strengthening. Word-initially, consonant contrasts may be neutralised or consonants may be lenited or deleted (Hale, 1962; 1964; Blevins, 2001; see §1.2 and §2.1.2.3). Phonetic studies are necessary to provide an explanation of this pattern (Blevins, 2007) and to evaluate or support the claim for an underlying VC(C) syllable or VCV planning unit in Arrernte (e.g., Breen & Pensalfini, 1999; Tabain *et al.*, 2004; see §1.2.1)

(iv) While there is evidence of pre-palatalisation in Arandic languages (Breen, 2007; Harvey, 2011), there have been no experimental phonetic studies on the subject.

(v) It has been shown in a direct palatographic and acoustical study that velar stops vary in the anteriority of the constriction according to the target of the following vowel in Australian languages (Butcher & Tabain, 2004)[14] and that such stops undergo stronger vowel-dependent coarticulation than in other languages such as English (e.g., Tabain & Butcher, 1999; Butcher & Tabain, 2004; see §2.1.2.4).

A more detailed phonetic description of coarticulatory processes in Australian languages would inform current phonetic theory, such as that concerning the role of consonant place in coarticulation and coproduction models more generally, the DAC model of coarticulation resistance. Such a description would also inform the use of the primary metric for analysing consonant-vowel coarticulation, the Locus Equation.

1.5 Structure of the study

The structure of this dissertation is as follows. A literature review follows this chapter, in Chapter 2, which comprises a discussion of the most important topics, principles and models referred to in subsequent chapters, many of which have been introduced in the present chapter. The structure of this chapter is outlined at the beginning of Chapter 2.

Chapter 3 outlines the methodology employed in Chapters 4, 5 and 6, the experimental chapters. In §3.1, the selection of subjects is outlined, while in §3.2 and §3.3, the data collection and analysis methods are summarised, with comments on segmentation and labelling procedures. In §3.4, methods specific to each experimental chapter are documented; §3.4.1 addresses the methods

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[14] Butcher and Tabain (2004) examined /kV/ realisation in English, Arrernte, Yanyuwa, Yintjiparnti (or Yindjibarndi), Warlpiri and several other Australian languages.

employed in Chapter 4, on consonant-vowel coarticulation, 3.4.2 addresses Chapter 5, on vowel dispersion and variability and §3.4.3 addresses Chapter 6, on V-to-V coarticulation. §3.5 concludes briefly.

The first experimental chapter, Chapter 4, as mentioned, addresses consonant-vowel coarticulation. In §4.1, the hypotheses for this chapter are introduced. §4.1.2 comprises a recapitulation of the methodology that is employed in that chapter. §4.2 constitutes the results of the experiments, divided into sections according to language groups, and comprises §4.2.1 on a Locus Equation analysis of consonant-vowel coarticulation, §4.2.2 on coarticulation in the context of the phonemic retroflex stop (with specific regard to pre-palatalisation of apicals in Arrernte) and the palatal stop, and §4.2.3 on vowel-dependent velar stop coarticulation. §4.3 presents a general discussion of the results of §4.2.1, §4.2.2 and §4.2.3. §4.4 concludes.

The second experimental chapter, Chapter 5, comprises a summary of vowel variability in formants 1 and 2, vowel positioning in the acoustic space, and vowel dispersion. §5.1 comprises an introduction to the chapter and the hypotheses and a brief restatement of the methodology, while in §5.2 the results are presented, divided into sections according to language groups. §5.3 constitutes a summary and discussion of the results with regard to the effects of prosodic prominence and word position and the factors of speaker and language group. §5.4 concludes.

The third experimental chapter, Chapter 6, addresses trans-consonantal vowel-to-vowel coarticulation. §6.1 comprises a presentation of the hypotheses and a recapitulation of the methodology. In §6.2, the results are reported, divided into sections according to language group. §6.3 constitutes a discussion of the results, with particular regard to the effects of the word-medial consonant and the flanking (or ‘trigger’) vowel on the target vowel, differential formant effects, the effects of the measurement point, directional and prosodic effects, and the effects of inventory size. §6.4 concludes.

In the final chapter, Chapter 7, there is a summary of the findings and a presentation of conclusions. The chapter is divided into three main sections: §7.1, which provides a summary of consonant-vowel coarticulation results, §7.2, which provides a summary of vowel variability and dispersion and vowel-to-vowel coarticulation results, and §7.3, which offers closing remarks. A bibliography and appendices follow.

2 Literature Review

Coarticulation has been defined in Chapter 1 as contextual variability in the acoustics of successive consonants and vowels, which involves an overlapping of (near) adjacent speech sounds. As mentioned in §1.1, coarticulation interacts with not only biomechanical constraints and articulatory economy but also, for example, cognitive processes, perceptual distinctions and language-specific phonological processes. This chapter presents the literature on coarticulation with two foci: one, spatial coarticulation between consonants and vowels and also between vowels across a single consonant, and two, coarticulation in Australian languages in particular. Acoustic data from a range of languages show that the magnitude of coarticulation is affected by factors such as consonant place of articulation and vowel quality and relatedly, the extent to which the segment is articulatorily constrained, the phonological inventories involved, prosodic prominence and position within the syllable and word. These findings will be discussed in this chapter. It is structured as follows: in §2.1, an introduction to the literature on coarticulation is presented, including a discussion of a coproduction framework and V-to-V coarticulation in §2.1.1 and of consonant-vowel coarticulation in §2.1.2. In §2.2, the literature addressing the subject of coarticulation resistance is discussed, with special attention to Recasens' DAC model of coarticulation resistance. §2.3 comprises a discussion of Lindblom's (1990) hyper- and hypo-articulation theory, with reference to vowel dispersion theories and to vowel systems and phonemic contrasts. In §2.4, the literature addressing the effects on prosody on coarticulation is discussed. General research questions follow in §2.5.

2.1 Coarticulation

In a very early study of coarticulation, Rousselot (1897-1901) conducted an articulatory analysis of vowel-to-consonant (V-to-C) coarticulatory effects in CV sequences spoken by native French speakers. The sequences comprised /bi/, /ba/, /zi/ and /za/. He found that in some sequences the tongue assumed the position for the vowel at the beginning of the preceding consonant. Traces of the lips and tongue during the production of these sequences showed that the tongue was higher during the consonant when the following vowel was /i/ than when it was /a/. Three decades after Rousselot, the term 'coarticulation' was introduced by Menzerath and de Lacerda (1933) in their articulatory study of German. Employing the articulatory measure of kymograms (or 'wave writers'), they investigated German syllable-initial labial consonant and vowel sequences. They argued that the articulators were preparing for the vowel during the production of the labial consonant. More generally, they pointed out the lack of stable articulatory positions during these sequences. A good recent overview of coarticulation issues is Farnetani and Recasens (2010).

2.1.1 Vowel-to-vowel coarticulation and gestural coproduction

Perhaps the most promising model of coarticulation accounting for the temporal overlap of movements or gestures for adjacent segments is a coproduction model. Recall from §1.1 that the standard coproduction model posits waves of gestural activation over time and context-sensitivity arises primarily from temporal and gestural overlap (Fowler & Saltzman, 1993, p. 173). On this view, gestural coordination is achieved by the implementation of constraints that link finer-grained components and thereby create dependencies among the components and among the articulators (Fowler & Saltzman, 1993). According to this account, coordination creates a coarser-grained order in systems composed of finer-grained components (Pattee, 1976). The coordinative constraints are established transiently to implement 'linguistically significant actions of structures of the vocal tract' in speech, as has been established by studies examining compensatory responses to the randomly implemented, or unexpected perturbation of articulators in speech (Fowler & Saltzman, 1993, pp. 172-174). These compensatory responses 'appear to reflect the ongoing state of coordinative constraints that serve to establish gesture-specific patterns … among the articulators' (p. 174). (See also Daniloff & Moll, 1968; Benguerel & Cowan, 1974.)

In a coproduction model, vocalic and consonantal gestures remain somewhat separate articulatorily, such that in a VCV sequence, there is a vocalic gesture extending across the sequence, *i.e.*, a diphthongal vocalic gesture, and the consonantal gesture is 'superimposed' on it, as was suggested by Öhman (1966). This is, of course, a simplification; there is some evidence in the literature of certain consonants modulating (blocking or interrupting or delaying) V-to-V coarticulation to a greater or lesser degree (see, e.g., Öhman, 1966; Recasens, 1984b; Recasens *et al.*, 1997; Recasens & Pallarès, 2000; Fowler & Brancazio, 2000). (See §2.2.) In this way, V-to-V coarticulation may not be independent from C-to-V coarticulation. The magnitude of V-to-V coarticulation in a given VCV sequence appears to depend on precisely controlled patterns of articulatory activity, and in particular, on gestural constraint, involved in the production of the entire sequence (Recasens, 1984b, 1997; see also Fowler & Saltzman 1993, pp. 180-181; Fowler & Brancazio, 2000, p. 4). Thus, the typically inverse relationship between coarticulatory sensitivity and degree of articulatory constraint becomes more complex when V-to-V effects are accounted for (Gay, 1974; 1977; Carney & Moll, 1971; Recasens, 1984a,b; 1987; 1989; 1997; see §2.1.2 and §2.2).

Arguably the most important early account of V-to-V coarticulation was formulated by Öhman (1966), who examined coarticulation of voiced stops and adjacent vowels in both symmetrical (containing identical vowels) and asymmetrical (containing non-identical vowels) vowel-consonant-vowel (V1-C-V2) sequences for Swedish, English, and Russian. However, the first account appears to be that of Rousselot (1897-1901), discussed previously in §2.1, for French. In Öhman's principal study of a single speaker of Swedish, the first vowel was fixed, and the second varied. Öhman claimed that the articulatory motion from C to V2 is modified by V1, *i.e.* that there is a slow diphthongal articulatory gesture from V1 to V2, and superimposed on this is a rapid gesture for the consonant. In other words, he provided evidence that in a VCV sequence 'the tongue is able to make a distorted vowel gesture while it is executing the stop consonant.' (p. 166) Furthermore, he argued that the C-to-V effects depended on the degree to which the tongue was involved in the production of the consonant. Comparing results for Swedish, English, and Russian, he found that trans-consonantal coarticulatory effects were weaker in Russian, and claimed that this relative lack of coarticulation was due to gestural antagonism between vowels and articulatorily dominant palatalised consonants. It could be said that V-to-V coarticulation might be limited by Russian speakers in order that the 'output constraints' on the palatalised consonants not be violated (Manuel, 1990; see also, Choi & Keating, 1991, on Russian, Polish, and Bulgarian). In other words, Öhman here found evidence of language-particular coarticulation patterns, and these appeared to relate to biomechanical constraints.

Since Öhman's study, other acoustic and articulatory studies (using electropalatography or 'EPG', X-ray microbeam and, more recently, electromagnetic articulography or 'EMA' and electromagnetic midsagittal articulography or 'EMMA') have examined V-to-V coarticulation in languages such as English and Spanish (e.g., Butcher & Weiher, 1976; Recasens, 1989; Fowler & Brancazio, 2000; Cho, 2004) in order to determine how vowels and consonants interact in this type of coarticulation. It was shown that during the production of the consonant, the tongue dorsum coarticulates with the neighbouring vowels. Additionally, further evidence was provided of language-specific differences in V-to-V coarticulation, for example between Russian, in which palatalisation appears to block such coarticulation, and English, in which such coarticulatory effects are relatively strong (e.g., Choi & Keating, 1991).

Öhman's (1966) claim for the superimposition of the consonantal gesture is supported by more recent experimental findings. Fowler and Brancazio (2000) present evidence of 'some independence between V-to-V and V-to-C coarticulation [*i.e.*,] the magnitude of coarticulation in schwa [V1 in a V1-C-V1 sequence] can be greater than that in the consonant' (p. 28). According to Fowler and Saltzman (1993), vowel production might be continuous across the VCV sequence because in order to ensure that when a syllable-initial consonant is released the vowel then produced is the intended one, the speaker must implement the coordinative constraints well before the consonant release. There is insufficient time to implement these constraints merely during the consonant closure, which is short in duration.

Further evidence of the modulation of V-to-V coarticulation by the intervening consonant comes from a study of British English. Butcher (1989) conducted an articulatory (EPG) study of coarticulation and variability in tongue contact patterns in VCV sequences for consonants /p t k/ and vowels /i a u/. He found that V-to-V coarticulation was similar across /p/ and /t/ and was mainly anticipatory rather than carryover. /i/ both influenced and was influenced by /a u/, while /a/ and /u/ did not seem to influence each other in terms of linguo-palatal contact. V-to-V coarticulation did not seem to extend across /k/; Butcher states that 'any [V-to-V] coarticulatory effect … appears to be blocked by the tongue body gesture required for the intervening [velar] consonant.' (p. 45).

It appears that the predominant direction of coarticulation in VCV sequences depends on factors such as the degree of tongue dorsum raising in the intervocalic consonant (in accordance with the DAC model; see §2.2.1). In a number of studies, V-to-V, C-to-V and V-to-C carryover effects have been shown to exceed anticipatory effects at and across dorsal consonants (Gay, 1977; Kiritani, Tanaka, Hirose, & Sawashima, 1977; Bell-Berti & Harris, 1979; Recasens 1984b; 1985; Recasens & Espinosa, 2010; Farnetani, 1990; see also, Farnetani, Hardcastle, & Marchal, 1989). With respect to V-to-V coarticulation in particular, there is evidence of a predominance of the carryover component for both dorsal and non-dorsal consonants (e.g., Bell-Berti & Harris, 1979; Magen, 1984; Manuel & Krakow, 1984; Recasens, 1987; Farnetani, 1990). There is also some evidence of inter-speaker variation (e.g. American English: Magen, 1997; English, French and German: Hoole, Nguyen-Trong, & Hardcastle, 1993). With regard to V-to-C coarticulation, although in Recasens' early (1984a) study, he found a preponderance of carryover V-to-C effects in Catalan, many studies have shown an effect of factors such as place of articulation (and possibly also stress condition and speech rate; American English: Huffman, 1986) on the predominant direction of vowel-to-consonant coarticulation. The work of Recasens (1987; 1999), Manuel & Krakow (1984), Hoole, Gfroerer and Tillmann (1990), Farnetani, 1990, amongst others indicates that more retracted and articulatorily constrained or slower moving articulations such as dorsals and (alveolo)palatals will show a predominance of carryover effects, while more anterior articulations may show either a predominance of carryover or anticipatory effects (a review of this literature is provided by Recasens, 1999).

The 'time-locked' model of coarticulation developed by Bell-Berti and Harris (1979; 1981; 1982), which is consistent with a coproduction model,[15] predicts that the component gestures of a segment will begin at a relatively invariant interval before the achievement of the target for that segment (however see, e.g., Recasens, 1989; Magen, 1989). The model derives from the authors' analysis of lip rounding in VCnV sequences in American English using EMG and acoustical techniques. In both /uCni/ and /uCnu/ sequences, the activity of the orbicularis oris associated with the target vowel was seen to finish at a relatively fixed time point very soon after the vowel. Several other early studies analysed coarticulation in the form of lip rounding in VCV sequences using acoustic and articulatory techniques, including Benguerel and Cowan (1974), and Lubker and Gay (1982). Lubker and Gay (1982) investigated language-specific constraints on lip rounding coarticulation. The authors analysed V-to-V anticipatory labial coarticulation in Swedish VCV sequences. They found that speakers commenced the lip rounding gesture earlier than did speakers of English. The Swedish speakers also used less variable lip protrusion movements than did English speakers. The authors argued that this was due to Swedish having a phonemic lip rounding contrast between vowels, whereas English does not, and therefore that the speakers of Swedish were under greater pressure to ensure that adequate lip rounding was achieved in the post-consonantal vowel. The authors claimed that three of the five speakers appeared to use a look-ahead strategy, and the other two, a coproduction strategy (with time-locked gestures).[16]

Criticisms of coproduction models have focussed on two aspects. The models have been criticised for relying heavily 'on the inherent kinematic properties of the production process', and thus potentially neglecting the importance of acoustic and perceptual salience (Kühnert & Nolan, 1999, p. 23). They have also been criticised for making assumptions as to the vocalic or consonantal nature of the phonological segments under control, because in this model the consonantal and vocalic gestures are considered to be independent. According to Recasens (1985), consonantal and vocalic gestures are only independent when the consonant is one

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[15] It should be noted that time is controlled specifically in the time-locked model whereas it can be derived from the treatment of gestural dynamics in a typical coproduction model.

[16] According to the look-ahead model, coarticulation is a largely assimilative influence of one phonetic segment on another, such that segments influence one another in a context-sensitive way at the level of underlying linguistic features (Daniloff & Hammarberg, 1973). On this view, in a sequence with an unrounded V1 and a rounded V2, the first vowel is specified for a conflicting feature so lip rounding cannot spread leftwards beyond the medial consonant.

that leaves large regions of the vocal tract free to undergo vowel-dependent coarticulation, such as a labial or a denti-alveolar stop (p. 98; see §2.1.2). Therefore, according to Recasens, Öhman's (1966) model of V-to-V coarticulation and coproduction models are 'too general to account for a large number of articulatory types and coarticulatory patterns' (Recasens, 1985, p. 98).

In the following section, §2.1.2, the literature on coarticulation specifically between a consonant and vowel and the specific measures used in these studies will be discussed.

2.1.2 Measuring consonant-vowel coarticulation

2.1.2.1 Consonant-vowel coarticulation and the Locus Equation

Many studies of consonant-vowel coarticulation employ the Locus Equation (hereafter LE), a linear regression metric that is typically used to measure coarticulation in CV sequences. The locus equation will also be employed in the present study. Hence, a detailed explanation of the different permutations of the LE model and their implications is provided in this section. The LE appears to reflect place of articulation in consonants, and relatedly, differences in coarticulation resistance (Fowler, 1994; Brancazio & Fowler, 1998; Löfqvist, 1999; see §2.2). The LE was formulated by Lindblom (1963) but it was Krull (1987) who first claimed a relationship between LE slope and degree of coarticulation between the consonant and the vowel in a CV sequence; she found that Swedish labial consonants are more strongly coarticulated than dental consonants (see also Krull, 1989). Thus, the LE was originally employed as means of determining the magnitude of coarticulation in a consonant as a function of the following vowel, *i.e.*, the extent to which the second formant (F2) of a consonant is influenced by the F2 of the following vowel. In a later study, Chennoukh *et al*. (1997) demonstrated that locus equations depend both on degree of coarticulation and consonant place of articulation.

The LE permits the calculation of a LE slope value, which is a number normally between 0 and 1, that indicates the magnitude of vowel-dependent coarticulation. 0 indicates minimal coarticulation and 1, maximal. The LE also permits the calculation of the y-intercept - the point at which the main regression line or 'fitted line' would cross the y-axis - and the consonant 'locus', in the traditional Haskins (*i.e.* Haskins laboratory) sense of a theoretical point of formant origin (Delattre *et al.* 1955). The term 'second order' equation refer to the linear relation between slopes and y-intercepts (Chennoukh, Carré, & Lindblom, 1995; 1997; Iskarous, Fowler, & Whalen, 2010). If a straight-line transition between F2 vowel onset and vowel midpoint or target is assumed, the point of intersection of the line with the line y'x is an estimate of the acoustic locus frequency in Hz of a given consonant place of articulation (Sussman, McCaffrey, & Matthews, 1991; Harrington & Cassidy, 1999; Tabain & Butcher, 1999). Fowler (1994, p. 600) explains the existence of the linear relationship between vowel onset and midpoint as follows:

> 'if a vowel has a high F2, F2 will also be relatively high at the acoustic onset of the syllable, because vowel production began before consonant release, and vowel production affects the acoustic signal at release. If a vowel has a low F2, F2 will be low at acoustic-syllable onset for the same reason.'
>
> (p. 600; see further, §2.1.2.2)

Example LE plots for American English consonants are given in Figure 3 (adapted from Löfqvist, n.d.). These plots are of F2 during the vowel (the steady-state value) and at the vowel onset for bilabial, alveolar, and velar stops. The figures show the labial stops to have the highest slope value (0.86), and the alveolar stops to have the lowest slope value (0.37). The equation, for example, given for labial stops, y = 66 + 0.861x, indicates that the y-intercept (the point at which the fitted line would intersect the y-axis) is 66Hz (F2), and the slope value is 0.861.

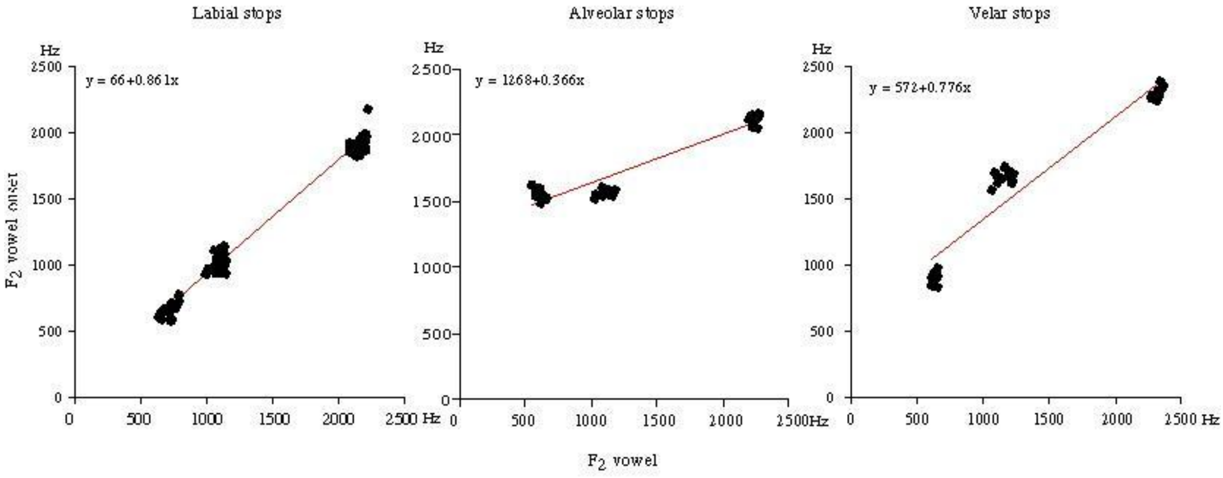

Figure 3. Example Locus Equation plots (adapted from Löfqvist, n.d.). L to R: labial stops, alveolar stops, velar stops. X-axis: F2 at the vowel midpoint, Y-axis: F2 at vowel onset.

The relevant equation is expressed by Flemming (1995) as Equation 1, where *F2* is the second formant frequency for consonant or vowel, where *k1* is the slope, and *c1* is the intercept on the y-axis, and where *k1* and *c1* are constants for a given consonant:

Equation 1. LE formula (Flemming, 1995)

$$F2c = k1F2v + c1$$

Alternatively, the LE has also been expressed as Equation 2 (after Klatt, 1987; Flemming, 1995) where *F2C* is the F2 frequency at consonant release, *F2V* is the F2 frequency at the vowel midpoint, *k1* is the slope and *F2L* is the F2 locus:

Equation 2. LE formula (Klatt, 1987; Flemming, 1995)

$$F2C = k1(F2V - F2L) + F2L$$

F2L can itself be expressed as Equation 3, where *c1* is the y-intercept:

Equation 3. LE formula (Klatt, 1987; Flemming, 1995)

$$F2L = c1/(1-k1)$$

Many recent LE studies comparing multiple places of articulation, such as those in the Australian literature, rely on previous studies conducted by Sussman (such as Sussman *et al*., 1991; Sussman, Hoemeke, & McCaffrey, 1992; Sussman, Hoemeke, & Ahmed, 1993; Sussman, Fruchter, & Cable, 1995; Sussman, Bessell, Dalston & Majors, 1997). These studies typically find high slopes for the bilabial and velar consonants and low slopes for the alveolar, retroflex/palato-alveolar and rhotic consonants, consistent with Recasens' (1985) hypothesis that consonants are less coarticulation resistant - or more highly coarticulated - when they involve weaker constraints on the tongue dorsum (see §2.2).

While Sussman *et al.* (1993) found that for male speakers of Urdu that slope values for the retroflex stop were consistently but only very slightly lower at 0.44 than the dentialveolar values at 0.5, Recasens (2006) points out that retroflexes are typically shown to exert prominent anticipatory coarticulation effects (primarily in American English retroflex /ɹ/) and therefore '[can] be specified for a high degree of articulatory constraint independently of their manner of articulation' (p. 629). Boyce and Espy-Wilson (1997), in their analysis of both the spatial and temporal aspects of F3 trajectories associated with the American retroflex /ɹ/, demonstrate that it is relatively context-insensitive and suggest that 'whether the segment preceding [it] is alveolar, velar, labial, or vocalic does not affect the essential shape or duration of the *F*3 trajectory.' (p. 3751).

Sussman *et al.* (1993) report velar and bilabial slopes values for male Urdu speakers: the velar was associated with the highest slope (0.97) and the bilabial with a moderately high slope (0.81). Sussman *et al.* also published slope values for

Thai, Cairene Arabic and American English speakers. For the Thai speakers, the averaged slope values were lower for the alveolar than the bilabial at 0.3 and 0.7, respectively. Male speakers of Cairene Arabic were also recruited for the study. Of the bilabial, alveolar and velar consonants, the lowest average slope value was given for the alveolar at 0.25, the velar had the highest slope value at 0.92, and the bilabial slope was similarly high at 0.77. It was found for American English that the velar had lower slope values than the bilabial, whereas in the same language, in a separate study, Sussman *et al.* (1991) found the bilabial to have the steepest slope, the alveolar to have the shallowest slope and the velar to have a slope very nearly as high as that of the bilabial.

Following on from Sussman's studies, Tabain (2000) found, in a study of CV coarticulation in Australian English, that velars were associated with the highest F2 slope values, and /ɹ/ and the palato-alveolar fricative were associated with the lowest slope values. The alveolar consonants were intermediate in slope. Sussman's work is discussed further in the next section. LE studies of Australian indigenous languages are discussed in §2.1.2.4.

2.1.2.2 Locus Equations, articulation and coarticulation resistance

There is some inconsistency in the results of studies comparing the LE and articulatory measures of coarticulation. Löfqvist (1999) examined the relationship between the LE and three articulatory metrics for coarticulation in American English. These metrics related to the relative (temporal) onset of consonant and vowel gestures and the magnitude of tongue movements during stop closure and during the vowel following the consonant, in VCV sequences (p. 2024). Löfqvist did not find a consistent relationship between slope values and CV temporal relations (*i.e.*, degree of articulatory overlap). Nor did he find that slope values could be predicted on the basis of the magnitude of tongue movement. He suggested that this mismatch could be due to a non-linear relationship between articulation and acoustics and the influence of adjacent vowels (in particular, the effect of the symmetry or asymmetry of the vowels in the /VpV/ sequences). In other words, he found insufficient support for the expected relationship between LE slope and degree of coarticulation. However, some evidence of this relationship is provided by Tabain (1998) and Iskarous *et al*. (2010). Comparing the LE and the results of an EPG analysis in speakers of Australian English, Tabain (1998) found that the LE is suitable as a gross measure of differences in coarticulation resistance between consonants[17] but is incapable of capturing fine-grained differences such as those between coronal places of articulation. Likewise, Krull, Lindblom, Shia and Fruchter (1995) and Tabain and Butcher (1999) provide evidence that the LE is unable to distinguish between coronal consonants in languages that have numerous coronal consonants, and also to distinguish consonants according to place if manner differs (see Fowler, 1994, for a discussion). Strong evidence for a relationship between LE slope and articulatory data is provided by Iskarous *et al.* (2010). Iskarous and colleagues demonstrated on the basis of articulatory (EMMA and X-ray microbeam) and acoustic data from American English that the LE slope 'is a direct reflection of the extent to which each consonant resists coarticulation with the vowel', and thus, of dorsal constraint (p. 2029).

Fowler and Brancazio (2000) were the first to strongly relate the LE slope method of quantifying CV coarticulation to coarticulation resistance. This articulatory study of American English examined the relationship between V-to-V coarticulation and coarticulation resistance by means of measures of tongue body fronting and tongue body height and acoustic measures of F2 and F1 at consonant release and two later points in the vowel. In the study, two speakers of American English produced CV sequences preceded by /ə/, in which V varied. Low resistant consonants were those associated with a larger frequency difference between vowel contexts. The speakers showed more anticipatory V-to-V coarticulation for low resistant consonants (e.g., /b/) than for high resistant consonants (e.g., /d/) but while consonantal coarticulation resistance affected articulatory evidence for trans-consonantal V-to-V coarticulation, it did not show consistent acoustic effects. In summary, the authors found weak evidence that there is more V-to-V coarticulation across low resistant consonants in American English.

In other studies indicating a relationship between slope values and coarticulation resistance, Recasens (1985a,b) found for Catalan that rankings of labial, dental, alveolar, palatal and velar consonants according to a supplementary metric of F2 formant frequency variation (*i.e.*, standard deviations; see §2.2) were similar to rankings according to slope values. Coarticulation resistance is discussed further in the next section and in greater detail in §2.2.

Locus Equations, linearity and Sussman's place categorisation theory

In several publications, Sussman (e.g., Sussman *et al.*, 1991; 1995) has argued that the F2 transitions to which the LE is applied provide *invariant cues* to consonant place, and that these cues are available because the speaker

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[17] At least, when frequencies are sampled at the burst rather than at the vowel onset.

intentionally produces the linear relationship between the F2 midpoint and F2 onset or offset of a LE precisely because it assists the listener in the categorisation of consonant place (termed the 'Orderly Output Constraint' or OOC; see, e.g., Sussman *et al.*, 1991; 1995; Modarresi, Sussman, Lindblom & Burlingame, 2004).

This argument runs counter to that of Fowler and colleagues, amongst others; anticipating the findings of Iskarous *et al.* (2010), Fowler and Brancazio (Fowler, 1980; 1994; 1998; Brancazio & Fowler, 1998; Fowler & Brancazio, 2000) and Bell-Berti and Harris (1981) demonstrated that the linear relationship between the two measurement points in the LE is the product of an invariant or near invariant magnitude of consonantal resistance to coarticulation by different vowels. By extension, 'the resistance of a consonant to coarticulation is roughly the same across the set of vowels with which it coarticulates' (Fowler & Brancazio, 2000).[18]

According to Fowler (e.g., 1994), the LE does not have a psychological reality as an absolute descriptor of place of articulation because both voicing and manner differences have been shown to affect slope values, as has been mentioned. Moreover, perceptual studies in which the vowel midpoint information is removed have shown good place categorisation of the consonants /b d g/ (Blumstein & Stevens, 1980). Nonetheless, it is clear that the LE remains a useful measure of consonant-vowel coarticulation. Iskarous *et al.* (2010) provide strong evidence that 'the linearity of locus equations and the linear relation between locus equation slopes and intercepts originates in linearity in articulation between the horizontal position of the tongue dorsum in the consonant and to that in the vowel.' (p. 2021).

2.1.2.3 Consonant-vowel coarticulation and the place of articulation imperative

Given the need to maintain perceptual constraints in a language, relative crowding in a particular region is thought to affect (phonetic) output constraints and thus to restrict coarticulation (e.g., Manuel, 1990; 1999). As discussed in Chapter 1, Australian languages typically possess three or four coronal categories, where the fourth category is the (laminal) dental category. Butcher (1995) reasoned that the crowding of the coronal 'area' will lead to heightened articulatory precision and therefore a reduction in (contextual and non-contextual) variability in the

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[18] On this view, the estimate of coarticulation resistance would be stable regardless of whether vowels are considered separately or as a whole. This is claimed to be the case because vowels use similar parts of the tongue and therefore vocalic gestures will be similarly compatible or incompatible with neighbouring consonants (Fowler & Brancazio, 2000, p. 6) but there is some evidence for less than complete invariance of resistance across vowel contexts (e.g., Recasens, 1984b; Carré, 1998; but *cf.* Sussman *et al.*, 1997).

realisation of these coronal consonants (see also, Tabain *et al*., 2004). In a later publication, Butcher (2006) articulated the principle of preservation of place contrasts, as discussed in Chapter 1. On this view, when a language possesses many place of articulation distinctions, cues to place will be protected, at least in intervocalic position (only in word-medial position are all place categories in contrast in the languages considered in this dissertation and it is in this position that formant transition patterns are optimal, as flanking vowels will provide cues to consonant place of articulation; see §1.2). As a result of this protection of place cues, place of articulation information will be carried by neighbouring vowels. The unusually large number of place distinctions in Australian languages, and the small number of manner distinctions, in addition to the large proportion of sonorants to obstruents (typically 70% to 30%), suggests that the maintenance of perceptual contrasts may be reliant on systematic differences in formant transitions at consonant boundaries (Butcher, 2006).

The place of articulation imperative is not only relevant to coronal consonants, but also consonant clusters and nasal segments. Recall that there is an avoidance of synchronic anticipatory coarticulation concerning nasalisation and place of articulation in heterorganic consonant clusters in Australian languages (e.g., Butcher, 2006; Fletcher, Butcher, & Loakes, 2008). Pre-stopping of consonants, as in Arrernte and Gupapuyngu (Butcher, 2006), has also been interpreted as serving to heighten cues at the left edge of the consonant (§1.2.1.1 and §1.2.3.1). (See the following section.) In an extension of the place of articulation principle, a language with few manner distinctions will protect cues to manner only weakly. Accordingly, speakers of Australian languages conflate manner contrasts - as in the lenition of phonemic stops in non-intervocalic positions e.g., both a velar stop and a velar fricative or approximant are present in Arrernte (§1.2.1.1) - but they do not conflate place contrasts (except for the fact that certain contiguous sequences are unattested, such as apical alveolar + retroflex clusters).

Additionally, the imperative operates in the strengthening and lengthening of the medial consonant, as mentioned in §1.2. Recent studies finding some evidence for the place of articulation imperative in the Australian context include Butcher (forthcoming a; 2006), Tabain and Butcher (1999), Fletcher, Stoakes, Loakes and Butcher (2007b) and Fletcher *et al.* (2010) on Kunwinjku (Bininj Gun-Wok), Kroos, Bundgaard-Nielsen, Goldstein and Best (2010) on Wubuy and Tabain *et al.* (2011) on Arrernte and Warlpiri. It is clear that work on Australian languages is particularly important in the investigation of the relationship between coarticulation and consonant inventories. In this dissertation it will be possible to make claims concerning the operation of the place of articulation imperative in C-to-V, V-to-C and V-to-V coarticulation.

Place of articulation and segment edge effects, cues and coupling

Cross-linguistically, the right edge (or release) of the consonant appears to be more perceptually salient than the left edge (Ohala & Kawasaki, 1984; Steriade, 1989; 1991). This is in part because the burst often provides reliable cues to place of articulation (the spectrum of the noise in the burst being principally determined by the resonating cavity in front of the constriction; see Ohala, 1990, p. 265). Given the perceptual importance of this right edge, one might expect greater consonant-dependent coarticulation resistance effects at the onset of V2 in V1-C-V2 sequences. However, Ohala (1990) points out that 'in addition to any phy*sic*al differences between VC and CV cues, *listeners' experience*, *including their native language background*, dictates which cues they pay most attention to' (p. 262; emphasis added). The results of Ohala's (1990) series of perception experiments in American English concerned with assimilation within consonant clusters suggest that there is a richer, more reliable set of place cues in the CV transition (*i.e.* at the right edge of the consonant) than the VC transition (*i.e.*, the left edge) (p. 265). His interpretation of these results was that the listener was guided by experience in analysing the cues in speech, and that 'the lack of salience of the VC transitions [was] mediated by linguistic experience' (p. 265; see also Traunmüller, 1999). By extension then, there may be language-specific variation in perceptual salience at consonant-edges.

If a reduction in V-to-C coarticulation occurs in the VC context, then this may indicate a protection of perceptual cues associated with the left edge of the consonant (see also §1.2.1.5 on the syllable in Arrernte).[19] This apparent protection has been observed in consonant clusters in Gupapuyngu and Warlpiri (Butcher, 2010), in Wubuy (Bundgaard-Nielsen, Baker, Harvey, Kroos, Best & Goldstein, 2009) and also in Arrernte in phonemic pre-stopping (Breen & Dobson, 2005).

Place of articulation and word-medial strengthening

In Australian languages, the word-medial or 'post-tonic' consonant appears to possess a special status, undergoing lengthening and strengthening, as in Warlpiri (e.g., Harrington *et al.*, 2000a; Pentland & Laughren, 2004; Butcher & Harrington, 2003; Butcher, 2004; see §1.2.4.5 and §2.4.2), and in palatals in Arrernte (Tabain

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[19] However, it is clear that further research should be done to provide evidence to support this claim.

et al., 2011), in Djapu (Morphy, 1983), in Nhanta, a language of Western Australia (Blevins & Marmion, 1994) and in Yolngu and Gunwinguan languages in general (Butcher, 2006). Given that post-tonic strengthening applies to the word-medial consonant, in a position in which all consonants are in contrast, it might be expected that here (in the VC transition) the spectral changes necessary to place of articulation distinctions will be perceptually optimised (Butcher, 2006). In other words, the transition between the consonant and vowel in VC contexts is more protected than it is in languages such as English, in which the transition in CV contexts is more protected (both in terms of spectral information and duration) (e.g., Harrington *et al.*, 2000a; Tabain *et al.*, 2004; see §1.2.1.5 and §2.1.2.4). Prosodic effects on coarticulation are discussed further in §2.4.

The present study will extend the Australian literature on medial strengthening by examining the effect of word-medial consonant place of articulation on vowels in the context of C-to-V and V-to-V coarticulation.

2.1.2.4 Previous studies of consonant-vowel coarticulation in Australian languages

Given the proposed relationship between coarticulation resistance and the nature of the consonant inventory (see §2.2) and the large number of place of articulation contrasts in Australian languages, particularly in the coronal region (§1.2), it is clear that the LE can be a useful tool with which to explore these languages. LE studies of Australian languages have mostly been conducted by Tabain and colleagues (e.g., Tabain, 2000; 2002; Tabain & Butcher, 1999). The findings for these languages can be summarised as follows: LE slopes are known to exceed 1[20] for these languages, especially for velar consonants (see, e.g., Tabain & Butcher, 1999) and CV and VC slope values tend to be relatively similar (Tabain *et al.*, 2004).

In their study of consonant-vowel coarticulation, Tabain *et al.*, (2004) found greater similarity between the CV and VC trajectory periods for Australian languages, Arrernte, Yanyuwa and Yindjibarndi (also known as Yindjiparnti), than for Australian English. For the Australian English speakers, they expected CV slope values to be lower than VC slope values on the basis that

> 'if a consonant is found to be LESS affected by the following vowel context than by the preceding vowel context, that consonant is organized as part of a

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[20] Values smaller than zero or greater than 1 are statistically unrealistic. Such values are generated by the standard Locus function in the Emu-R package. See Chapter 3 for full details of the methodology employed in this dissertation. For a discussion of slope values of greater than 1 for the velar consonant, see Lindblom, Krull and Sussman (2010).

> CV syllable. It can be argued that if coarticulation is at a minimum, the speaker has planned that sequence carefully, attempting to maximise the identity of both the consonant and the vowel.'
>
> (p. 179)

For the Arrernte speaker, the authors anticipated higher CV slope values than VC slope values, due to a proposed underlying VC(C) syllable. It was found that while in English, CV slope values were lower than VC slope values, Arrernte, slope values were similar in the two contexts. Tabain *et al.* (2004) contend that it may be necessary for a language to control spectral cues equally in CV and VC contexts when it has a large number of place contrasts and not manner contrasts in the consonants. The authors suggest that the results are consistent with an underlying VC syllable. Elsewhere, Tabain (2009b) has argued that Arrernte 'is the strongest example of an Australian language with an underlying VC syllable structure' (p. 36).

Tabain and Butcher (1999) employed the LE in addition to a measure of variability in the onset of the vowel in the same CV sequence. The authors found for Australian languages, Yanyuwa and Yindjibarndi, that peripherals (e.g., /p k/) possess higher slope values, and laminals such as palatals possess lower slope values, with slope values of apical consonants such as alveolars of an intermediate size. Apicals tended to have higher slope values than laminals. Tabain and Butcher interpret this to suggest that the tongue body is freer in an apical than in a laminal articulation, which indicates a negative correlation between lingual anteriority and coarticulation resistance such that the greater the anteriority, the lower the resistance. The authors found greatest variability at the onset of the vowel following the consonant when the consonant was peripheral (bilabial or velar). Both stops also showed the highest degree of coarticulation on the LE measure. The laminal consonants, including the palatal stop, showed the least coarticulation, and the apical consonants, the alveolar and the retroflex, were generally intermediate. The F2 transition results showed a great deal of overlap in formant frequencies between consonants. This pattern of velar stop behavior has been associated with the well known finding that velar stops possess a more anterior constriction when adjacent to front vowels than when adjacent to low and back vowels (English: Dembowski, Lindstrom & Westbury, 1998; English, Czech and Hungarian: Keating & Lahiri, 1993; French: Corneau, Soquet, & Demolin, 2000; Catalan: Recasens & Pallarès, 2001). The similar results for the bilabial were said to be due to an unconstrained tongue, free to anticipate the following vowel. Greater inter-speaker variability in anterior consonantal articulations (alveolar and dental), it was suggested, 'may be an indication that the degree of coarticulation between the consonant and the vowel is a function of the entire vocal tract configuration (*i.e.* passive articulator as well as active articulator).' (Tabain & Butcher, 1999, p. 352)

Butcher and Tabain's (2004) study of dorsal consonants in Australian English, Yanyuwa and Yindjibarndi included both acoustic data and palatographic data. It reported slope values for Australian English and Yanyuwa and Yindjibarndi speakers. Slope values for the Australian language speakers tended to be higher than those of the Australian English speakers. For all Yanyuwa and Yindjibarndi speakers, the velar slope value was just over 1, indicating maximal coarticulation. The authors also included a speaker of Arrernte, RF; this speaker's velar slope value was slightly lower at 0.76. They argued that this slope value is relatively low because there were no velar-front vowel, /ki/, tokens.

The present study will extend the examination of consonant-vowel coarticulation in Australian languages by adding to the previous work on Arrernte and Warlpiri and providing new analyses of Burarra and Gupapuyngu. An important component of this study will be the analysis of coarticulation resistance, which is discussed in the following section.

2.2 Coarticulation resistance

In investigating the role of consonant place of articulation and of vowel quality in coarticulation in the present study, comparisons will be made with regard to the magnitude of resistance to coarticulation. Coarticulation resistance is defined by Recasens and Espinosa (2009a) as '… a measure of [a segment's] degree of articulatory variability as a function of phonetic context.' (p. 2288) This resistance arises from the interaction between coarticulation and biomechanical and linguistic (language-particular) constraints and appears to be greater when (i) when perceptual distinctions must be maintained; (ii) when a segment is inherently strong articulatorily; relatedly, (iii) when there is 'spatial overlap' (the sharing of articulators by adjacent or near adjacent segments) or interarticulator 'coupling', e.g., tongue-body and tongue-tip coupling; and (iv) when articulatory strengthening of segments is induced by prosody or pragmatics (Recasens, 1985, p. 105; Fowler & Saltzman, 1993).[21] According to Farnetani (1999, p. 398), the greater the extent to which two contiguous articulatory gestures share common articulators, the greater the relevance of (relative) coarticulation resistance, such that the more resistant gesture will reduce the influence of the less resistant gesture (see also Fowler & Saltzman, 1993). These factors are discussed further

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[21] The phrase 'articulatory strength' is here used in the sense of Keating, Cho, Fougeron and Hsu (2003) such that articulatory gestures that are stronger, or more extreme, *i.e.*, larger in magnitude and/or duration, are greater in strength than gestures that are smaller.

below. Recasens' DAC model, which primarily accounts for the factors given in (ii) and (iii) but allows for an incorporation of factors given in (i) and (iv), is discussed in §2.2.1.

Coarticulation resistance is typically quantified by means of the LE (Fowler & Brancazio, 2000; see §2.1.2) and by calculating the standard deviation of formants (F2) at the consonant-vowel boundary for a consonant across a range of vowels (as discussed in §2.1.2.2). Low variability (small standard deviations) indicates a high degree of articulatory constraint exerted by the consonant on articulation and therefore on F2 at consonant release (Recasens, 1985). Both metrics then assume uniform degrees of coarticulation on consonants across vowel contexts (Carré, 1998; Recasens & Espinosa, 2009a,b).

The first coarticulation resistance study was undertaken by Bladon and Al-Bamerni (1976) for /l/ coarticulation in British Received Pronunciation (RP) English. The authors describe coarticulation resistance as a property that they propose is 'associated with phonetic specifications for speech segments in the form of [numerical] values whose magnitude varies' (p. 138). The authors' spectrographic study showed that the influence of adjacent voiceless stops on the degree of voicelessness in the laterals decreases from clear, dark to dark syllabic 'l'. The CR value is determined by a number of universal, language-specific, speaker-specific, and context-specific factors. They argue that '[a]ntagonistic vocal tract adjustments apart, coarticulation is inhibited only by coarticulation resistance (CR) at some point in the succession of speech events.' (p. 149) Other notable studies of coarticulation resistance include Bladon and Nolan (1977) for English, Recasens (1985), for Catalan, Engstrand (1981; 1983), for Swedish, Farnetani (1990), for Italian, Kühnert, Ledl, Hoole, & Tillmann (1991), for German, and Fowler and Brancazio (2000), for American English.

Various studies have demonstrated that coarticulation resistance is found when it prevents the confounding of paradigmatic contrasts by heightening phonetic clarity. In other words, speakers can protect 'phonetic gestures against coarticulatory influences that would interfere with achievement of the gestures' phonetic goals' (Fowler & Saltzman, 1993, p. 180). Additionally, coarticulation resistance is displayed by segments that are inherently strong articulatorily, because of the magnitude of dorsal-palatal contact (*i.e.*, contact between the upper surface of the tongue and the palate in lingual consonants) and/or tongue dorsum elevation, because of the formation of a double place of articulation (Recasens, 1984a,b; 1985; 1987; 1989; Farnetani, 1999, p. 398) and/or because of the biomechanical inertia involved (e.g., in palatal and dorsal consonants, see Recasens 1984b; Recasens & Farnetani 1990; Recasens *et al.*, 1997). A consonant requiring a very precise articulatory gesture – such as /s/, which requires the formation of a medial groove - will be more constrained articulatorily and thus more resistant to coarticulation (Recasens, 1997, p. 545). Therefore, as was suggested in §2.1.2.2, consonants potentially differ in resistance according to both place and manner of articulation (Australian English: Tabain, 2000, pp. 140-141; Catalan: Recasens, 1997, p. 545; American English: Fowler, 1994; but *cf.* American English: Sussman *et al*., 1995; Arrernte and Warlpiri: Tabain *et al.*, 2011). Both consonants and vowels differ in resistance (Recasens, 1997, p. 545).[22] This is because a major factor affecting the extent to which a segment resists coarticulatory overlap is the magnitude of dorsal constraint for that segment. Furthermore, the extent to which vowels exert V-to-C effects on adjacent consonants appears to relate to the degree of tongue dorsum constraint (as previously suggested), as does the onset of vowel-dependent coarticulation (Recasens, 1999).

In many studies, palatals tend to be relatively resistant compared to, for example, bilabials. Palatals, like /j/, involve a highly constrained articulation; the tongue dorsum is raised and fronted, allowing little dorsum variability (Hoole *et al*., 1990). Velars can be highly resistant because of the mechanico-inertial properties (sluggishness) of the primary articulator: the tongue dorsum. Labials tend to be less resistant than lingual consonants because they lack obvious articulatory constraints; the lip-rounding gesture does not intervene with tongue-body activity (Hoole *et al.*, 1990). Alveolars tend to display less coarticulatory variability than labials (Recasens, 1999), but more than palatals (e.g., Tabain & Butcher, 1999; see §2.1.2).

With regard to coarticulation resistance in vowels, /i/ has been shown to be highly resistant in several languages (e.g., American English: Stevens & House, 1963; Dutch: Pols, 1977; Catalan: Recasens, 1985). This appears to be due to a large magnitude of predorsum activation (or front dorsum raising). Stevens and House (1963) calculated C-to-V effects in American English CVC sequences by subtracting the vowel formant frequencies from those of the same vowel in a ‘null’ context. The vowel formants were shown to vary according to consonantal context. /i/ was least variable according to consonantal context. It is highly resistant because it involves a very constrained articulation; the tongue dorsum is both raised and fronted, allowing little dorsum variability (Hoole *et al.*, 1990). /i/ is known to exert V-to-C coarticulatory effects in tongue dorsum raising and fronting, *i.e.*, to be coarticulatorily ‘aggressive’ (Recasens, 1984a,b; see §2.2.1 on the relationship between coarticulation resistance and aggressiveness in the DAC

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[22] Vowels indeed exhibit constriction locations, although they involve less linguo-palatal contact than consonants (Wood, 1979; Recasens, 1985).

model), so, for example, Sussman, Hoemeke and McCaffrey (1992) showed that when LE slope values are plotted against intercepts, the consonants are less distinguishable according to place of articulation when occurring before /i/ than before /a/ (see §2.1.2). With regard to other vowels, Butcher (1989) found that /a/ is more susceptible to coarticulation by /i/ than is /u/ in English. Schwa is generally shown to be highly sensitive to coarticulatory effects from adjacent consonants as would be anticipated given the relative lack of dorsal constraint. According to Recasens (1984b), this is in accordance with the fact that 'for a vowel articulated with an idealized open tube, any constriction difference along the vocal tract has a marked effect on all formant frequencies' (p. 109). Given that the magnitude of coarticulatory sensitivity for vowels increases for /i/</a/ (Recasens *et al.*, 1997, p. 546), /i/ tends to be more coarticulatorily aggressive than /a/ (Recasens & Espinosa, 2009b; see §2.2.1).

Vowels in prosodically strong positions tend to resist coarticulation more than do vowels in weak positions. Several studies have shown that prosodically prominent segments tend to be more resistant to coarticulation by other segments (Fowler, 1981a; de Jong, Beckman, & Edwards, 1993; Magen 1997; Beddor, Harnsberger & Lindemann, 2002). Cho (1999; 2004) found for American English that point vowels [i a] tend to be hyper-articulated (see §2.3) in accented syllables and/or in domain-initial or -final position and are more resistant to coarticulation by neighbouring vowels.

As was identified in §2.1.1, there is evidence not only for a relationship between coarticulation resistance and consonant-vowel or vowel-consonant coarticulation, but also for a relationship between coarticulation resistance and V-to-V coarticulation (where the former is said to have an impact on the latter) (Recasens, 1984a; Recasens 1997, p. 546; Fowler & Brancazio, 2000, e.g., p. 28) but the resistance effects on V-to-V coarticulation are not necessarily manifested acoustically (in F1 or F2) in a consistent manner (p. 31). The temporal and spatial magnitude of V-to-V coarticulation appears to vary inversely according to the degree of tongue dorsum elevation or raising required for the intervocalic consonant, such that a palatal consonant, which requires more tongue body raising, constrains V-to-V coarticulation more than an alveolar, which requires less raising (Recasens, 1984a,b; 1987; 1989; 1991). Dorsal consonants in general appear to permit less V-to-V coarticulation than, say, bilabial consonants, as found for /k/ by Butcher and Weiher (1976) and Butcher (1989).

In this study, it will be possible to examine the relationship between C-to-V, V-to-C and V-to-V coarticulation and coarticulation resistance and to determine whether consonant places of articulation differ consistently in their capacity to resist and exert coarticulatory effects. It will also be possible to determine whether there are vowel quality and prosodic prominence effects on coarticulation resistance. The model of coarticulation resistance employed in these analyses is the DAC model, which is discussed in the next section.

2.2.1 Recasens' DAC model of coarticulation resistance

Recasens and colleagues (e.g., Recasens *et al.*, 1997) have developed a model termed the 'Degrees of Articulatory Constraint', or DAC, model, within the framework of a coproduction or gestural approach to speech production (as discussed in §2.1.1). This model formalises the relationship between coarticulation and articulatory constraint (principally, tongue dorsum constraints) and provides an account of articulatory conflict, with substantial evidence from acoustical and EPG data mainly from Catalan (e.g., Recasens, 1984a,b; 1985; Recasens & Pallarès, 2000; 2001) but also from Italian (Recasens, Farnetani, Fontdevila, & Pallarès, 1993), German (Recasens, Fontdevila, & Pallarès, 1995) and English (Recasens, 1989). Recasens' claim is that

> 'the degree of compatibility between a given gesture and adjacent gestures decreases with the degree of articulatory constraint. Thus, highly constrained gestures ought to block coarticulatory effects to a larger extent than gestures specified for lesser degrees of articulatory constraint.'
>
> (1986, p. 71)

The DAC model predicts that consonants that are maximally constrained (e.g., /c/, with a DAC value of 3, or /s ɫ r/, with a value of 4) will prevail upon less constrained ones (e.g., /t/, with a value of 2, or /p/, with a value of 0), while adjacent relatively unconstrained consonants may undergo articulatory blending (the blending or combining of information associated with two or more overlapping gestures).[23] With regard to coarticulation in VCV sequences in particular, an increase in the degree of articulatory constraint for a given consonant should result in an increase in the magnitude of the C-to-V effects and a decrease in the magnitude of the V-to-C and V-to-V effects (e.g., Recasens, 1984a,b; see also Byrd, 1996).

According to Recasens, the DAC model addresses the need for a model of coarticulation that can predict how much coarticulation will be permitted by a given segment and how it in turn will affect other, neighbouring, segments (Recasens *et*

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[23] According to Wood (1996), when gestures are in conflict, they may also be produced sequentially.

al., 1997, p. 544), that is sufficiently specific to account for a large number of articulatory types and patterns and

> ‘that makes no assumptions as to the vocalic or consonantal nature of the phonological segments under control. According to this view, … contrasting vowels and consonants differ as to the extent to which they allow context-dependent effects to occur and, thus, can be categorized according to contrasting degrees of ... resistance to coarticulation.’
>
> (Recasens, 1985, p. 98)

That is to say, the model is primarily concerned with generalised gestural specifications. The claim that a consonantal gesture will override or dominate a vocalic gesture if the two are antagonistic (Recasens, 1985, p. 112), presumably derives from the observation that vowels involve less linguo-palatal contact (p. 111).

The model assumes that coarticulatory resistance and coarticulatory aggressiveness are positively correlated. It appears that at least in some contexts, those segments that are most resistant to contextual variation also induce the greatest contextual variation in neighbouring segments (the ‘coarticulatory aggression effect’), *i.e.*, are most coarticulation aggressive (Bladon & Nolan, 1977; Farnetani, 1990; Fowler & Saltzman, 1993; Recasens, 1997; Recasens & Espinosa, 2009a; Recasens, 2012; but *cf.* e.g., Cho, 2001; 2004). Recasens outlines the relationship between degree of articulatory constraint, coarticulatory resistance or context-sensitivity, and coarticulatory aggressiveness or aggression, thus: ‘degree of articulatory constraint is inversely related to coarticulatory sensitivity (i.e., the extent to which a segment allows the coarticulatory influence of another segment) and directly related to coarticulatory aggressiveness (*i.e.*, the extent to which a segment exerts coarticulatory effects on another segment)’ (2006, p. 614). To put it differently, the degree to which a segment coarticulates with others - both how it is coarticulated by others, and how it induces coarticulation in others - appears to depend on its general capacity to resist coarticulation by other segments, and hence the degree of constraint involved in its articulation (e.g., Recasens *et al.*, 1997).

There is strong evidence that DAC values should be modifiable on the basis of language-specific articulatory patterns and constraints on variability (just as Bladon and Al-Bamerni recognised in their 1976 CR model), as has been recognised by Recasens (e.g., Recasens *et al.*, 1995; 1997; Recasens & Espinosa, 2005). In an EPG study of consonant clusters, Bombien, Mooshammer, Hoole and Kühnert (2010) found that the clear German /l/ appears to be darker than its equivalent in other languages and so the German clear /l/ should be assigned a higher DAC value than the clear /l/ in the standard model. It could also be suggested that the DAC model should be modified so as to be able to capture the several other factors, such as prosodic ones, that lead to cross-linguistic and inter-speaker differences in coarticulation resistance. As stated by Recasens (1985, p. 98), the DAC model is able to account for context-dependent effects such as those relating to prosodic prominence, which is discussed in §2.4.

2.3 Coarticulation and the theory of Adaptive Variability

Several studies address the speaker-oriented motive of economy of articulatory effort in coarticulation, which is balanced by the listener-oriented need for sufficient perceptual distinction or clarity of speech. Clarity of speech (see also §2.2 and §2.4) has been associated with reduced coarticulation within the limits imposed by articulatory biomechanics, and with larger articulatory movements and longer durations (e.g., Perrier, Payan, Zandipour, & Perkell, 2003; but *cf.* Matthies, Perrier, Perkell, & Zandipour, 2001). This adaptation of speech production to perceptual demands by the speaker has been termed ‘adaptive variability’ (Lindblom, 1983; 1989; 1990).

In Lindblom's (e.g., 1990) hyper- and hypo-articulation theory, speech varies from clear to less clear. The principles of Lindblom’s theory can be related to variability in the production of segments and thus to coarticulation (Tabain 2001). In clear speech, there may be an expansion of the vowel space such that vowels move away from the overall centroid of the space, termed the ‘grand centroid’. Vowel space expansion is also seen to occur in accented words, which are likely to be produced clearly by the speaker (see, e.g., de Jong, 1995; Harrington, Fletcher, & Beckman, 2000b; see §2.4 for a discussion of recent prosody-related findings in Australian languages). Hyper-articulation is not only associated with clear speech but also with prosodic boundary marking and prosodic prominence or focus, *i.e.*, hyper-articulation can be localised to the syllable (see, e.g., de Jong, 1995; Cho, Lee, & Kim, 2011). Languages are known to differ in their realisation of hyper-articulation (e.g., Cho *et al.*, 2011).

The hyper-articulation model offers an alternative view to the ‘sonority expansion’ model (Beckman, Edwards & Fletcher, 1992; Edwards, Beckman, & Fletcher, 1991; but see Fletcher & Harrington, 1995). It claims that speakers enhance the articulation of non-sonority contrasts under conditions of stress (e.g., a back vowel may be more retracted under stress, see de Jong, 1995; see also Lindblom *et al.*, 2007 on coarticulation and stress).[24]

Changes in both vowel quality and length may be brought about by segmental and prosodic contexts (see §2.4). Lindblom (1963) found that acoustic targets in the vowel are often not achieved. He called this 'undershoot' (see also Stevens & House, 1963; Koopmans van-Beinum, 1980). He found that short or lax and long or tense vowels gave different observed results in Swedish symmetrical CVC environments;

> '[a]s the vowel becomes shorter, there is less and less time for the articulators to complete their "on-" and "off-glide" movements within the CVC syllables ... In the acoustic domain, this is paralleled by undershoot in the formant frequencies'.
>
> (p. 1779)

There is a positive relationship between vowel undershoot and coarticulation, such that if undershoot increases, then so does coarticulation. This is because undershoot is a consequence of the increased overlap of muscular commands, and occurs because of the inertia of the articulatory system (Recasens, 1985). A decrease in undershoot and coarticulation will typically occur if duration increases and/or the segment is accented (Edwards *et al.*, 1991). However, the term 'undershoot' can be used to describe the vowel formant shift in any type of vowel reduction, including coarticulation. Formal models of acoustic vowel reduction as a function of speech rate have been proposed by Lindblom (1963) and van Bergem (1993; 1995).

Consonants can also undergo (localised) hyper-articulation driven by clear speech or prosody. For example, a phonemic plosive may involve a greater gestural magnitude when in a prosodically prominent or post-boundary (domain-initial) position. Greater gestural magnitude may be linked to a decrease in coarticulatory overlap (Fletcher & Harrington, 1999; de Jong *et al.*, 1993). See further, §2.1.2.3 on word-medial strengthening (see also §1.2.4.5 on post-tonic strengthening in Warlpiri). Theories of the particular realisation of vocalic hyper-articulation termed vowel space expansion or vowel dispersion are discussed in the following section.

2.3.1 Vowel dispersion theories

Joos (1948), after Essner (1947), demonstrated the relationship between F1 and F2 such that the former is negatively correlated with phonetic vowel height and F2 is negatively correlated with vowel backness. A diagram resembling a vowel

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[24] It should be noted that the hyper-articulation and sonority expansion models are not always confounded, e.g., in the case of cavity expansion when /i/ is hyperarticulated.

quadrilateral is produced by plotting vowels in the decreasing F1 x F2 plane. Many more recent studies show the importance of this F1 x F2 plane to judgments of vowel quality (see, e.g., Harrington & Cassidy, 1999; Harrington, 2010a). The theory that the distinctive sounds of a language tend to be positioned in the F1 x F2 acoustic space such that perceptual contrasts are maximised or otherwise optimised has been termed 'adaptive dispersion' (Liljencrantz & Lindblom, 1972; Lindblom & Engstrand, 1989; Lindblom, 1990). This theory is contrasted with the phonetic 'hot spot' and Quantal theories (see, e.g., Sussman, Hoemeke & Ahmed, 1993; Stevens & Blumstein, 1975; but *cf.* Livijn, 2000; Disner, 1984).

The principle of 'maximal dispersion' states that the vowels of a language will be dispersed maximally and evenly within the available phonetic space (Lindblom, 1963; Liljencrants & Lindblom, 1972). It has been argued that the arrangement of the vowels within the phonetic space is mainly determined by the number of vowels (Crothers, 1978, p. 100). According to Becker-Kristal (2010),

> 'maximisation of dispersion is typically achieved when vowels are evenly spaced, that is, when the shortest between-vowel distance in the inventory is repeated in many vowel pairs.'
>
> (p. 155)

Adaptive dispersion, or dispersion theory, predicts that any change in the number or distribution of vowels will be manifested in an acoustic reorganisation of these vowels and consequently in systematic differences in vocalic F1 x F2 specifications. Each vowel is said to act as a 'repeller' in a dynamic system. Dispersion theory accounts for a cross-linguistic preference for 'corner' or 'point' vowels, because these vowels can be reliably distinguished from one another, regardless of the size of the inventory.

In a modified version of the principle of maximal dispersion, the magnitude of dispersion is merely that which is necessary, and articulatory economy is balanced by perceptual distinctiveness. The 'sufficient dispersion' principle was developed by Lindblom (1986; 1990) and Lindblom and Maddieson (1988), for whom the principle is specified as a diachronic one;[25] an increase in the number of vowels in a system should cause that system to expand.

Strong support for dispersion theory is provided by a recent survey of two hundred and thirty of the world's languages (Becker-Kristal, 2010), which demonstrated that languages differing in the number of peripheral vowels will differ also in the F1 span of the acoustic vowel spaces, while languages differing in the

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[25] See Ohala, 1981.

number of non-peripheral vowels will differ in the F2 span of the vowel spaces. Becker-Kristal found that

> 'entire inventory formant spans and area sizes were ... positively correlated with the number of vowels in the inventory, with the number of peripheral vowels affecting the F1 dimension more, and the number of non-peripheral vowels affecting the F2 dimension.'
>
> (2010, p. 168)

With regard to vowel dispersion and coarticulation specifically, it appears that the smaller the magnitude of coarticulation resistance in a vowel, the greater its dispersion from the centre of the vowel space in various consonantal contexts (e.g., Catalan: Recasens and Espinosa, 2009c). Additionally, adaptive dispersion theory predicts that in a smaller vowel space, vowels should be freer to undergo contextual variability, because there should be more acoustic space available (Recasens & Espinosa, 2009c, p. 244; after Lindblom, 1986). However, there is only limited evidence to support this claim (Shona & English: Manuel, 1990; but *cf.* e.g., Mandarin and Cantonese: Mok, 2006; Shona & English: Beddor *et al*., 2002).

2.3.2 Vowel systems, variability and dispersion and V-to-V coarticulation

Following from above, a language possessing a smaller vowel system might be expected to tolerate greater variability in production (as suggested by, e.g., Dixon, 1980; Manuel & Krakow, 1984; Manuel, 1990; 1999; *cf.* Recasens & Espinosa, 2009b). Recall that the prediction (according to dispersion theory, see §2.3.1) is that in order to maintain sufficient 'distance' between vowels, the more crowded (or dense) the inventory, the more precise the realisation, whereas a smaller inventory will permit greater variation. However, both the magnitude of coarticulation and the organisation of coarticulation may be affected by several factors in addition to inventory size, including sociolinguistic factors (e.g., English, Shona, Ndebele, Sotho: Manuel, 1999), the identity of the segment (e.g., Swedish, English, Russian: Öhman, 1966; Catalan: Recasens, 1985a,b), and prosodic variables, including stress and timing patterns (e.g., English: de Jong *et al.*, 1993; Cho, 2004), in addition to language-specific phonological processes such as vowel harmony (e.g., Turkish: Boyce, 1990; Warlpiri: Nash, 1986; Jingulu: Pensalfini, 2002; see also Ohala, 1993) and consonant harmony (e.g., Kinyarwanda: Walker, Byrd, & Mpiranya, 2008; Central Arrernte: Tabain, 2009a).

In vowels, there is some evidence of a relationship between the size of the vowel inventory and the magnitude of V-to-V coarticulation (Manuel, 1990; 1999; but *cf.* Livijn, 2000; Mok & Hawkins, 2004). (Schwa appears to have a special status, as discussed in previously in §2.1 and §2.2.) Manuel (1990; 1999) addressed V-to-V coarticulation in several African languages. The author argued that such coarticulation was limited in those languages possessing more vowels, and, by extension, was limited by the demands of phonemic contrast. In a language possessing both high-mid and low-mid vowels, V-to-V coarticulation in [a] was limited when compared to a language possessing only one mid vowel. Similarly, in the Australian context, Dixon (1980) found that in languages with small vowel inventories there was a high magnitude of allophonic variation. He argued that the perceptual distance between the vowels must be sufficient, despite this variability. The implication was that in a language with a more crowded vowel space, coarticulation will be smaller in magnitude. Coarticulation may also commence earlier (Manuel, 1990). Arguably, this allows the speaker to achieve the target position with greater accuracy in order to preserve meaningful contrasts between vowels (Lubker & Gay, 1982; Martin & Bunnell, 1982; Ohala, 1981; Beckman & Shoji, 1984; Recasens, 1985).

Results reported by Livijn (2000), however, do not support the claim that the magnitude of V-to-V coarticulation is limited by the number of phonological contrasts. Livijn examined twenty-eight vowel inventories of various sizes with regard to a relationship between inventory size and the acoustic distance between the point vowels /i a u/. He concluded that 'languages use additional means for accommodating elements in crowded vowel spaces', with the addition of other dimensions such as length or nasality (see also Lindblom *et al.*, 2010).[26] Becker-Kristal (2010) argues that Livijn's (2000) failure to find a correlation between the number of vowels in a system and the size of the acoustic vowel space was due to a relatively small corpus (twenty-eight languages compared to Becker-Kristal's two hundred and thirty).

These findings are relevant to the discussion of coarticulation because the four Australian languages examined in the present dissertation, like those examined by Dixon (1980), possess small vowel inventories and a large number of consonant places of articulation. This dissertation will attempt to describe vowel variability and dispersion and V-to-V coarticulation with regard to the effects of inventory size, coarticulation resistance, and prosodic context, and to explore whether vowel realisation in the four languages can be explained by the principles of dispersion theory. The effects of prosodic context on coarticulation are discussed further in the next section.

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[26] In fact, Lindblom and Maddieson (1988) showed that secondary articulations develop when a system becomes too large for clear perceptual distinctions in the acoustic vowel space. Vallée (1994) and Schwartz *et al*. (1997a,b) claim that the upper limit for a viable system without secondary articulations is nine.

2.4 Effects of prosody on coarticulation

In this section, the relationship between coarticulation and prosody will be discussed, with regard to stress and accent effects (§2.4.1), articulatory strengthening and syllable and word effects (§2.4.2), and prosody and articulatory strengthening in the Australian language context (§2.4.3).

It is known that prosodic structures are reflected both spatially and temporally in articulation (e.g., Beckman *et al.*, 1992; Fougeron & Keating, 1997; Byrd & Saltzman, 2003; Cho & Keating, 2009). Numerous studies relate prosody and coarticulation in particular (e.g., Fowler, 1981a; Krull, 1989; Farnetani, 1990; Smith, 1995; de Jong, 1995; Byrd, Kaun, Narayanan & Saltzman, 2000; see Krakow *et al*., 1995, p. 78). However, coarticulation is merely one of a number of phonetic properties of individual segments that interact with prosodic prominence and position. The interaction between coarticulation and prosody involves prosodic prominence effects in vowels and consonants, temporal effects, and consonant and vowel harmony as lower level prosodic effects (on vowel harmony in Warlpiri, see §1.2.4.6).

2.4.1 Stress and accent effects

A number of studies suggest that stressed segments are less coarticulated with adjacent segments than are unstressed segments (e.g., Fowler, 1981a; de Jong *et al.*, 1993; Cho, 2005; Bombien *et al.*, 2010; see §2.1.2 and §2.3). Fletcher and Harrington (1995) and Harrington, Fletcher and Roberts (1995) examined the kinematics of accented and unaccented syllables in Australian English. The unaccented vowels were seen to resemble truncated rather than rescaled accented vowels (as found by, e.g., Beckman *et al.*, 1992), *i.e.*, unaccented vowels were more influenced by competing demands on the same articulator by incompatible gestures than were accented vowels.

The effects of accent may differ according to position within the prosodic domain. Vayra and Fowler (1992) found for the vowel /a/ in Italian that F1 and jaw opening decreased progressively for stressed vowels across initial, medial and final syllables (analogous to declination of fundamental frequency) while unstressed vowels showed least jaw opening and F1 decrease in medial syllables. A reduction of coarticulation within stressed syllables appears to be the main articulatory correlate of stress in American English (de Jong *et al.,* 1993). de Jong *et al.* (1993) utilised X-ray microbeam instrumentation to examine tongue, jaw and lip movement for three speakers who produced accented and unaccented syllables in context. The authors drew a link between their finding of reduced coarticulation under conditions of stress and hyper-articulation (after Lindblom, 1990; see §2.3). In a later microbeam study, de Jong (1995) argued that segments in pitch accented syllables in American English resist coarticulation with neighbouring segments. Similarly, Farnetani (1990) showed that smaller V-to-C effects in linguo-palatal contact occur for dental stops in Italian in stressed versus unstressed syllables (in an EPG study).

Cross-linguistically, the effects of stress and accent appear to be strongest in the vowel or syllable nucleus (Beckman & Edwards, 1994; Sluijter, 1995; Cho & Keating, 2009; Bombien *et al*., 2010; see §2.4.2). One of the more consistent findings in the literature is that vowels at higher levels of prosodic prominence tend to be produced with greater acoustic expansion or peripherality or with more extreme gestures in European languages (Dutch: Koopmans-van Beinum, 1980; English: Beckman & Edwards, 1994; de Jong, 1995; Cho, 2004; 2005; German: Mooshammer & Fuchs, 2002). For example, Palethorpe, Beckman, Fletcher, & Harrington (1999) and Harrington *et al.* (2000b) found for Australian English that prosodically prominent /i/ is produced with a higher tongue position (but not necessarily a higher jaw position) than prosodically weak /i/.

2.4.2 Articulatory strengthening and syllable and word boundary effects

As suggested in §2.1.2, there is a link between coarticulation resistance, articulatory strengthening and prosodic-domain edges (e.g., Fougeron & Keating, 1997, p. 3737; Cho, 1999; 2004; Keating, Cho, Fougeron, & Hsu, 2003). Syllable-, word-, and phrase-initial (*i.e.*, prosodic domain-initial) positions seem to be 'generally characterised by more "forceful" articulatory gestures' (Fujimura, 1990, p. 232). This strengthening increases information about a segment's identity in 'those positions where such information is most important' (Keating, 2006). On this view, utterance-, word-, and syllable-initial consonants will be longer and involve more lingual contact with the palate than corresponding prosodic domain-final consonants. In fact, according to Cho and Keating (2009), domain-final lengthening is 'one of the most conspicuous phonetic hallmarks of prosodic structure' (p. 466; see also Beckman *et al*., 1992; Byrd, 2000; Cho, 2006, amongst others).

With regard to syllable boundaries, on an articulatory strengthening hypothesis (see, e.g., Fougeron & Keating, 1997), syllable onsets are less variable than offsets. In this way, coarticulation patterns may indicate syllable structure. Additionally, as discussed in §1.2.1.5 and §2.1.2.4, if a consonant is affected less by the preceding vowel than the following one, then it may be argued that the consonant and vowel are organised as part of a VC syllable, whereas if it is affected more by the preceding vowel, it is part of a CV syllable (after Tabain *et al.*, 2004).

2.4.3 Prosody and coarticulation in Australian languages

Some of the phenomena outlined in the above sections such as stress, focus and boundary effects have also been explored in Australian languages (Harrington *et al.*, 2000a; Butcher & Harrington, 2003; Fletcher & Butcher, 2003). A recent survey of metrical stress in these languages is included in Goedemans (2010).

The results to date suggest that Warlpiri is unusual in the way in which prosodic prominence is realised, as discussed in §1.2.4.5, both with regard to (i) stress/accent and focus and (ii) edge-marking (e.g., Harrington *et al.*, 2000a; Butcher & Harrington, 2003). Further work is required to examine whether similar patterns are found in other Australian languages. In particular, further research is required to address the relationship between prosodic organisation and coarticulation in Australian languages, given that Beckman *et al*. (1992) and others have demonstrated the importance of such organisation in predicting patterns of gestural overlap, *i.e.*, by extension, the degree of consonant-vowel overlap.

As mentioned, one of the cross-linguistic articulatory hallmarks of prosodic prominence is believed to be the articulatory expansion of prominent syllables (e.g., Beckman *et al*., 1992). In general, in Australian languages, a strong effect of prosodic context has not been found on vowels in the F2 x F1 plane, but there is evidence of an effect of length (e.g., Fletcher & Butcher, 2003; Tabain & Breen, 2011). Fletcher and Butcher (2003) found for a female speaker of another three vowel language with a length distinction, Kayardild, that close vowels tended not to show effects of prosodic context but rather of vowel length (or an interaction between accentuation and length) (p. 908). Similarly, Bishop (2002a,b) found an effect in Kuninjku (or Kunwinjku, Bininj Gun-wok) of lengthening late in the word (or possibly, word-initial shortening), but there was no effect of accent on vowel formants. In Arrernte, a recent study by Tabain and Breen (2011) of female speakers showed an effect for older subjects of prosodic context (stress) on the openness of the low central vowel in accordance with the sonority model (§2.3), *i.e.*, /a/ was associated with a higher F1 when prominent. In general, however, central vowels did not show significant effects of prosodic context on F1 and F2 at the vowel midpoint or on duration.

There is some evidence of domain- or phrase-final strengthening (e.g., Fletcher & Butcher, 2002) and pre-boundary lengthening (e.g., Fletcher & Evans, 2002) in languages such as in Bininj Gun-wok and Dalabon. There is also some evidence of medial strengthening (Butcher & Harrington, 2003), and domain-initial strengthening and lengthening (see §1.2.4.5), although in many Australian languages word-initial consonants have undergone lenition or loss (see Blevins, 2001). (See also §2.1.2.3.) Nevertheless, it is typically the medial consonant that undergoes articulatorily strengthening (and lengthening), and this consonant may be a carrier of prosody (Butcher & Harrington, 2003).

In this dissertation, word-level prosodic effects on V-to-C and V-to-V coarticulation will be examined. It will be considered whether the findings are consistent with Butcher and Harrington's claims for Warlpiri that medial consonants are strengthened and are potentially the carriers of prosodic prominence and whether these claims can be extended to other Australian languages. Further, potential coarticulatory evidence for preferred syllable structure will be discussed with regard to the ideas outlined in §2.4.1 and §1.2.1.5. The research questions of the study are summarised in the following section.

2.5 General research questions

It is clear that, whilst the majority of the literature on coarticulation has addressed commonly studied languages, such as English, there are sufficient grounds for undertaking the present study. This section will present the primary research questions, taking into account a number of points made in the preceding discussion of the relevant literature. These questions are separated into three subsections: general questions, including questions relating to the relationship between coarticulation and coarticulation resistance, those relating to coarticulation and prosody, and those relating to trans-consonantal V-to-V coarticulation.

2.5.1 General

As discussed extensively in §2.1.2 and §2.2, certain consonants and vowels have been found to be more resistant to coarticulation by neighbouring segments and to exert more coarticulatory influence on those segments. Drawing on studies by Recasens (1985), Tabain and Butcher (1999) and Lindblom *et al*. (2007), amongst others, primarily making use of the LE metric (§2.1.2), the following research question will be asked regarding consonant place of articulation and vowel quality and the magnitude of coarticulation and resistance to coarticulation:

RQ1) Does the place of articulation of a consonant or the quality of a vowel determine the extent to which it is coarticulated by an adjacent segment in Australian languages, and by extension, does it determine the extent to which it exerts coarticulation in other segments?

With regard to coarticulation resistance in vowels, several studies (e.g., Recasens, 1985; 1991; Hoole *et al.*, 1990) have shown that /i/ is less contextually variable than the other point vowels, /a u/. Recall from §2.2 that this may be because it involves a raising and fronting of the dorsum.

As discussed in §2.1, §2.2 and §2.3, some earlier studies have suggested that the size of the vowel inventory explains some differences in coarticulation and resistance to coarticulation, as does the number of coronal categories in the consonant inventory. Recall that the consonant inventories of Burarra and Warlpiri are similar, comprising bilabial, apico-alveolar, apico-retroflex, lamino-palatal and dorso-velar categories, while Arrernte and Gupapuyngu have the maximal number of consonant places of articulation (see Chapter 1). RQ2) is:

RQ2) Can it be inferred that language-specific inventory-related differences explain some differences in coarticulation and resistance to coarticulation, e.g., does the number of coronal categories in the inventory appear to affect the magnitude of consonant-vowel coarticulation or of trans-consonantal V-to-V coarticulation across coronals?

In several studies by Fowler and colleagues (Fowler, 1994; Brancazio & Fowler, 1998; Fowler & Brancazio, 2000; Iskarous *et al*., 2010), it has been argued that differences in LE slope values reflect differences in coarticulation resistance (see §2.1.2 and §2.2). It is therefore asked whether it appropriate to draw a link between coarticulation resistance and the LE with regard to Australian languages, in order to determine whether this link holds universally rather than merely in the context of European languages. More generally, this work will evaluate the LE within the limits of the acoustic phonetic study of coarticulation.

A further set of analyses will explore some specific issues relating to earlier work on Australian languages concerning a) pre-palatalisation of apicals and retroflexion and b) vowel-dependent velar coarticulation (as introduced in §1.4; see §1.2.1.3 on pre-palatalisation in Arrernte and §2.1.2.4 on velar coarticulation).

2.5.2 Coarticulation and (vocalic) prosodic effects

Prosodic prominence is known to affect the magnitude of coarticulation between consonants and vowels and between vowels. As noted in §2.4, several observations have been reported in the literature regarding the effects of prosodic prominence on coarticulation resistance and aggressiveness. It has been demonstrated that English vowels occurring in prosodically prominent positions are more resistant to coarticulation by neighbouring vowels (e.g., Cho, 1999; 2004). RQ3) is:

RQ3) Are prosodically prominent vowels more likely to exert coarticulation and less likely to undergo coarticulation in Australian languages, all else being equal (after, e.g., Fowler, 1981a; Cho, 1999; 2004)?

The aim is to determine whether the effects previously reported for Warlpiri, namely word-medial or post-tonic strengthening and consonants as potential carriers of prosodic prominence, are typical of other Australian languages. In other words, it is asked whether medial strengthening in Australian languages bears a consistent relationship to the extent to which prosodic prominence in vowels affects the magnitude of consonant-vowel and vowel-to-vowel coarticulation.

2.5.3 Trans-consonantal vowel-to-vowel coarticulation

The most general research question with regard to trans-consonantal V-to-V coarticulation relates to a coproduction model of coarticulation (§2.1.1). This type of model predicts a diphthongal, gradual and continuous vowel movement onto which the consonantal gesture is superimposed. In accordance with such a model, in formant patterns it can be predicted that the strength of V-to-V coarticulation increases in a gradual manner closer to the consonant boundary unless there is some perturbation associated with the consonant (such as formant depression associated with bilabials). It is asked

RQ4) Does V-to-V coarticulation occur in Australian languages, suggesting an underlying vocalic diphthongal gesture?

Further, it can be asked, drawing on findings relating to the role of the intervening consonant in V-to-V coarticulation (e.g., Recasens, 1984b; 1987; 2002; Brancazio & Fowler, 1998; Fowler & Brancazio, 2000; Cole, Linebaugh, Munson, & McMurray, 2010; see §2.1 and §2.2):

RQ5) Does the place of articulation of the intervening consonant modulate trans-consonantal V-to-V coarticulation? Does a high coarticulation resistant consonant block such coarticulation (Öhman, 1966; Recasens, 1984b; 1987; 1997; Fowler & Brancazio, 2000)?

It is suggested that V-to-V coarticulation might be limited in these languages because of the need to preserve word-medial consonant contrasts (§2.1.2.3), especially in the Australian context, given the large number of place of articulation contrasts in word-medial position (§1.2). The methodology employed in this dissertation is summarised in the next chapter.

3 Methodology

Three sets of experiments were conducted with the aim of describing consonant-vowel and trans-consonantal V-to-V coarticulation in the four languages. The research questions have been stated in §2.5. The present chapter provides an outline of the methodology involved in these experiments, comprising a description of the subject selection (§3.1), data collection (§3.2) and data analysis (§3.3). The third section is further divided into segmentation and labelling (§3.3.1), formant calculation (§3.3.2), and finally, methodological details regarding the experiments presented in Chapter 4 (§3.4.1), Chapter 5 (§3.4.2) and Chapter 6 (§3.4.3). Finally, in §3.5, conclusions are presented. Specific hypotheses to be tested in each experiment are given at the beginning of each chapter.

3.1 Subject selection

Twelve speakers took part in the study. Three adult female native speakers were recorded for each of four Australian indigenous languages, comprising Arrernte, Burarra, Gupapuyngu and Warlpiri. Speakers were female, aged between 30 and 65 at the time of recording, and were not aware of the purposes of the research (more information concerning age is unavailable). See Table 9. In this study, only speakers of a particular sex were selected due to male-female differences (e.g., Fant, 1960; 1970; as in previous coarticulation studies such as Tabain, 2000; 2009b, p. 36; Tabain & Breen, 2011).

Table 9. Speakers participating in the study. Column 1: initials, column 2: language, column 3: age; column 4: recorder type and recording conditions.

Speaker	Language	Age
MM	Arrernte	50-59
VD	Arrernte	50-59
TR	Arrernte	30-39
DP	Burarra	30-39
KF	Burarra	55-65
MW	Burarra	30-39
AM	Gupapuyngu	40-49
BT	Gupapuyngu	40-49
EG	Gupapuyngu	40-49
BP	Warlpiri	30-39
KR	Warlpiri	50-59
RR	Warlpiri	50-59

3.2 Data collection

The entire corpus was collected and digitised by Professor Andrew Butcher.[27] The recordings were made between October 1988 and April 1991. Some of the Burarra recordings were made in Gochanjinyjirra in the Northern Territory. The Arrernte speakers and the Warlpiri speakers (with the exception of BP) were recorded with a Revox B-77 Mk II open reel half-track tape recorder, using a Sennheiser MD-427 microphone. The Burarra speakers and BP were recorded in the field, using a Sony TCM-5000EV cassette recorder with a frequency response of 90 to 9,000Hz (manufacturer's figures). The microphone was a Sony ECM-D8 omnidirectional electret condenser microphone, which has a frequency response of 150 to 15,000Hz, a signal-to-noise ratio of over 40 dB (at 1000Hz) and a dynamic range of more than 76 dB (manufacturer's figures). Of the Gupapuyngu speakers, EG and BT were recorded with a Kudelski Nagra 4.2 full-track recorder and a Nakamichi CP-1 microphone in a sound-treated room. AM was recorded in the field with the Sony TCM-5000EV cassette recorder (as above). All recordings were digitised at a sampling rate of 22.05 kHz and with 16-bit resolution, using either Syntrillium Cool Edit Pro version 1.2 or Adobe Audition 1.5. Good clear recordings were obtained for all speakers except for Burarra speaker, DP, and Warlpiri speaker, BP. Tokens were rejected if the formants were not visible.

Speakers were asked to repeat isolated real words after receiving prompts in their native language in the form of word lists. In general, three tokens of each word type were elicited. Tokens were produced at a self-selected normal rate, and the rate was not varied. Andrew Butcher notes of the corpus that '[t]he word lists were designed to include all of the consonants in the language in all of the vowel contexts in each of word-initial, -medial, and -final positions' (Butcher & Tabain, 2004, pp. 30-31). Tokens were typically bi- or tri-syllabic words.

Whenever possible, in the present study, words were confined to the alternating consonant and vowel pattern (CV1CV2) in order to facilitate comparison, both because this is a common sequence across Australian languages and because in this pattern we can observe the largest number of cues to vowel quality and *word-medial* consonant place of articulation (Wright, 2004).

Prosodically, each token displays post-lexical (or phrasal) prosodic prominence, *i.e.*, each word is realised as a full intonational phrase. Therefore, prosodic effects applying to both the utterance/phrase level and the word level are relevant. Also, as

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there are three repetitions of each word, there is some 'listing' prosody and, typically, speakers produced a falling F0 contour utterance-finally.

3.3 Data analysis

Tokens were extracted from the recordings using Praat version 4.3.12 (Boersma & Weenink, 2005). Audacity Version 1.2.6, open-source software for the editing of audio files, in line with standard procedure, was employed to reduce incidental background noise (bird calls, etc.) for those speakers recorded in the field (see previous, §3.2). Segmentation and labelling was performed in the EMU Speech Database System (e.g., Cassidy & Harrington, 2004; Harrington 2010a), which is an integrated set of tools for the creation and analyis of speech databases (EMU version 2.3 and previous).

3.3.1 Segmentation and labeling

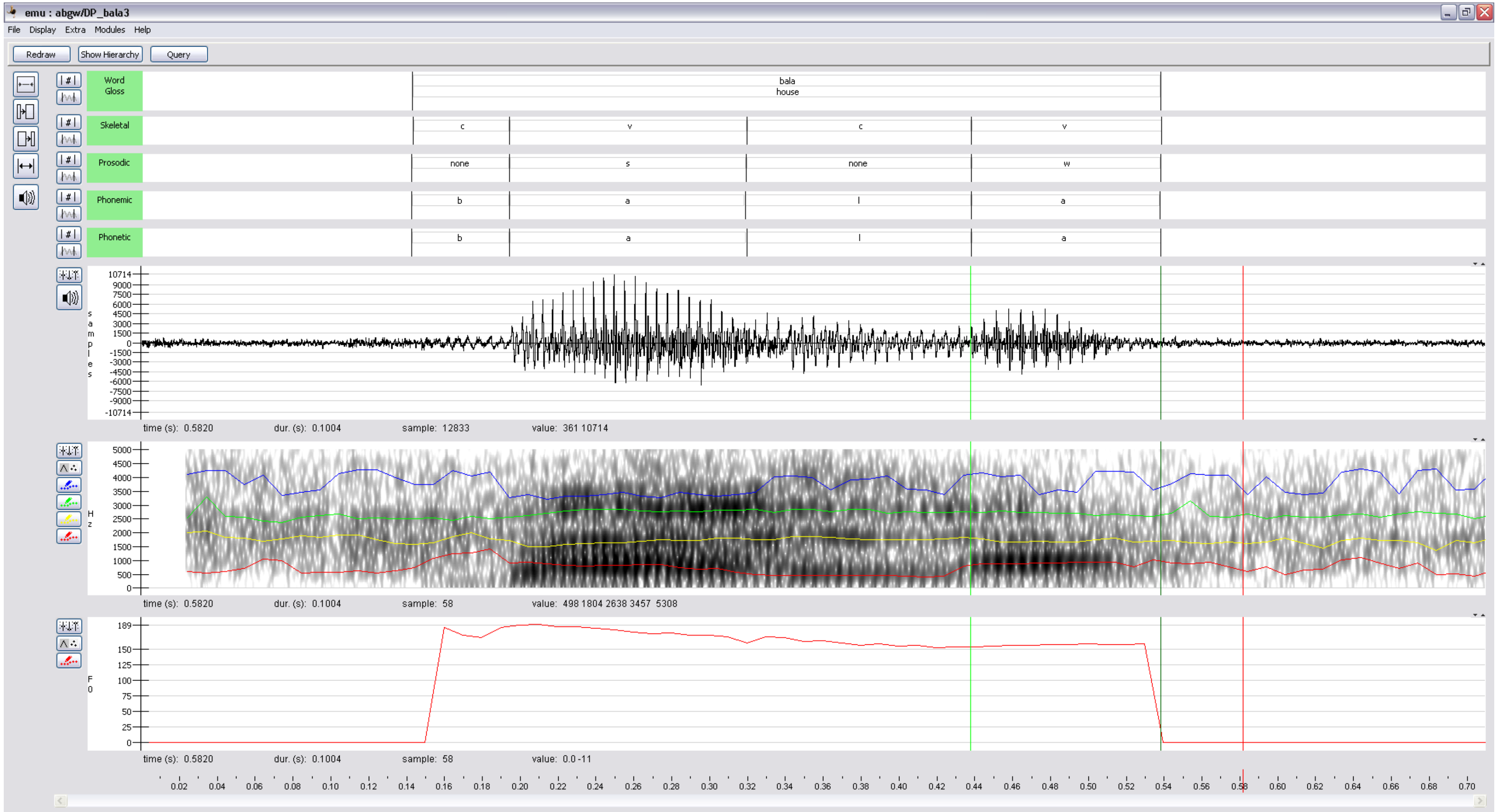
In EMU, segmental boundaries between segments were determined precisely based on visual inspection of spectrographic and waveform records. Segmentation criteria were as follows: the intervals for plosives were marked from the offset of periodicity in the preceding vowel to the offset of the burst, in order to extract values at the vowel onset. The onsets of the vowels were marked at the onset of periodicity and the offsets at the offset of periodicity. Amplitude is often at a minimum during the plosive consonant, whereas vowels tend to have the greatest amplitude (Stevens, 1980). Therefore, the onset of intervocalic consonants was identified as occurring at the time point of an abrupt reduction in amplitude in the acoustic waveform associated with consonant constriction. The offset of the stop was placed at an abrupt increase in amplitude for the following vowel, or at the end of the release burst, if this occurred.

Segmentation of nasals, liquids, and glides was performed on the basis of changes in the waveform and spectral discontinuities in the spectrogram according to the standard literature. Vowel targets were taken to occur at the temporal midpoint of the vowel on the assumption that this corresponds to the most steady-state portion of the vowel (Harrington & Cassidy, 1999, p. 62) and on the basis that the same assumption is made by Recasens and Espinosa (2006a; 2009c) for similar purposes. The vowel midpoint is assumed to be least affected by adjacent segments (see, e.g., Watson & Harrington, 1999; Harrington, 2010b, p.85). The word-final, non-contrastive vowel in Arrernte words, which occurs in citation and utterance-final words (Tabain & Breen, 2011) is treated provisionally as phonemic (and described as /ɐ/ or /a/; see previous discussion in §1.2.1). Regarding the annotation of word-initial apicals in these languages, given Butcher's (1995) argument that the majority of word-initial consonant realisations in mainland Australian languages vary between the two phonemes in opposition, and given a lack of a strong consensus in how to represent word-initial apicals phonemically, word-initial consonants were labelled on the basis of both the phonemic and orthographic descriptions provided by Butcher (forthcoming b) and a conservative analysis of the acoustic data.

In EMU, the following five tiers are derived on the basis of this segmental annotation:

1. a word and associated gloss tier;
2. a skeletal (C or V) tier;
3. a prosodic prominence or ‘prosodic’ tier;
4. a phonemic tier;
5. a phonetic tier.

For example, in Figure 4, the word is <bala> from Burarra, meaning ‘house’, the skeletal representation is CVCV, the prosodic prominence annotation is V1 strong, V2 weak, the phonemic representation is /bala/ and the broad phonetic representation is [bala], although background noise makes it difficult to detect the presence of a voicing bar associated with word-initial [b].



time (s): 0.5820 dur. (s): 0.1004 sample: 12833 value: 361 10714

time (s): 0.5820 dur. (s): 0.1004 sample: 58 value: 498 1804 2638 3457 5308

time (s): 0.5820 dur. (s): 0.1004 sample: 58 value: 0.0 -11

Figure 4. Illustration of an annotated spectrogram and waveform in the EMU Graphical User Display for the Burarra speaker, DP, <bala> ‘house’, showing hierarchical tiers with annotation (top), waveform (upper middle), spectrogram (lower middle), and F0 or pitch trace (bottom panel).

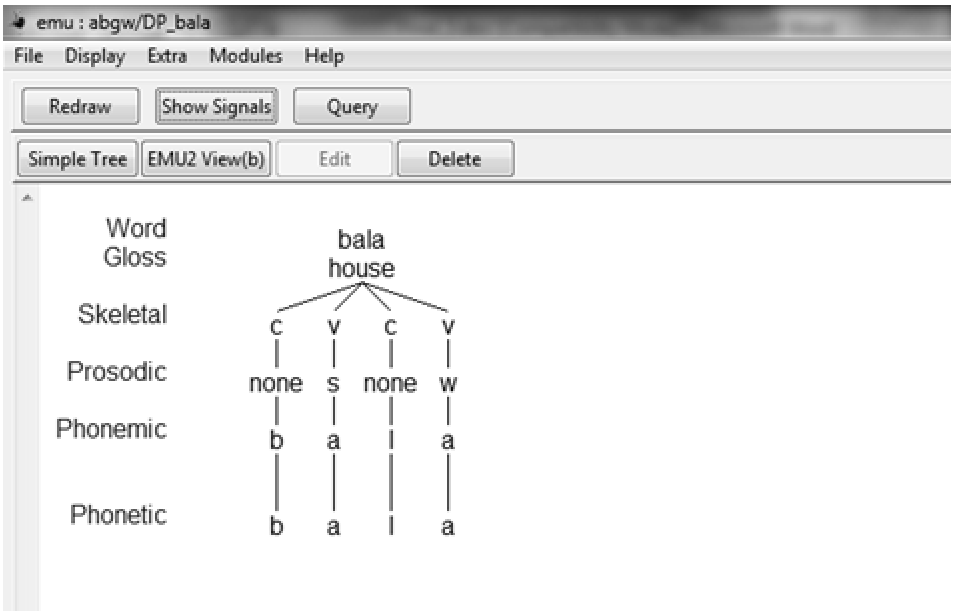


Figure 5.Illustration of the hierarchy view in the EMU Graphical User Display for the Burarra speaker, DP, <bala> ‘house’, showing tiers and associated labels with hierarchical relationships specified.

Table 10. Labels used in annotation on the Prosodic and Skeletal tiers.

Tier	**Label**	**Comment**
Prosodic	s	Prosodic prominence (F0 peak) associated with the vowel
	w	Lack of prosodic prominence associated with the vowel
	none	Consonant
Skeletal	c	Consonant
	v	Vowel

The Word and Gloss tier comprises a description of the orthography and standard meaning of the relevant word according to word lists provided by Butcher (forthcoming b). Annotation of the Prosodic (prominence) and Skeletal tiers is discussed in §3.3.1.1 and §3.3.1.2 and the symbols are defined in Table 10. The Phonemic tier contains the phonemic representation of the word, based on Butcher’s word lists (forthcoming b) and the relevant literature, and the Phonetic tier contains a phonetic transcription of the word. The labels are linked according to their hierarchical relationship within the Hierarchy View, as shown in Figure 5.

3.3.1.1 Prosodic tier

On the prosodic (prominence) tier, vowels were labelled according to prosodic prominence. The legal (permitted) labels are given in Table 10. The prosodic prominence of vowels was determined on the basis of published prosodic descriptions (see §1.2), an auditory impressionistic analysis and an acoustical analysis; where possible, prosodically prominent vowels were identified as such on the basis of a sharp upwards F0 (pitch) excursion within the vowel. In the token illustrated by Figure 4, the F0 trace (shown in the bottom panel) shows higher F0 frequencies during the first vowel than the second vowel. The annotation is therefore <bala> /'bala/, with prosodic prominence on the first vowel marked in the Prosodic tier as 's', while the second vowel is marked as 'w'.

3.3.1.2 Skeletal tier

On the skeletal tier, segments were labelled according to their consonant or vowel nature, according to standard acoustical criteria, as shown in Figure 4. The legal labels are also given in Table 10.

3.3.2 Formant calculation

The first three formant frequencies were calculated using the EMU speech database analysis system, specifically, the tkassp routine in the Speech Analysis set of tools. These formants convey the most information concerning consonant place of articulation and vowel quality. The parameters for formant calculation comprised Linear Predictive Coding (LPC) using the autocorrelation method of linear predictive coding for formant tracking and the Durbin recursion with a fixed order of 10, a pre-emphasis of 0 and a 25ms Blackman window with a frame shift of 5 ms and a bandwidth of 300Hz. The fundamental frequency (F0) was extracted using a pitch-tracker based on the Schaefer-Vincent (1983) periodicity detector (included as part of the EMU package), with a minimum F0 of 50Hz, a maximum of 500Hz and a frame shift of 5ms. The first three formant frequencies of all segments were checked and corrected manually (in a conservative manner) by inspecting the trajectories on the spectrogram and (in the case of vowels) by identifying outliers in ellipse plots in the F1/F2 plane. Formant tracks were extracted from EMU into R 2.9.2 (and 2.14.0 in the later stages of the research; R Development Core Team, 2008) using the R-based interface. Statistical procedures in EMU(R) were used to verify impressionistic analyses. Data were not normalised following Tabain and Breen (2011, p. 72), amongst others.

3.3.3 Summary of measurement points

The measurement points in this study are outlined here and will be discussed further in §3.4 according to the relevant chapter. In Chapter 4, in the Locus Equation, F2 variability and consonant locus analysis, the time points are in the vowels preceding and following the relevant consonant at V_{MID} (0.5 or 50% into the vowel), V_{ON} (0.1 or 10%) and V_{OFF} (0.9 or 90%) in F2 only. In the analysis comparing retroflexes and palatals, the measurement points in the vowel preceding the relevant consonant were V_{MID} (0.5), V_{EQ}

(at an equidistant point between V_{MID} and V_{OFF} or 0.7) and V_{OFF} (0.9) into the vowel, and V_{ON} (0.1), V_{EQ} (at an equidistant point between V_{ON} and V_{MID}, or 0.3) and V_{MID} (0.5) into the vowel following the consonant in F1, F2 and F3 (in the statistical procedures). In the vowel-dependent velar coarticulation analysis, the time points are V_{ON} (0.1) and V_{MID} (0.5) into the vowel following the velar consonant in F2 only.

In Chapters 5 and 6, only vowels in CV1CV2 words are considered, separated into V1 and V2 contexts and controlling for the place of articulation of the word-medial consonant (but not the word-initial consonant). In Chapter 5, in the analysis of vowel variability and dispersion, F1 and F2 formant frequencies are extracted at V_{MID} (0.5) only. In Chapter 6, in the V-to-V coarticulation analysis, the time points are $V1_{MID}$ (0.5), $V1_{EQ}$ (0.7) and $V1_{OFF}$ (0.9) into the vowel preceding the word-medial consonant, and $V2_{ON}$ (0.1), $V2_{EQ}$ (0.3) and $V2_{OFF}$ (0.5) into the vowel following the consonant in F1, F2 and F3.

The measurement points are summarised for convenience below. In Chapter 4:

- V_{ON}: onset (0.1 into V)
- V_{MID}: midpoint (0.5 into V)
- V_{OFF}: offset (0.9 into V)
- V_{EQ}: (0.3 or 0.7 into V; an equidistant point between V_{MID} and V_{ON}/V_{OFF})

In controlled CV1CV2 words, in Chapter 5:

- $V1_{MID}$: 0.5 into V1 (midpoint)
- $V2_{MID}$: 0.5 into V2 (midpoint)

In controlled CV1CV2 words, in Chapter 6:

- $V1_{MID}$: 0.5 into V1 (midpoint)
- $V1_{EQ}$: 0.7 into V1 (an equidistant point between $V1_{MID}$ and $V1_{OFF}$)
- $V1_{OFF}$: 0.9 into V1 (offset)
- $V2_{ON}$: 0.1 into V2 (onset)
- $V2_{EQ}$: 0.3 into V2 (an equidistant point between $V2_{ON}$ and $V2_{MID}$)
- $V2_{MID}$: 0.5 into V2 (midpoint)

The main procedures employed in each of the three experimental chapters will now be discussed in detail.

3.4 Experimental chapters

In the experiments presented in this work, word-medial consonants were confined to oral bilabial, alveolar, retroflex or postalveolar, palatal and velar stops, as these stop places of articulation are shared by the four languages. As discussed previously in §1.2, neutralisation of consonant place of articulation contrasts occurs word-initially and for this reason, amongst others, the focus in this dissertation is on word-medial consonants. In those languages in which there is a suggested fortis/lenis distinction (Burarra and Gupapuyngu, see §1.2), consonant environments were collapsed in order that the Burarra and Gupapuyngu data were more comparable to the Arrernte and Warlpiri data. Moreover, there were no obvious differences in the actual transitions/loci of the fortis/lenis consonants in this corpus. Also for reasons of comparability, secondary articulations and laminal dentals were not included in the analysis.

It has been mentioned that apical neutralisation and apical harmony apply in various contexts in these languages (§1.2). In the present study, word-initial apicals were labelled on the basis of both the phonemic and orthographic descriptions (after Tabain, 2009a, p. 490*f*) provided by Butcher (forthcoming b) and a conservative analysis of the acoustic data (primarily, F3). However, as in such recent studies of Australian languages as Tabain (2012), no attempt was made to demarcate more or less canonical realisations of the apical consonants (e.g., to separate consonants in neutralised word-initial position from those in word-medial position) because of the limited number of tokens available.

3.4.1 Consonant-vowel coarticulation

3.4.1.1 Locus Equations, F2 variability and F2 loci

In the first set of experiments, presented in Chapter 4, LE slopes were used to measure coarticulation between a consonant and an adjacent vowel (see §2.1.2.1 for a discussion of this metric). Words included in this and other experiments in Chapter 4 are given in Appendix A. Recall that a slope value of one indicates maximal vowel-to-consonant coarticulation and a value of two, minimal coarticulation. The following consonants were chosen in order to investigate a large variety of V-to-C effects: bilabial /p|b/, alveolar /t|d/, retroflex or apico-postalveolar /ʈ|ɖ/, palatal /c|ɟ/ and velar /k|g/. The retroflex stop is typically sub-apical in these languages but it can be sublaminal in Arrernte and Gupapuyngu (as discussed in §1.2). In Arrernte, it can be pre-palatalised (see §1.2.1.3 and §3.4.1.2). Therefore, it was particularly important to use a measure like the LE to pick up on this kind of variation in place of articulation.

Both CV and VC LE slopes were generated using the locus function in the EMU-R package in the R programming language. LE slopes were calculated (i) in contexts in which the vowel is prosodically prominent, (ii) in contexts in which the vowel is not prosodically prominent (after Lindblom *et al.*, 2007). Examples of sequences analysed in this set of experiments are as follows, using a broad phonemic transcription: in Warlpiri, speaker KR, /ka/ and /ʈi/ (CV) and /uk/ and /aʈ/ (VC) in <mukarti> /mukaʈi/ 'hat' e.g., [mokʰaʈɪ]. The number of tokens per speaker and consonant is given below in Table 11 and Table 12 for all prosodic prominence and trajectory period (CV, VC) contexts. Typically, the number of tokens for a given place of articulation and prosodic prominence condition was *lower* in the VC context (perhaps because words often commence with a consonant in Burarra, Gupapuyngu and Warpiri, but do not end in one). Words were not confined to bisyllabic words in order that there were sufficient tokens to conduct LEs with the factor of prosodic prominence. Recall that the word-final non-contrastive vowel in Arrernte words is treated provisionally as phonemic (and described as /a/; see previous discussion in §1.2.1 and §3.3.1) to aid comparison of the four languages, to test the extent of coarticulation in consonant-vowel and vowel-consonant sequences and to determine whether this set of four Australian languages conforms to those languages previously studied with regard to coarticulation and coarticulation resistance.

With regard to the distribution of consonants in terms of position-in-word, across languages, in the CV condition, there are both word-initial and word-medial consonants, while in the VC condition, consonants are much more likely to be word-medial than word-initial or -final. The distribution for the Arrernte speakers of word-final vowels relative to non-final vowels in the CV condition (when prosodic prominence is weak) is given in Table 13. According to the table, for MM and VD, more than half of the tokens derive from word-final environments.

In the LE analysis, the particular measurement points (V_{MID} and $V_{ON}/_{OFF}$; see preceding discussion) were selected because they were very close to the vowel-consonant boundary while avoiding some consonant perturbation at the boundary. As discussed in §2.1.2.1, there are constraints on the grain or precision of analysis when using locus equations; as Löfqvist states, 'a single consonant production does not have a LE slope' (1999). Vowels must be considered together, not independently, and fewer observed values will provide a rather less reliable slope estimate. Phonemic long vowels are present in only two of the four languages; these long vowels were included in the prosodically prominent vowel context in the LE slope analysis (i) because long vowels are typically not excluded from LE analyses in the literature and (ii) because of the fact that the accuracy of the LE relies on the inclusion of a large number of tokens.

Table 11. Number of tokens per speaker and consonant in CV Locus Equations in strong and weak prosodic contexts. Where n<10 is marked by *, S = Strong, W = Weak.

C	**V**	**A**			**B**			**G**			**W**			**Total**
		MM	**VD**	**TR**	**DP**	**KF**	**MW**	**AM**	**BT**	**EG**	**BP**	**KR**	**RR**	
p	**S**	73	75	26	132	86	167	160	190	35	36	106	53	1139
	W	62	74	9*	182	156	221	135	142	29	52	181	67	1301
t	**S**	33	47	7*	44	33	51	9*	13	0*	20	12	12	265
	W	25	30	6*	60	48	57	27	46	24	28	76	33	454
ʈ	**S**	33	25	6*	6*	13	6*	28	26	7*	2*	1*	0*	125
	W	63	85	12	53	47	70	48	49	27	25	23	18	520
c	**S**	51	37	17	100	55	117	41	52	19	32	105	38	664
	W	71	104	10	126	86	173	40	58	21	44	87	38	858
k	**S**	68	70	15	153	101	195	85	106	52	59	134	63	1101
	W	133	163	15	155	108	179	145	171	40	69	177	72	1427
Total		612	710	95	1005	733	1230	709	853	247	365	901	394	

Table 12. Number of data points per speaker and consonant in VC Locus Equations in strong and weak prosodic contexts. Where n<10 is marked by *, S = Strong, W = Weak.

		A			**B**			**G**			**W**			**Total**
V	**C**	**MM**	**VD**	**TR**	**DP**	**KF**	**MW**	**AM**	**BT**	**EG**	**BP**	**KR**	**RR**	
S	**p**	34	38	12	52	47	72	47	53	25	18	35	30	463
W		42	48	15	24	21	33	13	9*	3*	13	18	16	243
S	**t**	9*	6*	9*	19	17	30	27	46	24	18	35	24	240
W		18	17	6*	12	7*	10	10	15	12	15	4*	6*	109
S	ʈ	48	54	12	52	47	71	44	46	23	21	20	15	453
W		30	33	8*	18	22	23	4*	1*	3*	6*	4*	3*	126
S	**c**	34	42	13	37	27	44	20	19	15	12	11	18	292
W		40	26	14	52	17	56	30	34	6*	15	40	21	345
S	**k**	77	95	12	52	36	72	83	101	30	23	36	31	648
W		51	50	15	56	34	48	38	45	18	30	53	30	468
Total		374	403	93	374	268	459	312	359	147	165	248	185	

Table 13. Arrernte distribution of vowels in CV Locus Equations when prosodic prominence is weak.

		MM	VD	TR	Total
p	**Word-final**	43	47	0	90
	Total	62	74	9	145
t	**Word-final**	14	23	3	40
	Total	25	30	6	61
ʈ	**Word-final**	49	76	9	134
	Total	63	85	12	160
c	**Word-final**	47	68	1	116
	Total	71	104	10	185
k	**Word-final**	102	130	5	237
	Total	133	163	15	311
Grand total		609	800	70	

If the LE slopes show an effect of prosodic prominence for Gupapuyngu and Warlpiri, this may be due to prosodic prominence and/or vowel length (given that long vowels tend to be associated with prosodic prominence in these languages) and this will be addressed in the discussion. Using identical measurement points, F2 consonant loci (after Delattre *et al*., 1955, as discussed in §2.1.2.1) were calculated per consonantal place and speaker by means of the locus function in the EMU package per speaker. On the view of Delattre *et al*. (1955), consonant places of articulation can be characterised by consonant loci and vowel-consonant transitions may 'be regarded as movements' from the consonant locus to the steady state of the vowel (p. 769).

Variability in F2 at the vowel-consonant boundary measurement points (V_{OFF} in the VC trajectory and $V2_{ON}$ in the CV trajectory) was calculated in the form of standard deviations ('SD values'). The standard deviation (SD or σ) is a measure of variation about the mean ($\bar{x}$) and includes approximately 68% of the data. Therefore, a low SD value indicates that the F2 frequencies at a given measurement point tend to occur close to the mean, whereas a high SD value indicates a larger spread of values about the mean. This variability is thought to reflect articulatory variability (e.g., Recasens, 1995). Like the LE (see §2.2), the SD is believed to provide information about the degree of articulatory constraint (DAC value) associated with a consonant and therefore its context-sensitivity or coarticulation resistance (Stevens & House, 1963; Bladon & Al-Bamerni, 1976; Recasens, e.g., 1985; see Iskarous *et al*., on the relationship between the SD measure of context sensitivity and the LE slope). Hence, a high SD value is interpreted as indicating that there is little articulatory constraint associated with the consonant, allowing a high magnitude of variability in the vowel (in F2) at the vowel-consonant boundary. The calculation of SD values is particularly important given Butcher's (1996) claims regarding variation in Australian languages; he argues that spectral cues are equally controlled at both edges of the consonant, and thus acoustic distinctiveness is preserved well at both edges (Butcher, 2006; Tabain *et al.*, 2004; see §2.1.2.3). Recall from Chapter 2 that the DAC model predicts that the magnitude of coarticulation resistance in consonants is inversely related to F2 variability in adjacent vowels (at the vowel-consonant boundary).

Statistical analysis

Pearson's product-moment correlations (using the cor test function in the R programming language) of LE slope against SD value per speaker were calculated in order to determine correlation coefficients, which in this case are a measure of the linear dependence of the two variables. A correlation of 1 would indicate that the two variables are closely related, *i.e.*, that the LE slope values indicate not only the magnitude of coarticulation between a consonant and a vowel, but also the magnitude of coarticulation resistance in the consonant. Given that ɑ=0.05, df=19 and the test is one-tailed (a positive relationship is expected), correlations of 0.369 and over are unlikely to be due to chance and can be described as statistically significant. Correlations that are higher than 0.549 are significant at 0.01.

In order to make cross-linguistic and cross-speaker claims, a Linear Mixed Model analysis was used (using the lme4 package in the R programming language).[28] This procedure robustly handles the random factor of speaker and the presence of missing values and it provides greater power than traditional analyses (see, e.g., Bates, 2005; Cnaan, Laird & Slasor, 1997). In the LE slope subsection of the study, the dependent numerical (or ordinal) variable is the LE slope value, the fixed factors are consonant place of articulation, the order of the vowel relative to the consonant or 'trajectory period' (CV or VC) and prosodic prominence in the vowel (strong, weak). Both interaction and additive effects are examined. A notable study in which a regression analysis is run on LE slope values is that of Iskarous *et al*. (2010). Tukey's post-hoc procedure was used to identify significant contrasts (adjusted for the random factor of speaker). Tukey's is conservative in the case of unequal sample sizes. A Linear Mixed Model (LMM) procedure was also used for an investigation of F2 consonant locus (fixed factors: consonant place of articulation,

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[28] Tabain and Butcher (1999) also applied linear regression analyses to slope value data. In future work it may be more statistically sound to utilise a procedure derived from the work of Pedhazur (1973) and Tabain *et al*. (2004), although this procedure has reduced power.

language group; random factor: speaker), with Tukey's post-hoc analysis. In conducting both procedures, unrealistic values were not removed prior to the analysis given that these values may be meaningful (in reflecting variability in constriction location).

In addition, to capture individual speaker behaviour, factorial ANOVAs were run per speaker (using the general regression function, 'lm', in the R programming language, after Gries, 2009) to identify main effects of consonant, prosodic condition (the vowel is prosodically prominent or not prominent) and trajectory period (the sequence is VC or CV) on slope values. Alpha was set at 0.05. Interaction effects were not calculated. Type III analyses of variance were run (using the Anova function in the car package in the R programming language). The ANOVA model was applied to individual speakers separately as some locus equation slope values were missing (when too few relevant tokens existed). Whilst ANOVAs are not typically conducted per speaker, this method is necessitated by the nature of the corpus, that is, the corpus having been carefully designed to illustrate contrasts between the phonemic consonants and vowels and not to examine coarticulation in particular, and the resulting missing values. This method has been used frequently in the literature (see, e.g., Magen, 1997; Fowler & Brancazio, 2000; Nguyen & Fagyal, 2003; Recasens & Espinosa, 2010; Tabain *et al.*, 2011). In order to identify significant interactions between levels within a factor, such as consonant or prosodic condition, Tukey's Honest Significant Difference method (using the Tukey HSD and aov functions in R) was employed to calculate a set of 95% confidence intervals between means associated with each level of each factor with the specified family-wise probability of coverage. Significant differences between means were reported. Shapiro-Wilk tests of normality were computed and reported when significant. SD values were calculated per speaker. Mean SD values were calculated using the tapply function in the R programming language per consonant, trajectory (VC or CV) and prosodic condition. After, e.g., Tabain and Breen (2011), Levene's t-tests (specifically, modified robust Brown-Forsythe Levene-type tests based on the absolute deviations from the median) were used per language group with the factor of trajectory period to test for equality of variance between the VC and CV conditions.

3.4.1.2 Comparing retroflexes and palatals

The interaction between retroflex and palatal stops and preceding and following vowels was specifically investigated. The particular motivation in examining the retroflex consonant derives from work such as Henderson's (1998) dissertation in which he identifies what is termed 'pre-palatalisation' in vowels preceding retroflexes in Arrernte (see §1.2.1.3). In Burarra, Gupapuyngu and Warlpiri, the primary interest was in examining how the retroflex stop differs from other coronal consonants in exerting coarticulatory effects in adjacent vowels (specifically in /a/). In this analysis, the apico-alveolar stop was utilised as a sort of 'control', as it is generally thought to be less articulatorily constrained than the retroflex and the palatal, and is described as such within the DAC model, see, e.g., Recasens, 2008. As discussed in §1.2, only in consonant-medial position are all place categories in contrast; the apical opposition may be neutralised word-initially (and also post-consonantally; see Butcher, 1995). It can be predicted that in the non-Arandic languages, there is F3 lowering in adjacent vowels, particularly in the preceding vowel, a lower F3 being the main acoustic cue to retroflexes (e.g., Hamann, 2003).

In order to investigate whether the factor of word position affects the magnitude of pre-palatalisation in Arrernte, as claimed by Breen (2001) for the low central vowel, and to investigate retroflex-vowel coarticulation in Burarra, Gupapuyngu and Warlpiri F1, F2 and F3 frequencies were compared in the shared /a/ vowel preceding and following retroflex, alveolar and palatal contexts (separated into word-initial and non-word-initial VC contexts for Arrernte speakers only as no word-position effects were found for the other languages at the first pass). Word lists are given in Appendix A.

Procedures - Comparing retroflexes and palatals

The procedures for comparing retroflex and palatal stops were as follows. Phonemic retroflexes were identified as discussed at the beginning of §3.4 and in §3.3.1. Mean F1, F2 and F3 frequencies were compared in /a/ (and in the word-final non-contrastive vowel in Arrernte, see §1.2.1), being that vowel that is shared by the four languages and that is most likely to be affected by differences in place of articulation in adjacent consonants (according to the literature discussed in §2.1.2 and §2.2), preceding and following singleton retroflex, alveolar and palatal stops. Some values were unobtainable for Arrernte speakers. Table 14 shows that for Arrernte speaker, TR, only word-initial /aʈ/ tokens exist, and there are insufficient /at/ tokens in any word position. Few CV tokens exist for this speaker. In the CV context, the consonant was word-medial only, because this is where the largest number of place of articulation contrasts are realised (as discussed in §1.2 and elsewhere in Chapter 1). In the Burarra, Gupapuyngu and Warlpiri tokens analysed, no words commenced with a vowel.

In order to represent visually the trajectories associated with different consonant contexts, it was necessary to average and linear time-normalise trajectories using the relevant EMU-R routines (see §3.4.1.2). Wilcoxon rank sum tests were subsequently conducted on the F1, F2 and F3 formant frequencies. The measurement points for the tests were V_{MID}, V_{EQ} and V_{OFF} (or 50%, 70% and 90%, respectively) into the vowel preceding the stop (VC sequence), and V_{ON}, V_{EQ} and V_{MID} (or 10%, 30% and 50%) into the vowel following the stop (CV sequence).[29] The data extracted at these three points was then collapsed into a single vector per formant, which was assumed to *represent the overall trajectory shape*, and which was then subjected to the Wilcoxon rank sum tests with adjusted significance levels as follows:

a) Arrernte speakers, 9 comparisons per formant per speaker, $\alpha=0.05$, $\beta=0.0055$ ($\beta=0.05/9$);
b) Burarra, Gupapuyngu and Warlpiri speakers: 6 comparisons per formant per speaker, $\alpha=0.05$, $\beta=0.0083$ ($\beta=0.05/6$).

F3 consonant loci were calculated per speaker and per trajectory period (VC, CV) with V_{MID} and V_{ON}/V_{OFF} measurement points as in the LE slope analysis. In the case of the Arrernte speakers, consonant loci were calculated for all VC contexts (word-initial and otherwise) for ease of comparison across language groups.

Table 14. Arrernte - numbers of tokens per speaker and context in the retroflex and palatal analysis where 'WI' indicates word-initial context and 'NWI', non-word-initial context. VC and CV trajectory periods are represented separately.

			A			**Total**
			MM	**VD**	**TR**	
VC	**WI**	**/#at/**	7	9	N/A	16
		/#aʈ/	16	18	6	40
		/#ac/	16	10	9	35
	NWI	**/at/**	N/A	N/A	N/A	N/A
		/aʈ/	10	14	N/A	24
		/ac/	9	27	N/A	36
CV	**N/A**	**/ta/**	7	11	3	21
		/ʈa/	23	56	2	81
		/ca/	12	30	1	43
Total			100	175	21	

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[29] V_{MID} was included because initial analyses made it clear that transition information tended to be present at this timepoint.

Table 15. Burarra, Gupapuyngu and Warlpiri - numbers of tokens per speaker and context in the retroflex and palatal analysis.

		B			**G**			**W**			**Total**
		DP	**KF**	**MW**	**AM**	**BT**	**EG**	**BP**	**KR**	**RR**	
VC	**/at/**	9	10	9	3	3	3	6	12	6	61
	/aʈ/	27	23	36	17	21	12	24	42	27	229
	/ac/	30	21	35	4	3	3	12	11	12	131
CV	**/ta/**	9	10	12	9	11	9	6	12	9	87
	/ʈa/	45	44	58	17	25	12	15	24	18	258
	/ca/	60	34	70	11	9	9	9	11	9	222
Total		180	142	220	61	72	48	72	112	81	

3.4.1.3 Vowel-dependent velar coarticulation

In this additional investigation of velar consonants, which is motivated by the findings of Butcher and Tabain (2004), and also by the articulatory findings published by Fletcher and colleagues (e.g., Fletcher *et al*., 2007a), velars were examined before front, central and back vowels, /i a u/. F2 formant frequencies (Hz) were extracted at V_{ON} and V_{MID} in vowels following the velar per speaker. The distribution of tokens is given in Table 16. It should be noted that for Burarra speaker, TR, almost no tokens exist for /ki/ and /ku/. Words are given in Appendix A.

In this case, the formant frequency data is raw and not normalised or converted into ERB (equivalent rectangular bandwidth) values, hence comparisons were made within rather than between languages except in the case of the LMM analysis. Both the position of this CV pair within the word, and the word size, were not constrained (after Butcher & Tabain, 2004).

The measurement points are consistent with those utilised in the LE procedure and as such, are expected to provide information concerning consonant-vowel trajectories, and specifically, concerning the influence of the vowel on the consonant. For example, if F2 frequency does not differ between V_{ON} and V_{MID}, then vowel-dependent consonantal coarticulation is maximal, whereas, if F2 frequency differs significantly between V_{ON} and V_{MID}, vowel-dependent coarticulation is minimal. As in the retroflex analysis and elsewhere, the word-final Arrernte vowel is provisionally classified as /a/ for the purposes of this experiment.

Language groups were tested for differences with regard to vowel-to-velar stop coarticulation by means of an LMM analysis with the dependent variable of F2 formant frequencies at V_{ON} and V_{MID} and the fixed factors of measurement point (two levels: V_{ON} and V_{MID}), vowel quality (three levels: /i a u/), language group (four levels) and with the random factor of speaker.

Two sample (paired) t-tests were conducted on /ki/, /ka/ and /ku/ at two points in F2 in the vowel: V_{ON} and V_{MID}, per speaker, to determine whether V_{ON} and

V_{MID} values were significantly different for a particular CV context. The Welch correction was used in the case of unequal variances; degrees of freedom may therefore be fractional.[30] If there is no significant difference between the measurement points, it can be assumed that there is maximal C-to-V coarticulation. The distribution of sequences is given in Table 16.

In order to inform the discussion of (relative) F2 frequencies in the front vowel or /ki/ context, Welch (unpaired) t-tests were conducted on F2 at V_{ON} and V_{MID} in /ki/ and /ci/ sequences per speaker. If there is no difference between /ki/ and /ci/ at V_{MID} or V_{ON}, it can be surmised that the sequences do not differ in F2 at vowel midpoint or consonant offset, respectively. Of course, it cannot be assumed that constriction location or the pattern of linguo-palatal contact follows from this analysis. The distribution of /ci/ sequences is provided in Table 17 (/ki/ distribution is provided in Table 16).

Table 16. Number of tokens including /ki/, /ka/ and /ku/ sequences for each language and speaker.

Lang	**Sp**	**kV**	**n**	**Lang**	**Sp**	**kV**	**n**
A	**MM**	**ka**	126	**G**	**AM**	**ka**	89
		ki	3			**ki**	36
		ku	15			**ku**	91
	VD	**ka**	153		**BT**	**ka**	110
		ki	3			**ki**	36
		ku	8			**ku**	112
	TR	**ka**	11		**EG**	**ka**	36
		ki	N/A			**ki**	15
		ku	N/A			**ku**	33
Total			319	**Total**			558
B	**DP**	**ka**	179	**W**	**BP**	**ka**	58
		ki	16			**ki**	33
		ku	82			**ku**	41
	KF	**ka**	128		**KR**	**ka**	126
		ki	11			**ki**	67
		ku	54			**ku**	111
	MW	**ka**	216		**RR**	**ka**	48
		ki	19			**ki**	38
		ku	106			**ku**	50
Total			811	**Total**			572

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[30] Welch correction employs a corrected number of degrees of freedom to assess the significance of the t-statistic that is computed in the customary manner.

Table 17. Number of tokens including /ci/ sequences for each language and speaker.

Lang	Sp	n
A	**MM**	10
	VD	11
	TR	6
B	**DP**	10
	KF	3
	MW	12
G	**AM**	27
	BT	36
	EG	11
W	**BP**	30
	KR	72
	RR	27

3.4.2 Vowel variability and dispersion

The method described in this section is employed in Chapter 5 in an analysis of vowel realisation with a focus on vowel variability and dispersion. As discussed in §2.3, according to adaptive dispersion theory, individual vowel variability should relate meaningfully to vowel system size, and system size to dispersion, such that 'vowels should be freer to vary in small than in large vowel systems because there should be more acoustic space available in the former case' (Recasens & Espinosa, 2009c; see Lindblom, 1986). Further, as discussed in §2.4, in commonly studied languages such as English, prosodically prominent vowels are typically more peripheral in the F2 x F1 space, more dispersed, and less variable than prosodically weak vowels. The analysis is relevant to several research questions, namely RQ1) with regard to the effect of vowel quality on coarticulation, RQ2) with regard to inventory-related language effects on coarticulation and RQ3) with regard to the effects of prosodic prominence on vowels on coarticulation (§2.5). The particular procedures are discussed in the following sections.

3.4.2.1 Procedures – Vowel variability and dispersion

Acoustic vowel spaces were analysed in F1/F2 for CV1CV2 words only, separated into V1 and V2 contexts, e.g., in Gupapuyngu, <bäba> /ba:ba/ 'gumnut', in which /a:/ is V1, and /a/ is V2. All phonemic vowel qualities are included in the analysis.[31] The corpus for the experiments in this chapter comprises a broader selection of words and, in particular, consonantal contexts (*i.e.*, not only stops but also, e.g., laterals, nasals and rhotics), than in the experiments in Chapter 4. Words that were not included in the word list pertaining to experiments in Chapter 4 are given in

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[31] Both short and long vowels can be compared in Gupapuyngu in the VC condition but not in Warlpiri, as no long vowel tokens exist in this particular corpus in the V1 condition in CV1CV2 words for this language.

Appendix B. For the sake of consistency and comparison across the four languages, long vowels are excluded from the analyses comparing V1 and V2 conditions. Both the magnitude of variation in the F2 x F1 plane and the plane(s) in which variation occurs were examined. As formant structure depends both on the vowel and on the particular articulatory characteristics, palate shape and vocal tract size of an individual speaker, speakers are considered individually and the discussion draws on the outcomes of statistical procedures applied to each speaker individually. The distribution of the vowel categories is given in Table 18. The phonemic vowels of Arrernte are taken provisionally to be /ə a i u/, where the close vowels are marginal or low in frequency (after, e.g., Breen, 2001; see §1.2.1.2).

For all four languages, F1 and F2 formant frequencies were extracted from $V1_{MID}$ and $V2_{MID}$ (vowel midpoints; see, e.g., Cox, 2006, for a justification). The two dimensions are adequate to capture distinctions between vowels. $V1_{MID}$ and $V2_{MID}$ formant frequency values, SD values and Euclidean distances (or 'ED values') were calculated. Euclidean distances were utilised in order to measure 'the expansion of the vowel space relative to its centre' (Harrington, 2010a). The Euclidean distance of a given vowel, *p*, is the straight line measure between that vowel and the centre of the vowel space, *q*. The Euclidean distance between these two points, where $\sum$ indicates summation and *n* is any positive integer, is given by Equation 4:

Equation 4. The Euclidean distance equation.

$$\sqrt{\sum_{i=1}^{n}(p_i - q_i)^2}.$$

The Euclidean distance method is useful for determining whether there are changes in vowel quality, *i.e.* vowel centralisation or hyper-articulation, across segmental, prosodic or other conditions (see §2.3).

Linear Mixed Model (LMM) procedures were used for two investigations of F1 and F2 formant frequencies at the midpoints of vowels in CVCV words:

(i) an investigation of the effect of word-medial consonant place, language group and vowel quality (fixed factors: F1/F2 formant frequencies, vowel quality, word-medial consonant place, language group; random factor: speaker);

(ii) an investigation of a cross-linguistic effect of prosodic prominence and word position (*i.e.*, a comparison of V1 and V2) when the effect of language group is removed (fixed factors: F1/F2 formant frequencies, vowel quality, prosodic prominence/word position (V1, V2), random factors: language group, speaker).

Separate procedures were conducted for F1 and F2 frequencies (and for VC and CV conditions in (i)). Interactions could not be tested because of singularities. Procedure (i) primarily relates to RQ1) while (ii) addresses the hypotheses outlined in §5.1.1.

Factors of word position and prosodic prominence in vowel realisation

In order to further address the prosodic factors of word position and prosodic prominence in the raw F1 and F2 frequencies at V_{MID} and with regard to the research questions outlined in §2.5.2, vowels were separated into V1 and V2 contexts in the C1V1C2V2 words, as shown in Table 18 and Table 19. Vowel quality is clearly very much restricted in the V2 context. The vowels in V1 position are prosodically prominent (in these tokens; the criteria for determining prosodic prominence are discussed in §3.3). Welch-corrected t-tests were run per speaker and formant to compare vowel qualities in word-final/weak (CV) and word-initial/strong (VC) positions (using the t-test function in the R programming language). As the Welch correction for unequal variances was used, degrees of freedom may be fractional. In order to control for the probability of false positives when the number of t-tests per speaker and formant increases, Bonferroni correction was applied to $\alpha=0.05$ such that for the Burarra speakers $\beta=0.025$ (2 tests per speaker per formant) and for the Gupapuyngu and Warlpiri speakers, $\beta=0.0167$ (three tests per speaker per formant). For Arrernte, no adjustment to α is required.

The comparisons were as follows: for Arrernte speakers, only /a/ was compared in word-initial and –final positions (see discussion in §1.2.1.2). For the Burarra speakers, both /i/ and /a/ were compared across positions. For the Gupapuyngu and Warlpiri speakers, /i a u/ were compared across positions. Vowel qualities were not compared within a condition. In order to identify prosodic/positional effects on standard deviations per speaker and formant, paired t-tests were modified to resemble the standard Levene test for homogeneity of variances whereby the mean (*i.e.*, mean standard deviation) value of each condition is subtracted from each value in that condition and the resulting absolute values are tested (where $\alpha=0.05$; after, e.g., Tabain, 2009). Tests were constrained to short vowels only.

Such tests could not be run for Arrernte and Burarra due to widely differing sample sizes between V1 and V2 contexts. In order to compare the dispersion in the vowel space between V1 and V2 conditions for Burarra, Gupapuyngu and

Warlpiri speakers, before applying any tests, the Shapiro-Wilk test (Royston, 1982) for normality was applied to the data and ED values were found to be non-normally distributed. The nonparametric Wilcoxon rank sum test with continuity correction was applied to paired samples using the wilcox.test function in the R programming language after Harrington (e.g., 2006; 2010a). $\alpha=0.05$. Arrernte speakers were not considered in this analysis because only a single vowel quality occurs in the CV condition (§1.2.1.2).

Table 18. Number of tokens (CV1CV2 words) in the V1 condition per vowel. Total n per speaker is given in the rightmost column.

Lang	**Sp**	**a**	**a:**	ə	ɛ	**i**	**i:**	**o**	**u**	**u:**	**Total**
A	**MM**	35	N/A	38	N/A	7	N/A	N/A	8	N/A	88
	VD	45	N/A	57	N/A	4	N/A	N/A	5	N/A	111
	TR	4	N/A	9	N/A	3	N/A	N/A	0	N/A	16
B	**DP**	69	N/A	N/A	13	26	N/A	25	34	N/A	167
	KF	31	N/A	N/A	7	20	N/A	22	20	N/A	100
	MW	68	N/A	N/A	15	21	N/A	37	43	N/A	184
G	**AM**	61	39	N/A	N/A	24	17	N/A	43	27	211
	BT	64	47	N/A	N/A	24	21	N/A	47	44	247
	EG	27	21	N/A	N/A	0	12	N/A	20	18	98
W	**BP**	58	N/A	N/A	N/A	23	N/A	N/A	32	N/A	113
	KR	90	N/A	N/A	N/A	36	N/A	N/A	44	N/A	170
	RR	68	N/A	N/A	N/A	42	N/A	N/A	46	N/A	156
Total		620	107	104	35	230	50	84	342	89	1661

Table 19. Number of tokens (CV1CV2 words) in the V2 condition per vowel. Total n per speaker is given in the rightmost column.

Lang	**Sp**	**a**	**i**	**u**	**Total**
A	**MM**	88	N/A	N/A	88
	VD	112	N/A	N/A	112
	TR	17	N/A	N/A	17
B	**DP**	160	5	2	167
	KF	87	13	0	100
	MW	176	5	3	184
G	**AM**	99	42	70	211
	BT	122	51	74	247
	EG	60	15	23	98
W	**BP**	48	30	35	113
	KR	80	39	51	170
	RR	70	440	46	556
Total		1119	640	304	2063

3.4.3 Vowel-to-vowel coarticulation

In Chapter 6, the magnitude of V-to-V coarticulation in real-word (C1)V1C2V2 words was measured per speaker, formant and word-medial consonant place of articulation. The word-medial places of articulation were identical to those in §3.4.1: /p|b/, /t|d/, /ʈ|ɖ/, /c|ɟ/ and /k|g/. Word-medial, but not word-initial, consonants were controlled, in accordance with the literature (e.g., Öhman, 1966). This is done because it is the *word-medial* consonant that is most likely to have an effect on the magnitude of V-to-V coarticulation and, further, because word-medially there is no neutralisation of place categories in Australian languages. The formants under examination were F1, F2 and F3 (F3 is included primarily to observe retroflex-to-vowel effects). In the C1V1C2V2 context, every V1 is prosodically prominent and every V2 is prosodically weak, as in Chapter 5, thus, preliminary claims can be made about any effect of prosodic prominence in the flanking (or changing) vowel on the magnitude of V-to-V coarticulation. As long vowels occur infrequently in the corpus, vowels were constrained in this experiment to phonemic short vowels. Given the nature of the corpus, the number and type of tokens for each speaker and language vary, as shown in Table 20 for the word-medial consonants /p|b t|d ʈ|ɖ/ and in Table 21 for /c|ɟ k|g/. In Arrernte, there is a very small number of appropriate C1V1C2V2 sequences in the corpus due to the phonotactics of the language. These words are thought to be /ə/ initial underlyingly. (See §1.2.1.4.) All words in this experiment were included in the word lists in Appendices A and B.

Table 20. Number of tokens (CV1CV2 words) in the V-to-V coarticulation experiment according to word-medial consonant /p|b t|d ʈ|ɖ/, to V1 and V2, and to language and speaker. Total n per speaker is given in the rightmost column.

C	**Lang**	**Sp**	**V1V2**						**Total**
			aa	**ai**	**au**	**ia**	**ua**	**uu**	
p|b	**A**	MM	4	0	0	3	0	0	7
		VD	6	0	0	3	0	0	9
		TR	0	0	0	0	0	0	0
	B	DP	9	0	0	2	4	0	15
		KF	6	0	0	3	3	0	12
		MW	9	0	0	2	3	0	14
	G	AM	6	0	2	0	0	4	12
		BT	6	0	3	0	0	5	14
		EG	6	0	3	0	0	3	12
	W	BP	6	0	0	0	0	0	6
		KR	5	0	3	0	3	0	11
		RR	6	0	3	0	3	0	12
t|d	**A**	MM	0	0	0	0	0	0	0
		VD	0	0	0	1	0	0	1
		TR	0	0	0	0	0	0	0
	B	DP	6	0	0	0	0	0	6
		KF	4	0	0	0	0	0	4
		MW	6	0	0	0	0	0	6
	G	AM	3	0	0	0	6	3	12
		BT	3	0	0	0	3	3	9
		EG	3	0	0	0	6	3	12
	W	BP	3	3	0	0	0	3	9
		KR	3	3	0	3	0	3	12
		RR	3	3	0	3	0	3	12
ʈ|ɖ	**A**	MM	0	0	0	0	0	0	0
		VD	3	0	0	0	0	0	3
		TR	0	0	0	0	0	0	0
	B	DP	10	0	0	0	2	0	12
		KF	6	0	0	0	4	0	10
		MW	9	0	0	0	4	0	13
	G	AM	0	0	2	0	0	0	2
		BT	0	0	3	0	3	0	6
		EG	0	0	3	0	0	0	3
	W	BP	3	0	0	0	0	0	3
		KR	0	0	0	0	0	0	0
		RR	0	0	0	0	0	0	0

Table 21. Number of tokens (CV1CV2 words) in the V-to-V coarticulation experiment according to word-medial consonant /c|ɟ k|g/, to V1 and V2, and to language and speaker. Total n per speaker is given in the rightmost column.

C	**Lang**	**Sp**	**V1V2**						**Total**
			aa	**ai**	**au**	**ia**	**ua**	**uu**	
c|ɟ	**A**	**MM**	0	0	0	0	0	0	0
		VD	3	0	0	0	0	0	3
		TR	0	0	0	0	0	0	0
	B	**DP**	6	0	0	3	2	0	11
		KF	3	0	0	4	0	0	7
		MW	9	0	0	2	0	0	11
	G	**AM**	2	0	0	0	0	0	2
		BT	0	0	0	0	0	0	0
		EG	0	0	0	0	0	0	0
	W	**BP**	3	0	0	0	0	0	3
		KR	0	0	0	0	0	0	0
		RR	3	0	0	0	0	0	3
k|g	**A**	**MM**	1	0	0	0	6	0	7
		VD	3	0	0	0	0	0	3
		TR	0	0	0	0	0	0	0
	B	**DP**	7	0	0	0	0	2	9
		KF	4	0	0	0	0	0	4
		MW	9	0	0	0	0	3	12
	G	**AM**	3	0	6	6	3	5	23
		BT	6	0	6	6	3	5	26
		EG	3	0	0	0	6	3	12
	W	**BP**	3	0	0	0	2	2	7
		KR	3	0	0	0	3	6	12
		RR	3	2	3	0	3	6	17

3.4.3.1 *Procedures – Vowel-to-vowel coarticulation*

In the analysis of V-to-V coarticulation, formant trajectories during (C1)V1C2V2 were examined. Following Recasens (1984), coarticulation was 'considered to occur when observable frequency differences between two vowels caused analogous differences to occur at some moment in time on the other side of the lineup point.' (p. 1632) In order to represent more formally the pattern operating in the data, statistical analyses were also performed, as discussed in the following sections. Two procedures were utilised. The measurement points were the same for both procedures: F2 was measured at $V1_{OFF}/V2_{ON}$ and $V1_{MID}/V2_{MID}$ and at equidistant points ($V1_{EQ}/V2_{EQ}$) in the target (or fixed or encroached) vowel. As in the pre-palatalised apical and retroflex procedure, the data extracted at these measurement points were collapsed into a single vector per formant that constituted a simplified *overall trajectory shape*. An illustration of the measurement points is provided in Figure 6, in which the left plot represents V1 from onset to $V1_{OFF}$ and the right plot, V2 from $V2_{ON}$ to offset. These measurement points permit comparisons of trajectories across flanking vowel environments (procedure 1) and across both flanking vowel and word-medial consonant place environments (procedure 2).[32] F3 is assumed to reflect the distance of the constriction location from the glottis and any retroflexion exerted by the consonant, but cannot be assumed to reflect vowel-dependent lip rounding, given a potential lack of lip rounding and protrusion (Dixon, 1980, p. 130; Butcher, 2006). As such, flanking vowel /i/ may cause a raising of F3 in target vowel, /a/. Flanking vowel, /u/, may cause a lowering of F3 in target vowel, /a/. Significant differences may not be very visually distinct in the plots because of constraints on plot size (on the printed page).

In addressing the relevant research questions and hypotheses, the limited availability of sequences in the data set is taken into account, e.g., where the close vowel lies, where the central vowel occurs and where the prosodic prominence lies, given evidence of a tendency for stressed close vowels to exert more coarticulatory effects across the consonant than unstressed vowels (e.g., Lindblom *et al.*, 2007; see §2.1.2 and §2.4).

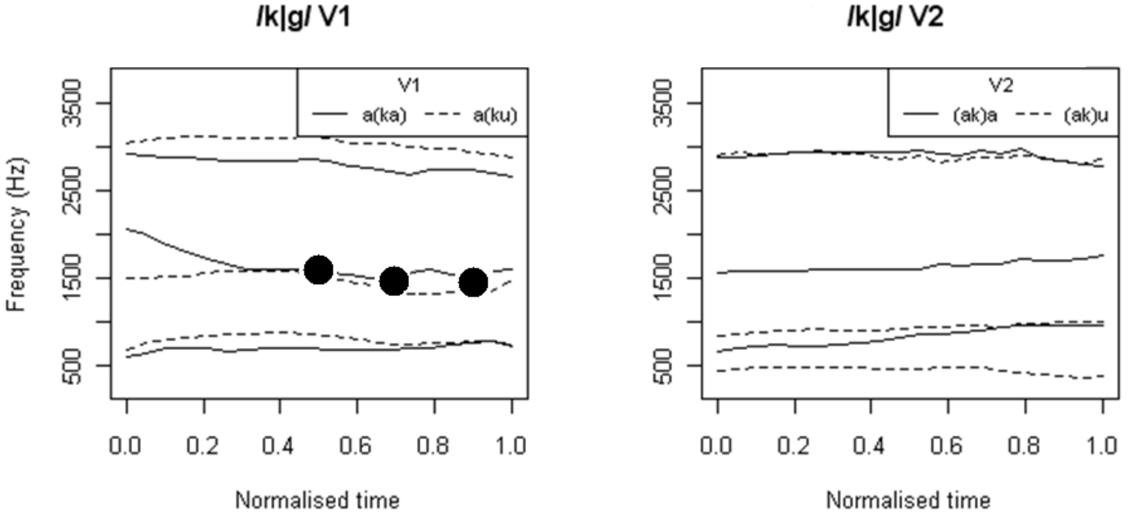

Figure 6. Averaged, time-normalised F1, F2 and F3 trajectories in vowels in superimposed sequences /ak|ga/ (solid line) and /ak|gu/ (dashed line) in which the first vowel (left) is fixed. Measurement points, $V1_{MID}$ (0.5), $V1_{EQ}$ (0.7) and $V1_{OFF}$ (0.9), are indicated by filled black circles in the target vowel.

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[32] In the early stages of the development of this chapter, an Öhman type 'difference score' method was used, which assumes that two sequences differing in the quality of the flanking vowel will be associated with identical formant frequencies at the target vowel midpoint. This was found not to be the case. As such, the measurement points in the present set of experiments include the vowel midpoint. In a further set of preliminary experiments, time point was included as a fixed factor in the analyses of variance. However, these results were not retained in the final version given that they were not found to add any useful information to that provided by the plots associated with procedure 1.

Procedure 1 – Individual consonant places of articulation; addressing the effect of the flanking vowel on the target vowel

In order to test for differences between sequences (in that half of the target vowel closer to the vowel-consonant boundary), in a modification of the methods employed by Recasens (1986) and Fowler and Brancazio (2000), unpaired t-tests were run per pair of sequences, e.g., /apa/ and /ipa/, per speaker and formant (unpaired tests were used because sample sizes differ). This procedure is relevant to research question RQ1), in particular concerning whether the quality of the vowel determines the extent to which it is coarticulated by an adjacent segment, and by extension, the extent to which it exerts coarticulation in other segments. It is also relevant to question RQ3), concerning whether prosodically prominent vowels are more likely to exert coarticulation than weak vowels, although this can only be examined in a very preliminary way. Given trends towards normality of distribution but unequal population variances, the Welch correction was employed to provide a valid t-test in the presence of unequal population variances (hence, as has been stated, degrees of freedom may be fractional). When the target vowel was V1, the measurement points were $V1_{MID}$, $V1_{EQ}$ and $V1_{OFF}$ (0.5, 0.7 and 0.9 into the vowel), as illustrated in Figure 6. When the target vowel was V2, the measurement points were $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$ (0.1, 0.3 and 0.5 into the vowel). $V1_{MID}$ and $V2_{MID}$ are included in the set of measurement points because it is known that V-to-V coarticulatory effects can extend from one vowel into the steady state period of another vowel (e.g., Recasens 1984b; 1987), specifically, the V-to-V transition may start earlier than $V1_{MID}$ and end later than $V2_{MID}$.[33] t, when significant, indicates that the trajectories are significantly different, *i.e.*, there is V-to-V coarticulation in the asymmetrical sequence, if and only if the differences are in the correct direction for such coarticulation, e.g., flanking vowel, /i/, is associated with higher F2 frequencies in the target vowel, /a/, than is flanking vowel /a/. α was set at 0.05.[34]

Procedure 2 – Differences between consonant places of articulation; addressing the effects of the medial consonant place and the flanking vowel

In order to test for differences between consonant places of articulation in the modulation of V-to-V coarticulation, ANOVAs were run per speaker and per formant (F1, F2 and F3) with the dependent variable of formant frequencies in the target

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[33] As has been suggested previously, at the first pass in this set of experiments, it became clear than V-to-V transitions often commenced slightly prior to the midpoint in a V1 target vowel and often ended slightly after the midpoint in a V2 target vowel.

[34] No Bonferroni correction was used because of the likelihood that it would increase the probability of producing false negatives in this particular context.

vowel (with measurement points as in the t-tests) and with the independent variables of flanking vowel quality, e.g., /i/ or /u/ and medial consonant place of articulation, e.g., /p/ or /t/. This procedure permits the answering of research questions RQ1), RQ3), and, in particular, RQ5), which concerns whether *the place of articulation of the word-medial consonant* modulates V-to-V coarticulation. On the use of analyses of variance for single speakers, see §3.4.1. The procedure is similar to that employed by Fowler and Brancazio (2000) in their study of consonantal coarticulation resistance and vowel-to-vowel coarticulation in that the factor of consonant place is specified. The ANOVAs were multivariate analyses of covariance, using the linear (regression) model function, ‘lm’, in the R programming language. Interaction effects were not calculated. Measurement points were identical to those in the unpaired t-tests in this section. When the target vowel is V1, measurement points are $V1_{MID}$, $V1_{EQ}$ and $V1_{OFF}$. When the target vowel is V2, measurement points are $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$. Sequences were pooled per speaker and formant according to the target vowel – e.g., all /aCV/ sequences were pooled for Warlpiri speaker KR for each of F1, F2 and F3 – with word-medial consonant (/p t ʈ c k/ or as available) and flanking vowel (/i a u/ or as available) as fixed factors in order to detect the effects of both the flanking vowel and the consonant place on the target vowel for a given speaker. Tukey’s Honest Significant Difference (HSD) post-hoc comparisons were then run. While Tukey’s procedure is designed for normally distributed data with homogeneity of variance and equal sample sizes per group, alternatives such as the Dunnett-Tukey-Kramer pairwise comparisons procedure are also not ideal as they assume unequal variances (which cannot be assumed in this context according to analyses performed per numeric vector). α was set at 0.05.

In both ANOVAs and Tukeys post-hoc procedures, if, for a given speaker, the factor of medial consonant place is associated with significant coefficients more frequently than the factor of flanking vowel quality, it can be stated that the factor of consonant place contributes more to the realisation of the fixed vowel (specifically, the half of the fixed vowel closer to the consonant-vowel boundary) than does the quality of the flanking vowel. Alternatively, if the factor of medial consonant place is less frequently associated with significant coefficients than the factor of flanking vowel quality, it can be stated that the factor of consonant place contributes less to the realisation of the fixed vowel than does the quality of the flanking vowel.

3.5 Summary

This chapter has outlined the methodology of the various experiments involved in the dissertation. In summary, in the following chapter, Chapter 4, the primary methods are the Locus Equation (LE), F2 loci, and F2 standard deviations (SD values) for the analysis of coarticulation resistance, in Chapter 5, the analysis of F1 and F2 values and Euclidean Distances (ED values) for the analysis of vowel variability and dispersion, and in Chapter 6, the analysis of VCV formant trajectories for the investigation of V-to-V coarticulation. In the following chapter, the results of the first set of experiments, which relate to consonant-vowel coarticulation, will be reported.

4 Consonant-vowel coarticulation

4.1 Introduction

In this chapter, the subject of coarticulation between a consonant and a vowel is addressed. The principal aim of this chapter is to describe consonant-vowel coarticulation with specific reference to the effects of consonant place of articulation (RQ1)), and secondarily to the effects of the order of the consonant and vowel relative to each other (trajectory periods VC or CV), to prosodic prominence (RQ3)), and to language-specific inventory-related differences (RQ2)), where possible. An additional, minor, aim is to assess the soundness of the link presented in the literature by, e.g., Fowler and Brancazio (2000), between coarticulation resistance and the Locus Equation (LE).

The structure of this chapter is as follows: in §4.1.1, hypotheses are presented, according to three themes: §4.1.1.1, on consonant place of articulation, §4.1.1.2 on the matter of trajectory periods and the direction of coarticulation and §4.1.1.3 on prosodic contexts. In §4.1.2, the methodology utilised in this paper is recapitulated.

In §4.2, coarticulation between a consonant and a vowel is quantified by means of the LE (see §2.1.1) and variation in the vowel at the vowel-consonant boundary is quantified as a measure of coarticulation resistance or context-sensitivity. Each language group is addressed in turn and results are summarised briefly for each language group. LE results are given in §4.2.1.1 for Arrernte speakers, in §4.2.1.2 for Burarra speakers, in §4.2.1.3 for Gupapuyngu speakers and in §4.2.1.4 for Warlpiri speakers. In §4.2.1.5, F2 consonant loci, in the classic sense, are reported per language group. All LE results are summarised briefly in §4.2.1.6.

In §4.2.2, the results of a comparison of retroflexes and palatals are given, with special regard to pre-palatalisation of the phonemic retroflex stop, /ʈ/, in Arrernte (§1.2.1.3). Results are discussed per language group and are divided into preceding and following vowel contexts; Arrernte is addressed in §4.2.2.1, Burarra, in §4.2.2.2, Gupapuyngu, in §4.2.2.3 and Warlpiri, in §0. For Arrernte speakers only, the preceding vowel context is divided into word-initial and non-word-initial contexts in order to examine the effects of word position on pre-palatalisation in this language. All pre-palatalised apical, retroflex and palatal consonant results are discussed in §4.2.2.6.

In §4.2.3, coarticulation between the velar stop and the following vowel is addressed. The results of analyses across all speakers are presented in §4.2.3.1. Subsequently, results are presented per language group; Arrernte is addressed in §4.2.3.2, Burarra in §4.2.3.3, Gupapuyngu in §4.2.3.4 and Warlpiri in §4.2.3.5.

In §4.3, a general discussion of all results is undertaken. This discussion is divided into three sections: §4.3.1 on the effect of consonant place of articulation on consonant-vowel coarticulation, §4.3.2 on the effect of trajectory period (CV or VC) and §4.3.3 on the effect of prosodic prominence. In §4.4, conclusions and implications are presented.

4.1.1 Hypotheses

As discussed in §2.5, the research questions relevant to this chapter relate to four main topics: coarticulation and coarticulation resistance, consonant place of articulation, trajectory period (CV or VC) and prosodic context.

4.1.1.1 Effect of consonant place of articulation

The effects of consonant place of articulation and trajectory period will be examined in this chapter (see RQ1)). Recall that a high LE slope value indicates a high magnitude of vowel-to-consonant coarticulation (§3.4.1.1). Given this, and given previous findings for various consonant places of coarticulation (§2.2), it is hypothesised:

H1) There is an effect of consonant place of articulation on F2 LE slope values; slope values are especially high for velar stops, indicating a high magnitude of vowel-dependent coarticulation, high for bilabial stops, intermediate for apical stops and low for palatal stops, indicating a low magnitude of vowel-dependent coarticulation.

In examining retroflex-to-vowel coarticulation with particular regard to pre-palatalisation in Arrernte, after Henderson (1998) and Breen (2001), whose major research findings are discussed in §1.2.1.3, it is hypothesised that:

H2) In Arrernte, pre-palatalisation occurs in /a/ vowels preceding phonemic retroflex stops, as indicated by higher F2 and F3 values and by lower F1 values at the vowel offset than in vowels preceding alveolar stops (see also H7)).

H3) In Arrernte, there is an effect of word position on formant frequencies in /a/ preceding a pre-palatalised phonemic retroflex stop; F2 and F3 raising and F1 lowering effects are stronger at the offset of the vowel preceding the stop when the vowel is word-initial than when it is not word-initial.

While it is not predicted that pre-palatalisation will be found in the non-Arandic languages (Evans, 1995, pp. 728-729), this has not yet been shown experimentally.

In examining velar consonants in greater detail, after Recasens (1985) and Recasens and Espinosa (2009a) for Catalan, and Hoole *et al.* (1990) for German, amongst others, and in the Australian context, Butcher and Tabain (2004; see §2.1.2.4), it is hypothesised that:

H4) There is an effect of vowel quality on preceding velar consonants in F2; F2 frequencies at vowel onsets (V_{ON}) by midpoints (V_{MID}) following velar consonants form three distinct groups according to three distinct targets in the vowels, /i a u/. Further, the close vowel /i/ exerts strong F2 raising effects such that there is maximal coarticulation between V_{ON} and V_{MID} in /ki/.

H4) is tested by comparing F2 formant frequencies extracted at V_{ON} and V_{MID} in /i a u/ following the velar stop. It will be asked whether there a difference in the magnitude of vowel-dependent velar stop production between languages that possess the additional coronal place category (dental) and languages that do not.

4.1.1.2 Effect of trajectory periods

As discussed in Chapter 2, various studies have indicated that the type of trajectory period (VC or CV) may have an effect on the magnitude of coarticulation exerted by a vowel on a consonant and also on the magnitude of variability in the vowel near the consonant boundary, and thus, on consonantal context-sensitivity (§2.4). The general hypotheses with regard to all four languages are:

H5) There is no effect of trajectory period on LE slope values, indicating a similar magnitude of vowel-dependent coarticulation in both periods (after Tabain *et al*., 2004).

Accordingly, hypothesis H6) predicts that just as trajectory period has no effect on LE slope values, it has no effect on SD values in F2 because a positive correlation between LE slope values and SD values is predicted (e.g., Recasens, 1985; see §3.4.1):

H6) There is no effect of trajectory period on SD values in F2 at the vowel-consonant boundary; SD values are similar in the vowel following the consonant (V_{ON} in CV) to those in the vowel preceding (V_{OFF} in VC), indicating equivalent consonantal sensitivity to the coarticulatory influence of the vowel (after Recasens, 1985a,b; Tabain *et al.*, 2004).

Modification of the higher formants, specifically, F3 lowering, is commonly associated with retroflex consonants (Fant, 1968; Stevens & Blumstein, 1975; Steriade, 1995; Ladefoged & Maddieson, 1996, pp. 27-28) in Hindi (Ohala & Ohala, 2001) and in Australian languages (Butcher, forthcoming a), and is associated with tongue retroflexion and the large size of the sublaryngeal cavity. In accordance with Fant (1968) and Stevens and Blumstein (1975) amongst others, and on the basis of the discussion in §2.1.2, a general cross-linguistic hypothesis regarding retroflex-to-vowel coarticulation is put forward to determine whether there is a (near) universal tendency with regard to F3 lowering in the vowel preceding the consonant; it is hypothesised that:

H7) There is an effect of trajectory period on retroflex-to-vowel coarticulation in Burarra, Gupapuyngu and Warlpiri; F3 lowering is greater in magnitude in the VC context than in the CV context (hence, there is greater F3 consonant-dependent coarticulation on preceding vowels than following ones).

H7) predicts that F3 lowering is greater in magnitude in the VC trajectory period than in the CV period such that cues are enhanced at the left edge of the consonant.

4.1.1.3 Effect of prosodic prominence

It was established in §2.4 that prosodic prominence can have an effect on the following (see §3.3.1.1 for a discussion of how prosodic prominence is defined):

(i) the magnitude of coarticulation between a consonant and a vowel;
(ii) the amount of variability in the vowel near the consonant boundary.

The hypothesis is that, according to the hyper-articulation model (see §2.3), as prosodic prominence 'shifts articulations toward the hyper-articulate end of the continuum' (de Jong *et al.*, 1993), and assuming that a more coarticulation resistant consonant will exert stronger constraints on adjacent segments,

H8) There is an effect of prosodic prominence on LE slope and SD values; slope values and SD values at the vowel-consonant boundary (V_{OFF} in VC, V_{ON} in CV) are lower when the vowel is prosodically weak than when it is strong (see also Cho, 1999; 2001; 2004; 2005; de Jong *et al.*, 1993; de Jong, 1995; Lindblom *et al.*, 2007).

4.1.2 Methodology

The methodology pertaining to this chapter is discussed in full in §3.4.1. It can be divided into those procedures concerning Locus Equations, the comparison of retroflexes and palatals, and vowel-dependent velar coarticulation. Recall that in the analyses in this chapter, word size is not constrained.

4.1.2.1 Locus Equations, F2 variability and consonant loci

As described in §3.4.1.1, F2 formant frequencies were extracted from vowels at midpoints (V_{MID}) and at the vowel-consonant boundary (V_{OFF} in the VC period and V_{ON} in the CV period) and were analysed per consonant place of articulation, trajectory period and prosodic context (whether the vowel is prominent or non-prominent) using the LE method. An evaluation of the systematic influences of consonant place of articulation, (vocalic) prosodic prominence and trajectory period was based on Analyses of Variance (ANOVAs). The fixed factors in the linear regression model were consonant place of articulation (five levels: /p t ʈ c k/), trajectory period (two levels: VC, CV) and prosodic prominence (two levels: strong, weak). Pairwise post-hoc comparisons were performed with the Tukey's HSD method. An initial evaluation of the main effects of consonant place of articulation, prosodic prominence, trajectory period and language group on slope values across speakers and language groups was based on a Linear Mixed Models (LMM) analysis. The fixed factors were consonant place of articulation (five levels: /p t ʈ c k/), trajectory period (two levels: VC, CV), prosodic prominence (two levels: strong, weak) and language group (four levels: Arrernte, Burarra, Gupapuyngu, Warlpiri) with the random factor of speaker. The relationship between LE slope values and F2 variability (SD) was examined by means of Pearson's correlations. Consonant loci were derived per consonant place from F2 frequencies extracted at V_{MID}. and V_{OFF}/V_{ON}. As discussed in §3.3.1.2, secondary articulations and laminal dentals in the Arrernte and Gupapuyngu data were not considered in order to permit generalisations across languages.

4.1.2.2 Comparing retroflexes and palatals

As outlined in §3.4.1.2, the effects of the phonemic retroflex consonant on formant frequencies in adjacent /a/ vowels were examined by means of the Wilcoxon rank sum test with the fixed factor of consonantal place of articulation (three levels: /t ʈ c/) per formant (F1, F2 and F3) and trajectory period (VC, CV). Recall that the measurement points were V_{MID} (0.5 or 50%), V_{EQ} (0.7 or 70%) and V_{OFF} (0.9 or 90%) into the vowel preceding the stop, and V_{ON} (0.1 or 10%), V_{EQ} (0.3 or 30%) and V_{MID} (0.5 or 50%) into the vowel following the stop. F3 minima were calculated for each trajectory period (since F3 is the best measure of retroflexion). For the Arrernte speakers, the effect of word-position on retroflex coarticulation in the VC condition was examined by means of Wilcoxon rank sum tests with the fixed factor of word position (word-initial, non-word-initial) in order to address H3). As in the slope value analysis, word lengths were not constrained in order to ensure the maximum number of comparisons.

4.1.2.3 Velar coarticulation

As described previously in §4.1.1.2, to examine vowel-dependent velar stop coarticulation in CV sequences (H4)), F2 frequencies were measured at V_{ON} and V_{MID} in front, central and back vowels, /i a u/, following velar stops, per speaker (after Butcher & Tabain, 2004). Paired t-tests were conducted on these F2 frequencies at V_{MID} and V_{ON} in order to estimate the magnitude of vowel-dependent velar coarticulation, that is, whether it is maximal or sub-maximal. All CV sequences were included; the CV sequence was not limited to word-final position, or to a bisyllabic word, as in the Butcher and Tabain (2004) study, because of the constraints of the corpus. /ki/ and /ci/ sequences were compared at the two measurement points, V_{MID} and V_{ON}, in order to inform the discussion of (relative) F2 frequencies in the /ki/ context.

4.2 Results

4.2.1 Results – Locus Equations, F2 variability and F2 consonant loci

Slope values calculated for all speakers and language groups are tabulated in Table 22 (full details of slope values, loci and SD values are given in Appendix A). These values will be discussed per language in §4.2.1.1 to §4.2.1.4. As a first stage of the analysis, a Linear Mixed Model (LMM) was used to examine the effects of consonant place of articulation, trajectory period, prosodic prominence and language on slope values. Speaker was included as a random factor. The results of the procedure were as follows: the main effects of consonant place and trajectory period were significant ($F(4,233)=31.44$, $p<0.0001$; $F(1,233)=10.4$, $p<0.05$). The CV trajectory period was associated with significantly higher slope values than the VC period, *i.e.*, vowels tend to exert weaker coarticulatory effects onto following consonants than onto preceding ones. However, there was no effect of prosodic prominence ($F(1,233)=1.15$, $p>0.05$) or language group ($F(3,233)=3.516$, $p>0.05$). There was a significant interaction between consonant place and language group ($F(12,220)=5.34$, $p<0.05$) and between consonant place and prosodic condition ($F(4,220)=5.96$, $p<0.05$), although these interactions were very much weaker than the main effect of consonant. No other interactions were significant.

According to Tukey's multiple contrasts, as illustrated by Figure 7 in which data are divided into VC and CV trajectory periods, peripheral consonants were associated with higher slope values than non-peripheral consonants at the p<0.05 level (thus stronger vowel-dependent coarticulation). According to the figure, slope values are not only higher but also less variable for palatals and peripherals when the vowel follows than when the vowel precedes (but this was not tested statistically).

Table 22. LE slope values (F2) for /p t ʈ c k/ stops collapsed across speakers within language groups. The consonant and the vowel quality are given in the first two columns (L). Both prosodic conditions (S=Strong and W=Weak, where Weak indicates a lack of an F0 peak associated with the vowel) and both trajectory periods (CV and VC) are given. Intercepts are given elsewhere in Appendix A. * indicates that for at least one of the three speakers, n<10. Row and column averages (x̄) are given in grey.

		A		**B**		**G**		**W**		**x̄**
C	**V**	**CV**	**VC**	**CV**	**VC**	**CV**	**VC**	**CV**	**VC**	
p	**S**	0.5	0.3	0.8	0.7	0.85	0.6	0.8	0.6	0.6
	W	0.7	0.7	0.8	0.5	0.9	0.8	0.8	0.7	0.7
t	**S**	0.7*	0.6*	0.6	0.7	0.7	0.4	0.7	0.6	0.6
	W	0.6	0.6*	0.7	0.4*	0.7	0.4	0.6	0.6	0.6
ʈ	**S**	0.3	0.5	0.2*	0.6	0.7	0.6	0.7	0.7	0.6
	W	0.9	0.8	0.5	0.5	0.7	N/A	0.7	0.7	0.7
c	**S**	0.4	0.3	0.6	0.3	0.7	0.6	0.6	0.4	0.5
	W	0.4	0.1	0.4	0.7	0.6	0.3	0.55	0.4	0.4
k	**S**	1	0.9	1	0.8	1	0.8	1	0.7*	0.9
	W	0.9	0.9	0.9	0.7	1	0.6	1	0.6*	0.9
x̄		0.6	0.6	0.7	0.6	0.8	0.6	0.7	0.6	

With respect to the interaction between consonant place and prosodic prominence, for /t c/ and to a lesser extent, /k/, LE slopes tend to be lower when the vowel is weak, but for /p ʈ/, slopes tend to be higher when the vowel is weak. With regard to the significant interaction between consonant place and language group, it appears that for /t c k/, slope values do not differ according to group, while for /p/, Gupapuyngu values are relatively high and Arrernte slope values are relatively low while for /ʈ/, Burarra slope values are relatively low (although the number of tokens is small). In order to investigate such differences between languages in consonant-vowel coarticulation in a more fine-grained manner, each language group is now considered in turn.

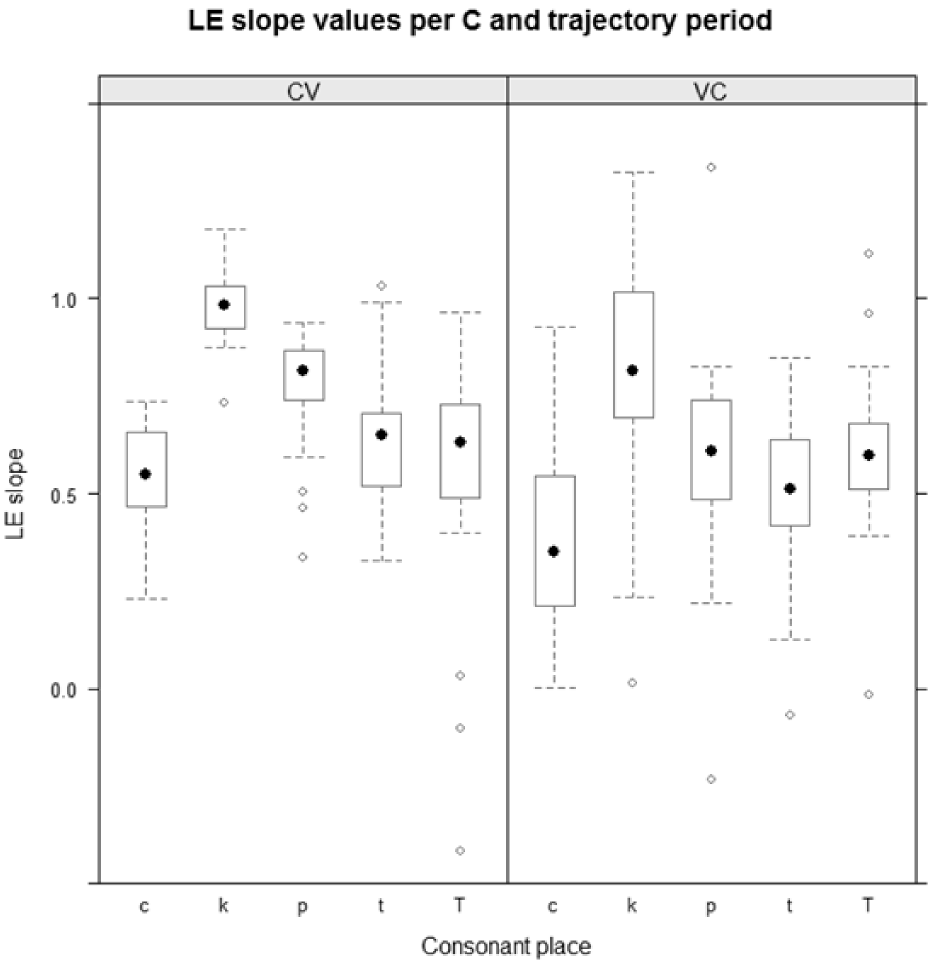

Figure 7. F2 LE slope values as a function of consonant place of articulation and trajectory period (CV, VC) across speakers, where ‘T’ represents /ʈ/.

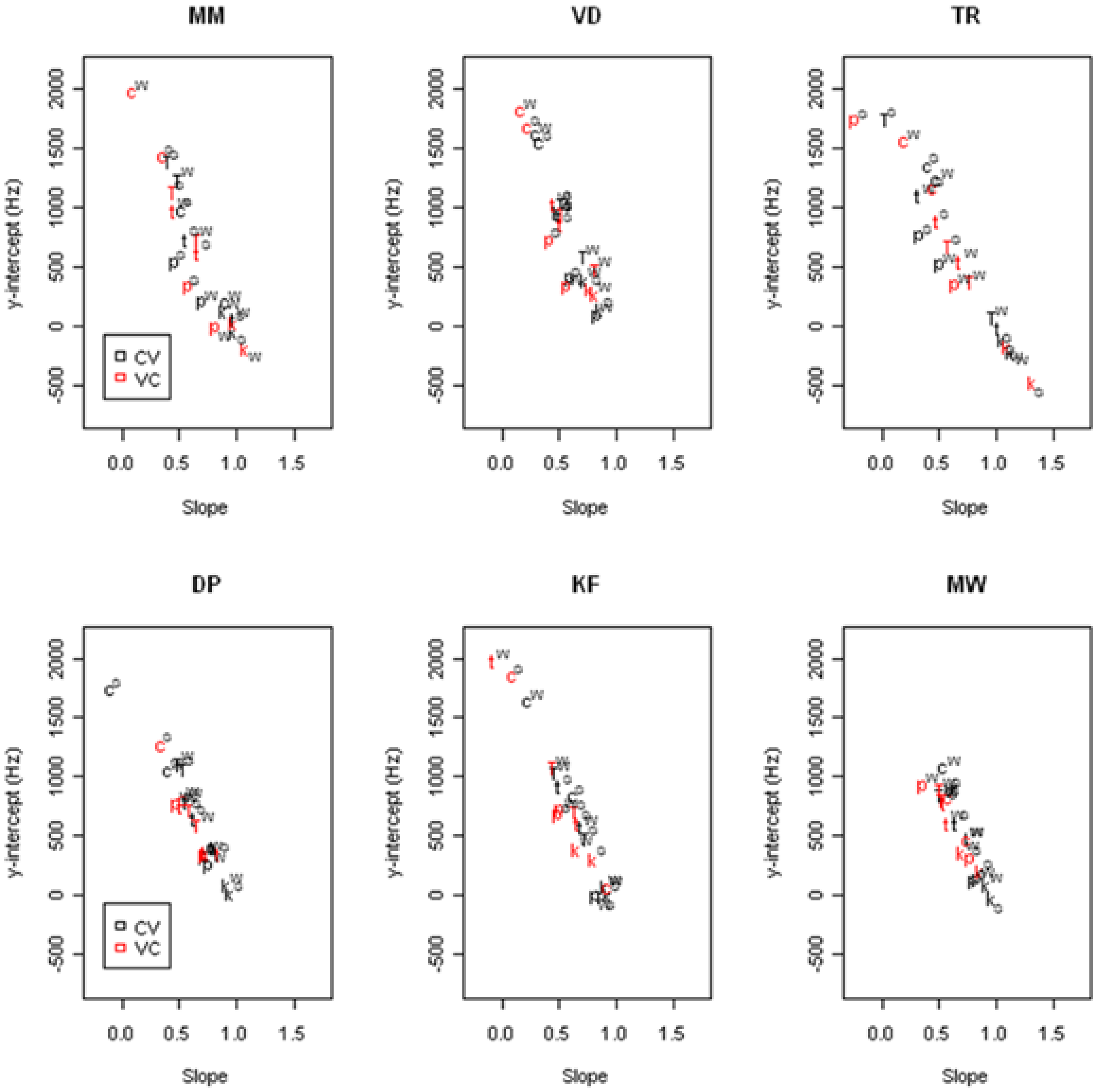

Figure 8. F2 LE scatterplots (slope by y-intercept) for Arrernte (upper) and Burarra (lower) speakers speakers in VC (red) and CV (black) and in Strong (S) and Weak (W) conditions. 'T' represents /ʈ/.

4.2.1.1 Locus Equations and Standard Deviation (SD) values – Arrernte

Slope values - Arrernte

Locus equation slopes for the Arrernte speakers are plotted against y-intercepts per speaker in Figure 8 (upper panel), labelled for consonant place, trajectory period (CV or VC) and prosodic context (S or W). Numbers of tokens are given in §3.4.1. There are main effects of consonant place of articulation, prosodic condition and trajectory period on LE slope for MM (F(1,33) 3.091, $p<0.05$) but not for VD (F(6,33) 0.67, $p=0.67$) or TR (F(6,33)=0.42, $p=0.86$). For MM, the identity of the consonant has an influence on the estimate (F(4,13)=4.0612, $p<0.05$). According to Tukey post-hoc tests, there are significant differences between the palatal and velar consonants ($p<0.05$) and between the retroflex and velar consonants ($p<0.05$); the velar is associated with higher values. All other comparisons are non-significant. The outliers in the plots, particularly for TR, appear to be due to two factors: (i) very irregular vowel distribution and (ii) the influence of surrounding segments.

For the Arrernte speakers, VC and CV slopes tend to be similar across consonant place and prosodic prominence contexts (slopes are given in Table 22). For MM and VD, there is a very weak tendency towards lower slope values and higher y-intercepts in the VC condition than in the CV condition. The bilabial and the retroflex slopes are higher in the weak vowel context, consistent with the results of the LMM across languages (although it is very likely that retroflex-to-vowel coarticulation is greater in magnitude than vowel-to-retroflex coarticulation, in particular, in the anticipatory direction), especially when those vowels follow (in CV). In velars, there is a tendency towards an equal or smaller slope when the vowel is prosodically weak.

For VD and TR, palatals are highly separated from the other stops, with low slopes and high y-intercepts, while there is some overlap of apicals and peripherals. Palatals are not highly coarticulated by either preceding or following vowels, but slopes are especially low when the vowel precedes.

SD values – Arrernte

The issue of vocalic F2 variability at V_{OFF} in the VC condition and at V_{ON} in the CV condition will now be addressed, specifically, the matter of SD values in the vowels before and after the consonant. Recall the prediction that the magnitude of coarticulation resistance in consonants is inversely related to F2 variability in adjacent vowels (at the vowel-consonant boundary; see §2.2 and §3.4.1.1). Recall that this analysis relates to H6), which states that there is an effect of trajectory period on F2 SD values (because of the effects of consonant place of articulation on variability in adjacent vowels).

In Figure 9, SD values are plotted for language group (where 'A' is Arrernte, 'B', Burarra, 'C', Gupapuyngu and 'D', Warlpiri) per trajectory period (CV, VC) when consonant place of articulation categories are collapsed, to give an overall idea of variability in each trajectory period per language. Levene's t-tests for equality of variance (spread about the median) revealed that for the Arrernte speakers, there is greater variance at the vowel offset (VC condition) ($F=15.73$, $p<0.0001$), suggesting that consonants are more sensitive to the coarticulatory effects of preceding vowels. In the CV condition, smaller SD values are observed for the Arrernte (and the Burarra) speakers than for the Gupapuyngu and Warlpiri speakers. This pattern is present in the VC condition but is less marked. For Arrernte, weak vowels are associated with slightly smaller SD values than strong vowels, indicating reduced context-sensitivity in consonants adjacent to weak vowels (thus, consonants are more resistant to weak vowel effects).

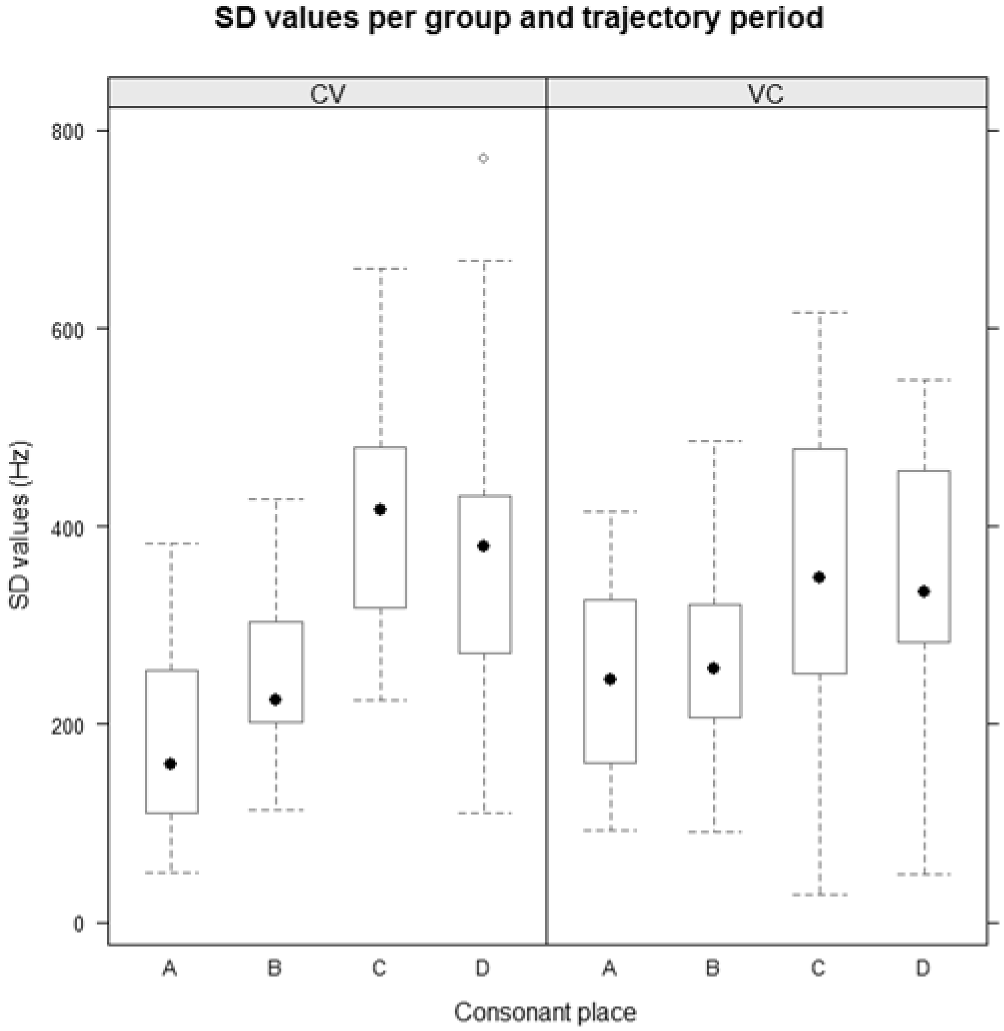

Figure 9. SD values (Hz) in F2 formant frequency at vowel terminal points or 'CV transition starting points' per language group (where 'A' is Arrernte, 'B', Burarra, 'C', Gupapuyngu and 'D', Warlpiri) and per trajectory period (CV, VC) when consonant place of articulation categories are collapsed.

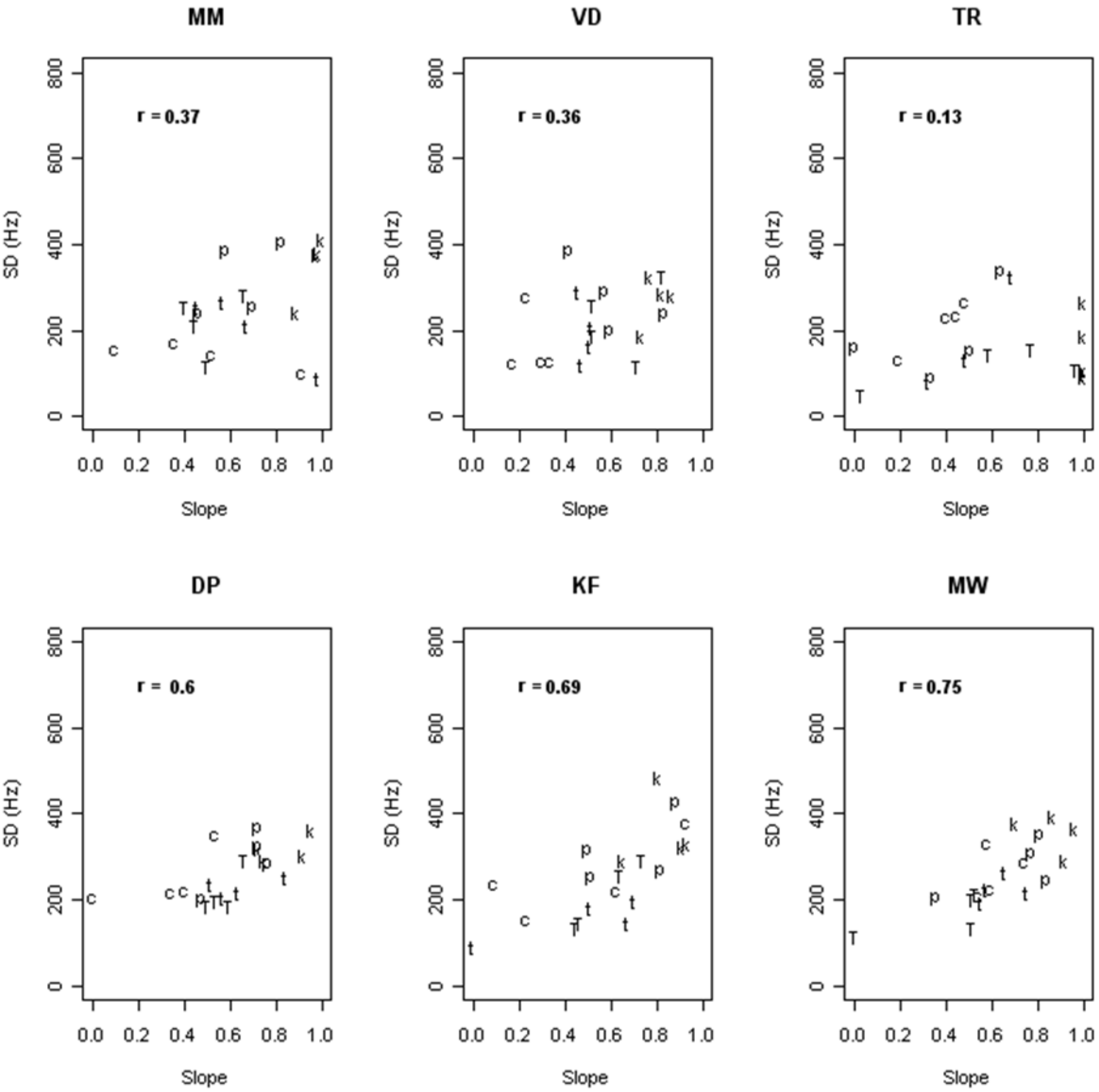

Figure 10. F2 LE slope as a function of standard deviations of the second formant frequency at the vowel terminal points for Arrernte (upper) and Burarra (lower) speakers showing the corresponding consonant label. Prosodic and trajectory periods (VC, CV) are collapsed. The correlation coefficient is given in bold. The consonants are /p t ʈ c k/. Here, 'T' represents /ʈ/.

SD values appear to covary with consonant place of articulation more than with trajectory period or prosodic prominence. There is a general trend towards lower SD values associated with the coronal stops, especially the palatal stop, and higher SD values associated with the peripheral stops (with the exception of the palatal stop for speaker TR). In Figure 10, SD values are plotted against LE slope values (at V_{OFF} preceding the consonant, or VC, and at V_{ON} following the consonant, or CV) per speaker. Values in the figure - but not in the analysis - are collapsed over prosodic and trajectory period to give a broad idea of variability according to consonant place. The Pearson's correlation coefficient is given per speaker in the top-right quadrant of the plot. Full details of the correlation results are given in Appendix A.

A weak tendency is observed for variability at the vowel-consonant boundary to increase as coarticulation between the consonant and the vowel increases (measured by the LE). In other words, those stops that appear to be more context-sensitive on the slope measure tend to some extent to be associated with higher variability in neighbouring vowels (at vowel-consonant boundaries). The mean correlation size between the slope and SD values for the Arrernte speakers is 0.29 (and 0.365 with the exclusion of speaker TR, for whom sample sizes are low). For speaker MM, for example, the peripheral stops tend to be associated both with higher slope values and with higher SD values than the non-peripheral stops, indicating strong context-sensitivity.

Summary – Arrernte

Across the Arrernte speakers, slope values tend to be high for velar stops, low for palatal stops, and intermediate for alveolar, retroflex and bilabial stops. /p/ and /ʈ/ tend to coarticulate more with weak vowels, especially in the CV trajectory period. Stops tend to coarticulate more with following than preceding vowels, especially when those vowels are prosodically weak.

A weak tendency is observed for variability at the vowel-consonant boundary to increase as coarticulation between the consonant and the vowel increases. Peripheral stops tend to be associated with greater variation than non-peripheral stops. LE slope values tend to be similar across VC and CV trajectory periods but SD values tend to be slightly higher in the VC condition (there is greater variance at the offset of the vowel preceding the consonant that at the onset of the vowel following), for all places of articulation.

4.2.1.2 Locus Equations and Standard Deviation (SD) values – Burarra

Slope values - Burarra

For the Burarra speakers, DP, KF and MW, LE slopes are plotted per speaker in Figure 8 (lower panel), labelled for consonant place, trajectory period (CV or VC) and prosodic context (S or W). For DP and MW but not for KF,[35] there are main effects of consonant place of articulation, prosodic condition and trajectory period on LE slope (DP, $F(6,33)=5.287$, $p<0.001$; KF, $F(6,33)=1.48$, $p=0.215$; MW, $F(6,33)=3.382$, $p<0.05$). For DP and MW, the place of the consonant has a very

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[35] This result for KF may be due to two unrealistic values in the VC condition and the weak vowel context for /t c/, which in turn appear to be due to the small number of data points, at least in the case of /t/.

significant influence on the estimate (DP, F(4,33)=6.82, p<0.0001; MW, F(4,33)=5.05, p<0.005). For DP, the trajectory period also has an influence (F(1,33)=4.42, p<0.05); slope values are lower in the VC condition (therefore, the consonant undergoes less coarticulation by the preceding vowel). All other comparisons are non-significant. Post-hoc comparisons for DP and MW show that the alveolar differs from other consonants (DP, /t k/, p=0.05; /t c/, p<0.01; /p t/, p<0.005; /t ʈ/, p<0.0005; MW, /t k/, p<0.05; /t p/, p<0.01); it is associated with lower slope values than /p/ and /k/ and higher slope values than /ʈ/ and /c/. As in the case of Arrernte speaker, TR, outliers in the plots, particularly for MW, appear to be due to two factors: (i) irregular vowel distribution and (ii) the influence of surrounding segments.

With regard to trajectory period and prosodic context, it is evident that there is a general trend towards lower slope values and higher y-intercepts in the VC condition than in the CV condition, especially for the peripherals, /p k/, and in the weak vowel condition than in the strong vowel condition (for DP and MW). That is to say, consonants tend to undergo less vowel-dependent coarticulation with the preceding vowel, especially when it is weak. For /t/ and /c/, the slope associated with the VC context is higher if and only if the vowel is prosodically prominent.

With regard to particular places of articulation, bilabial consonants tend to coarticulate more with preceding vowels than following ones, whereas palatals and velars tend to coarticulate less with preceding vowels. There is a higher magnitude of coarticulation of alveolars and palatals by preceding vowels when the vowel is prosodically prominent. Recall that across the four language groups, the slopes of alveolars and palatals tended to be slightly higher when the vowel is prosodically prominent. However, there was no interaction between consonant place and trajectory period.

There is a good deal of slope overlap, particularly in the bilabials and the coronals, as for the Arrernte speakers. Speaker MW shows most overlap, with the majority of values falling between 0.5 and 1 in slope and between 0 and 1000Hz in y-intercept.

SD values – Burarra

In Figure 9, in which SD values are shown per language group, while it appears that SD values tend to be very slightly higher in Burarra VC sequences than in CV sequences, Levene's t-tests for equality of variance (spread about the median) revealed that variance was similar across the two conditions (F=2.01, p=0.16). SD values are higher for /c k/ in the VC condition, indicating increased context-sensitivity to the preceding vowel. It is also evident that there is greater variability in both vowel conditions in Burarra than in Arrernte. However, both of these languages show less variability than Gupapuyngu and Warlpiri.

As shown in Figure 10 (lower panel), for all Burarra speakers, there is a trend, as shown in the figure, towards lower SD values for the non-peripheral stops and higher SD values for the peripheral stops (thus, peripherals are associated with greater context-sensitivity than non-peripherals). Any trends regarding trajectory period or prosodic prominence are very weak, with one exception: for MW, variability is higher when the vowel is strong, indicating increased sensitivity in the consonant to the coarticulatory influences of strong vowels.

Figure 10 (lower panel) shows a tendency for variability at the vowel-consonant boundary to increase as coarticulation between the consonant and the vowel increases. For example, on the whole, speaker KF shows higher SD values associated with the velar and bilabial stops than with the non-peripheral stops. A higher mean correlation size occurs for Burarra than for Arrernte; for the Burarra speakers, the linear dependence between the locus and SD variables is moderate at $r=0.68$. For all speakers, correlations are significant at $p<0.01$.

Summary – Burarra

Across the Burarra speakers, the palatal and retroflex stops tend to be associated with relatively low slope values and low F2 SD values at the vowel-consonant boundary, and bilabial and velar stops, with high slope and SD values, as was seen previously in §4.2.1.1 for Arrernte speakers. Slope values tend to be slightly higher in the CV condition, indicating that vowel-dependent coarticulation is slightly larger in magnitude when the vowel follows the stop. There is a weak tendency for consonants to be associated with smaller slope values, *i.e.*, to undergo less vowel-dependent coarticulation, when the vowel is weak. For MW, variability is higher in the context of strong vowels, but there are no observable effects for DP and KF.

4.2.1.3 Locus Equations and Standard Deviation (SD) values – Gupapuyngu

Slope values - Gupapuyngu

The Gupapuyngu speakers' LE slopes are plotted against y-intercepts per speaker in Figure 11 (upper panel), labelled for consonant place, trajectory period (CV or VC) and prosodic context (S or W). For AM and BT but not for EG (for whom there are fewer tokens), there are main effects of consonant place of articulation, prosodic condition and trajectory period on slope (AM, $F(6,33)=8.636$, $p<0.0001$; BT, $F(6,33)=3.6$, $p<0.01$). For AM and BT, consonant identity has a very significant influence on the estimate (AM, $F(4,33)=12.29$, $p<0.0001$; $F(4,33)=5.29$, $p<0.005$). Post-hoc comparisons show that the most reliable differences between means occur between the palatal and other consonants (AM, /c k/, p<0.005; /c t/, p<0.0005; /c p/, p<0.0001; /c ʈ/, p<0.0001; BT, /c p/, <0.05; /c ʈ/, p<0.01); /c/ is associated with lower slope value means than the peripherals (bilabials and velars) and higher means than the apicals. All other comparisons are non-significant.

There is a tendency towards a separation of the consonants into two groups: the non-peripherals (alveolars, retroflexes and palatals), which are associated with lower slope values and higher y-intercepts, and the peripherals (bilabials and velars), which are associated with higher slope values and lower y-intercepts. The peripherals and palatals are particularly well separated. Bilabial consonants tend to coarticulate more with preceding vowels but for lingual consonants, there is a tendency towards less coarticulation with preceding vowels, as shown in Figure 11, with the possible exception of the retroflex. Additionally, the Gupapuyngu speakers show a clear tendency towards higher y-intercepts in the VC condition. In both conditions, the magnitude of vowel-dependent coarticulation tends not to vary according to prosodic prominence, with the possible exception of palatals, which tend to be coarticulated less by weak vowels, as would be predicted.

SD values – Gupapuyngu

For the Gupapuyngu speakers, there is no clear effect of trajectory period (VC, CV) on SD values when consonant place of articulation categories are collapsed (Figure 9). However, Levene's tests revealed a trend towards greater variance at the vowel onset (CV condition) (F=3.4, p=0.06) *i.e.*, consonants appear to be very slightly more sensitive to the coarticulatory influence of following vowels. For /p t/, SD values tend to be higher in the CV condition.

Plots of Gupapuyngu slope values against SD values in Figure 12 (upper panel), show a tendency for variability at the vowel-consonant boundary to increase as coarticulation between the consonant and the vowel increases. Correlations between slope values and standard deviations are weak (r=0.39) to moderate (r=0.61). The mean correlation is 0.51. For AM, the correlation of 0.39 is significant at p<0.05, while the correlations of 0.54 for BT and 0.61 for EG are significant at p<0.01. All SD values are tabulated in Appendix A.

Across the speakers, SD values tend to be highest for the velar stop and lowest for the palatal (with the exception of AM, for whom the retroflex is associated with the lowest SD values), while those associated with the apicals tend to be intermediate. With regard to the trajectory period, for EG, mean SD values are higher in the CV condition (CV, mean SD=391Hz; VC, mean SD=308Hz).

Furthermore, across speakers, higher SD values tend to occur for lingual consonants when the vowel is prominent. No other trends are evident.

Summary - Gupapuyngu

For these speakers, the peripherals tend to be associated with relatively high slope values and high F2 variability at the vowel-consonant boundary, and the non-peripherals, with low slope values and low variability. There is a strong tendency for slope values to be higher in the CV condition (thus, consonants are coarticulated more by following vowels than preceding ones) but values tend not to differ according to prosodic prominence. Overall, F2 variability is high in magnitude relative to the Arrernte and Burarra results.

4.2.1.4 Locus Equations and Standard Deviation (SD) values – Warlpiri

Slope values - Warlpiri

LE slopes are plotted against y-intercepts per Warlpiri speaker in Figure 11 (lower panel), labelled for consonant place, trajectory period (CV or VC) and prosodic context (S or W). For KR and RR but not for BP,[36] there are significant or near significant main effects of consonant place of articulation, prosodic condition and trajectory period on slope (BP, F(6,33)=1.174, p=0.34; KR, F(6,12)=2.742, p=0.06, RR, F(6,12)=6.164, p<0.005). For KR, trajectory period has a significant influence on the estimate (F(1,12)=14.7, p<0.005); the VC condition is associated with relatively low slope values. For RR, consonantal place has a significant influence on the estimate (F(4,12)=9.06, p<0.005). Post-hoc comparisons for RR show a difference between the alveolar and the peripherals (/t p/, p<0.05; /t k/, p<0.005) and between the palatal and the peripherals (/p c/, p<0.05; /k c/, p<0.01); the alveolar and palatal are associated with lower slope values than the peripherals. No other comparisons are significant.

In general, for the Warlpiri speakers, there is a tendency for the non-peripheral stops to be lower in slope values and higher in y-intercepts than the peripheral stops, but the coronal stops are not well separated.

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[36] Again, this appears to be due to unrealistic values, in this case for the retroflex stop.

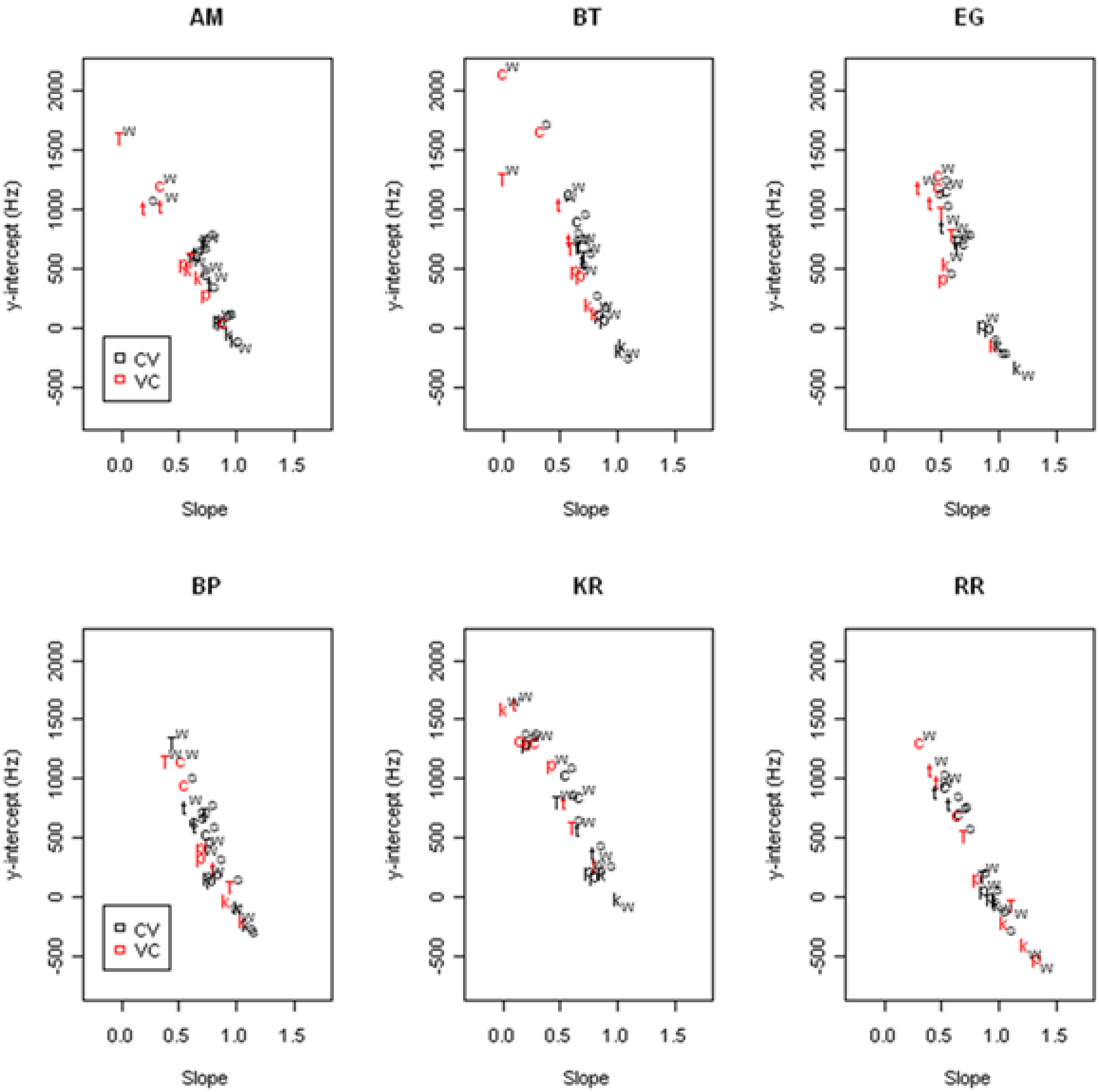

Figure 11. F2 LE scatterplots (slope by y-intercept) for Gupapuyngu (upper) and Warlpiri (lower) speakers speakers in VC (red) and CV (black) and in Strong (S) and Weak (W) conditions. 'T' represents an alveolar stop.

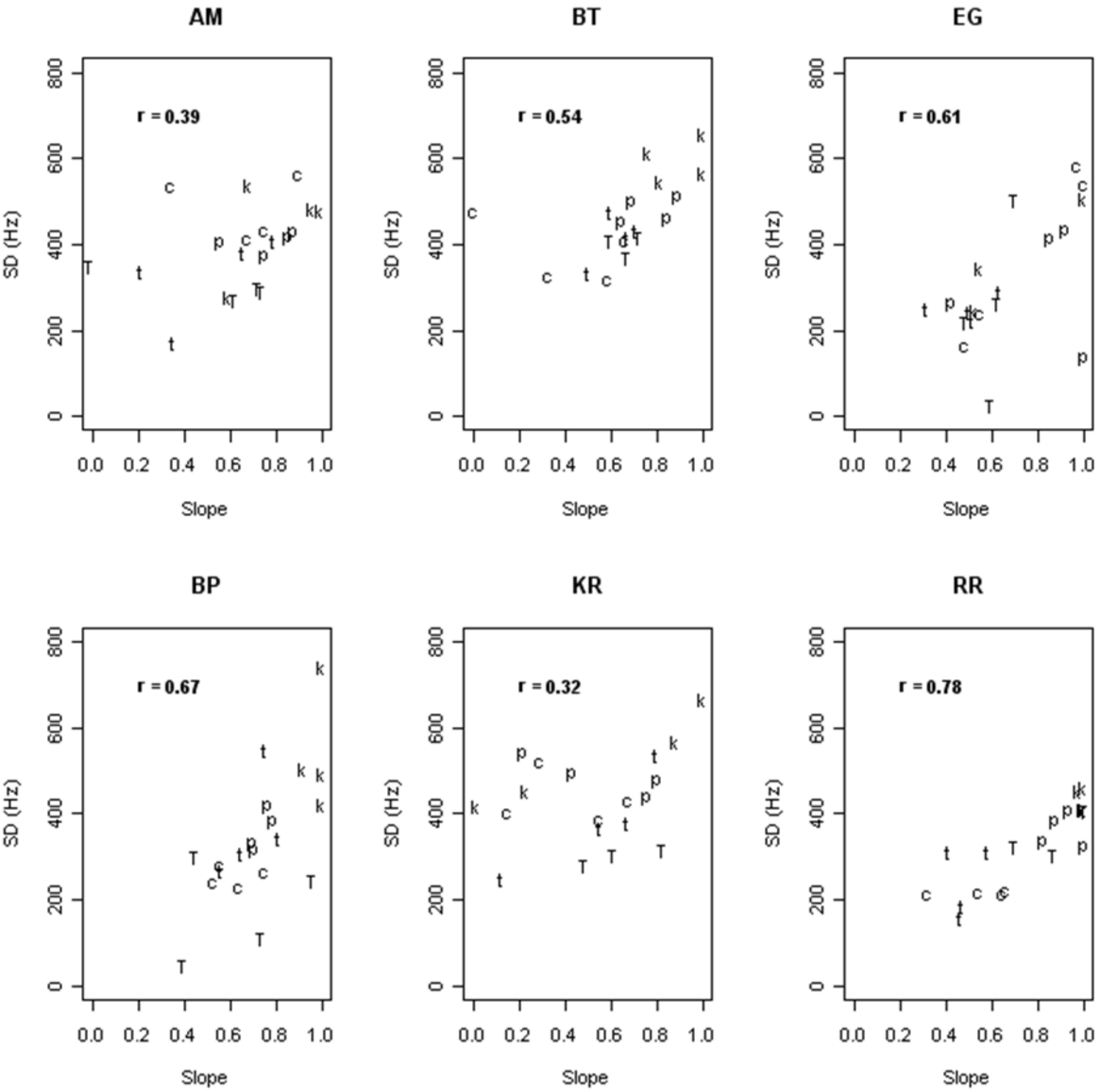

Figure 12. F2 LE slope as a function of standard deviations of the second formant frequency at the vowel terminal points for Gupapuyngu (upper) and Warlpiri (lower) speakers showing the corresponding consonant label. Prosodic and trajectory periods are collapsed. The correlation coefficient is given in bold. The consonants are /p t t̪ c k/. Here, ’T’ represents a retroflex stop.

With regard to trajectory period and prosodic context, for BP and KR, there is a tendency for the slope values in the VC context to be lower than the slope values for the CV context. There are two exceptions: BP, /t/ when the vowel is strong and KR, /t̪/, when the vowel is weak). That is, consonants tend to coarticulate less with the preceding vowel than the following one. Across speakers, in the CV condition, the lingual slope values associated with weak vowels tend to be slightly lower than for prosodically prominent vowels (*i.e.*, lingual consonants are less sensitive to the coarticulatory influence of weak vowels), e.g., in the case of the palatal stop, as is consistent wth the LMM results. In the VC condition, slope values tend to be similar across prosodic contexts, with the exception for speakers KR and RR of /p ʈ/, which are associated with lower slopes in the strong context.

SD values – Warlpiri

For the Warlpiri speakers, there is an effect of trajectory period (VC, CV) on SD values when consonant place of articulation categories are collapsed (Figure 9); there is greater variance at the vowel onset (CV) (F=520, p<0.0001), suggesting that, as is the case for Guypapuyngu speakers, consonants are slightly more sensitive to the coarticulatory influence of following vowels.

Plots of Warlpiri SD values against slope values are given in Figure 12 (lower panel). All values are tabulated in Appendix A. For BP, KR and RR, the palatal and retroflex stops tend to be associated with smaller SD values (thus, less context-sensitivity) than other consonants. Alveolar stops tend to be associated with low to intermediate SD values and bilabial and velar stops tend to be associated with the highest SD values. There are no other clear trends.

A tendency is observed for variability at the vowel-consonant boundary to increase as coarticulation between the consonant and the vowel increases; correlations between slope values and standard deviations are weak (r=0.32) to moderate (r=0.78). The mean correlation size is 0.59. For speakers BP and RR, correlations of 0.67 and 0.78, respectively, are significant at p<0.01. For KR, the correlation of 0.32 approaches significance at the 0.05 level.

Summary - Warlpiri

For the Warlpiri speakers, the peripherals stops tend to be associated with higher slope values and more variability in F2 formant frequencies at the vowel-consonant boundary than the non-peripheral stops. In general, slopes tend to be higher in the CV condition; hence, stops tend to coarticulate more with following than preceding vowels. Slope values tend to be similar across prosodic contexts.

4.2.1.5 Results - F2 consonant loci

In an LMM analysis of F2 loci in the traditional, 'Haskins', sense (after Delattre *et al.*, 1955) (with fixed factors: consonant place of articulation, trajectory period, language group; random factor: speaker) the main effect of consonant place was significant (F(4,232)=4.21, p<0.005). The main effects of trajectory period (F(1,232)=0.3261, p>0.05) and language group were not significant (F(3,232)=0.15, p>0.05); nor were any of the interactions significant (all F2 loci are tabulated in Appendix A).

As is illustrated in Figure 13 (in which loci are collapsed over prosodic prominence conditions, trajectory periods and language groups, given that these factors are not associated with significant effects), according to Tukey contrasts, the palatal consonant is associated with higher consonant loci than the velar and bilabial consonants (/c p/, z=-2.7, p=0.05; /c k/, z=-3.09, p<0.05), while the retroflex is associated with higher loci than the velar (z=2.7, p=0.05) and the difference between the velar and the alveolar only approaches significance (z=2.6, p=0.07); full results are given in Appendix A). These results therefore provide some acoustical evidence of an F2-locus, suggesting that this may be a universally valid index of consonant place of articulation. It is also shown in the figures that the palatal is associated with the highest (mean) locus and that the apical stops do not differ. The bilabial tends to be associated with slightly lower loci than the velar. In some cases, the peripheral loci are 0, indicating that there is no locus for these consonants (Tabain, 1996, p. 152), or negative (which occurs on some occasions when the slope for the bilabial is above 0.8 and for the velar is above 0.9). The high variability in the consonant locus that is associated with the peripheral and velar stops – and occurs primarily in the CV trajectory period for the velar stop - is likely related to the very high, often greater than 1, slope values (and recall that slopes tend to be greater in the CV condition), and ultimately to articulatory variability in the location of the constriction, *i.e.*, there is no real bilabial or velar locus in these languages (see §4.2.3 with regard to vowel-dependent velar coarticulation). There is in fact greater consonant locus variability in /k/ in the four languages (and also /ʈ/ in Arrernte) than in the other consonants. For the coronal places of articulation, consonant locus variability is similar in the two trajectory periods.

It is evident in Figure 14 that consonant locus variability is greater in Gupapuyngu and Warlpiri than in Burarra and, especially, Arrernte. With regard to locus variability per place of articulation, the peripherals tend to be more variable than the non-peripherals. In fact, in general, consonant locus variability appears to be positively correlated with slope variability as would be anticipated. For the Warlpiri speakers, the retroflex plosive is also associated with greater locus variability.

For the Arrernte speakers, shown in Figure 14 (lower left, marked ‘A’), according to Table 23 for the CV condition and Table 24 for the VC condition, the coronal stops tend to be associated with higher mean loci ($\bar{x}$=2000Hz) than the peripherals (/p/, $\bar{x}$=850Hz; /k/, $\bar{x}$=1200Hz), especially the bilabial. As shown in the same figure (lower right, ‘B’) and tabulated in Table 23 the CV condition and Table

24 for the VC condition, for the Burarra speakers DP and KF, /t/ and /ʈ/ are associated with the highest loci (x̄=1900Hz). For KF and MW, /c/ is also associated with high loci, while the peripherals tend to be associated with the lowest loci (/p/, x̄=1020Hz; /k/, x̄=985Hz). For the Gupapuyngu speakers, as shown in Figure 14 (upper left, ‘C’) and tabulated in Table 23 for the CV condition and Table 24 for the VC condition, the velar is associated with unrealistically low mean loci (x̄=-2.3). Of the realistic values, for all speakers, the bilabial stop is associated with the lowest mean loci and the palatal with the highest. Finally, after discounting unrealistic velar loci, typically, for Warlpiri speakers, as shown in Figure 14 (upper right, ‘D’), the bilabial is associated with the lowest mean locus and the palatal with the highest. The median velar locus is higher in Warlpiri than in the other three languages (M=1691z), suggesting a more anterior constriction, although the box extends to a much lower value, indicating great variability.

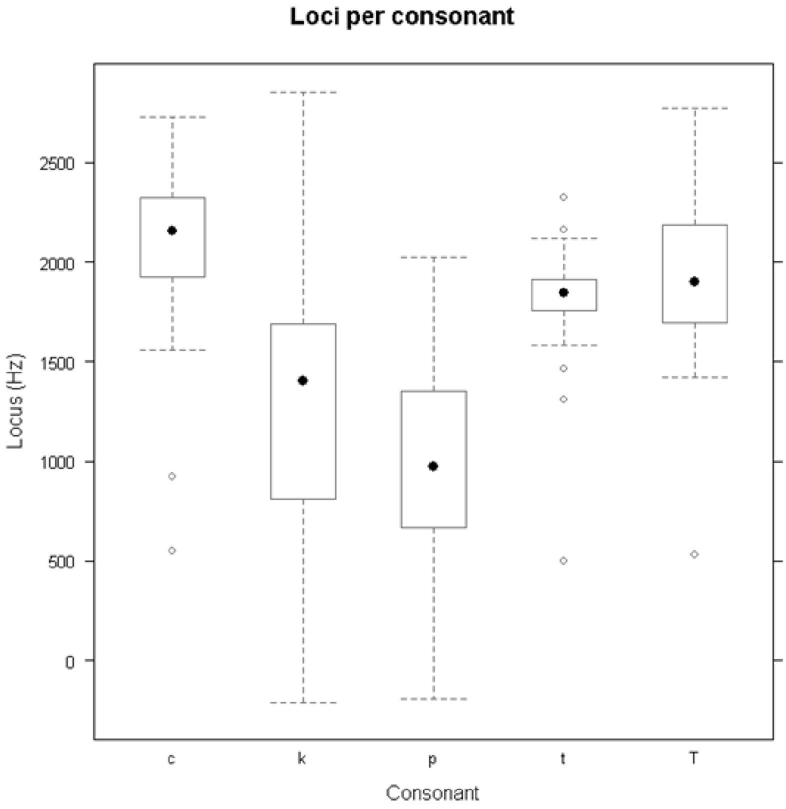

Figure 13. F2 consonant locus plotted against consonant place of articulation across speakers and language groups, where ‘T’ represents /ʈ/.

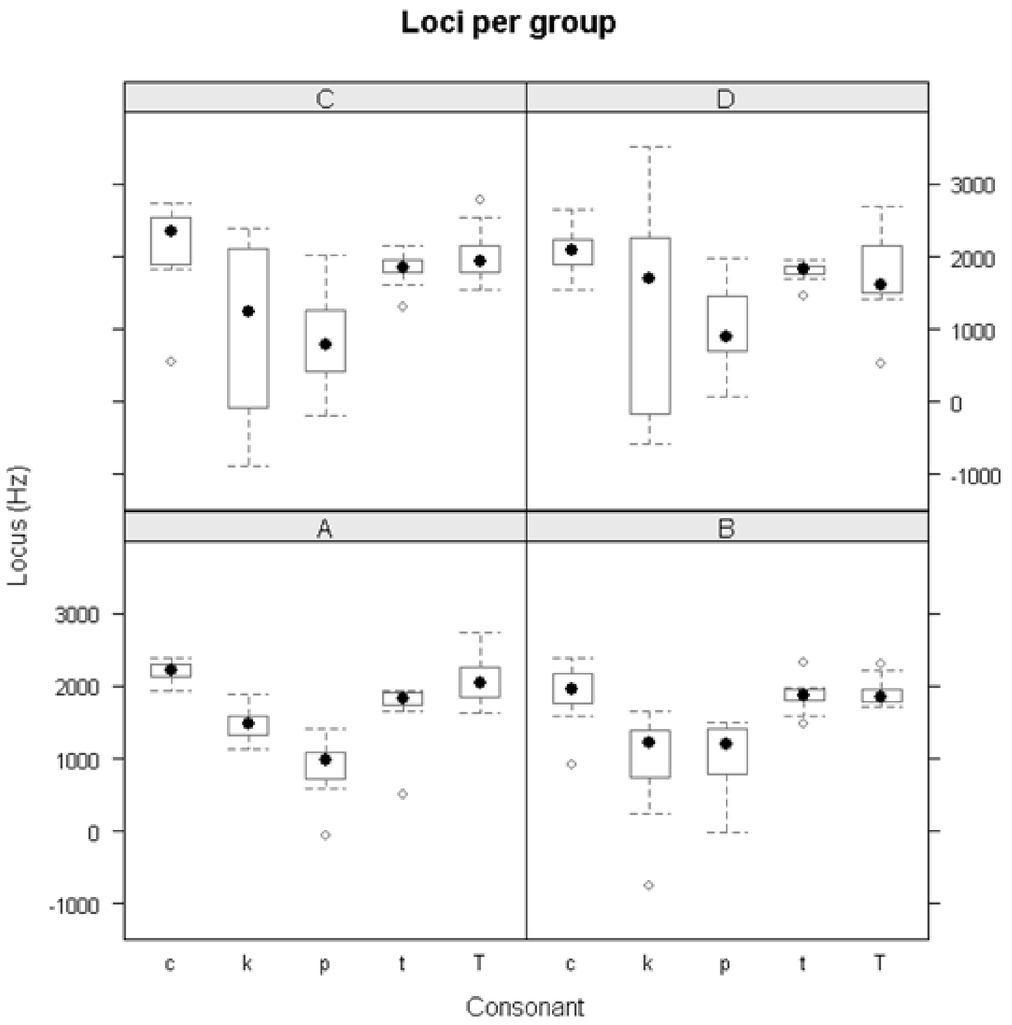

Figure 14. F2 consonant locus as a function of consonant place of articulation and language group (where 'T' represents /ʈ/, and where 'A' is Arrernte, 'B', Burarra, 'C', Gupapuyngu and 'D', Warlpiri).

Table 23. F2 consonant loci in the CV condition averaged per group. Measurement points are V_{ON} (0.1) and V_{MID} (0.5) into the vowel following the consonant. All unrealistic values removed prior to calculation of averages. Unrealistic values are marked by an asterisk.

C	**V**	**A**	**B**	**G**	**W**
p	**S**	1046	1027	553	763
	W	776	898	509	689
t	**S**	1835	1861	1947	1881
	W	1745	1944	1937	1763
ʈ	**S**	2010	1726	1968	2172
	W	2093	1812	1996	1607
c	**S**	2310	2250	2606	2375
	W	2390	2250	2290	2364
k	**S**	1502	373*	N/A	1984
	W	1404	1129	2111	2853

Table 24. F2 consonant loci in the VC condition averaged per group. Measurement points are V_{MID} (0.5) and V_{OFF} (0.9) into the vowel preceding the consonant. All unrealistic values removed prior to calculation of averages.

V	**C**	**A**	**B**	**G**	**W**
S	**p**	1151	1294	1124	1312
W		555	1475	1259	1536
S	**t**	1826	2006	1651	1725
W		1853	1638	1745	1830
S	ʈ	1893	1833	1640	1738
W		2185	1867	1760	1786
S	**c**	2171	1990	2026	1894
W		2106	1525	2020	2085
S	**k**	1497	1500	-1274*	2036
W		1668	1314	1066	1641

4.2.1.6 Summary – LE slope values, SD values and F2 consonant loci

As in previous studies, the peripherals (*i.e.*, velar and bilabial consonants) tend to be associated with the highest slope values, alveolar and retroflex consonants tend to be intermediate, and palatal consonants are associated with the lowest slope values (Table 25). The summary of trajectory period and prosodic prominence effects is given in Table 26 and Table 27 to show the overall patterns across the four languages. With regard to the central tendency, slope values tend to be slightly lower in the VC condition (when the vowel precedes the consonant), with the possible exception of Arrernte, in which there is no clear difference in slopes between trajectory periods. When language groups are collapsed, slope values are significantly higher in the CV condition, indicating more anticipatory than carryover vowel-to-consonant coarticulation, with the possible exception of /ʈ/, *i.e.*, there is a high magnitude of coarticulation with the following vowel, regardless of place of articulation. There are no significant effects of prosodic prominence on slope values - although there is an interaction between consonant place and prosodic condition - and no strong effects on standard deviations. When a trend is evident, it indicates consonants undergo less vowel-dependent coarticulation when the vowel is weak, as would be predicted. However, it was shown that in Arrernte in both trajectory periods, slopes associated with /p ʈ/ are relatively low when the vowel is prosodically prominent.[37] With regard to cross-linguistic differences in the behaviour of various places of articulation, for /p/, Arrernte slope values are relatively low and Gupapuyngu values are high, while for /ʈ/, Burarra slope values are relatively low.

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[37] Additionally, for Warlpiri speakers, KR and RR, in the VC trajectory period, slopes associated with /p ʈ/ are relatively low when the vowel is strong, perhaps supporting a claim of post-tonic strengthening.

With regard to F2 variation, there is some magnitude of positive correlation between slope values and SD values. Moreover, SD values are higher, *i.e.*, there is more coarticulation, for the peripherals than the non-peripherals, just as slope values tend to be more variable for the peripherals than the non-peripherals, as was shown Figure 7 and Figure 9. For the Arrernte speakers, greater variance occurs in the VC context, indicating that consonants are more coarticulatorily sensitive to preceding vowels, but for the Warlpiri speakers, the opposite is true. However, for the Burarra and Gupapuyngu speakers, there is no significant effect of trajectory period on F2 variance. There are no apparent prosodic effects, with the exception of a trend in Gupapuyngu towards higher values associated with lingual consonants when the vowel is prominent. No other trends are evident.

With regard to consonant F2 loci, peripherals are generally associated with lower values than non-peripherals. In Burarra, Gupapuyngu and Warlpiri, the velar locus is highly variable, suggesting that, as in the clas*sic* consonant locus diagrams (Delattre *et al*., 1955), the velar stop is associated with variable F2 consonant loci, dependent on vowel context. The high variability in the bilabial locus is likely due to a relative lack of lingual specification. Consistent with the claims of Tabain *et al*. for Arrernte, Yanyuwa and Yindjibarndi (2004; see §2.1.2.4), the results reported in this chapter indicate a lack of a significant effect of trajectory period on consonant F2 loci in Arrernte, Burarra, Gupapuyngu and Warlpiri.

Table 25. Summary of LE slope values as a function of consonant place of articulation according to trajectory period (VC, CV). * indicates that for at least one of the three speakers, n<10.

Lang	**Trajectory**	**Trend**
A	**CV**	c<p|t*|ʈ<k
	VC	c<p<t*<ʈ<k
B	**CV**	ʈ*<c<t<p<k
	VC	p|t*|ʈ|c<k
G	**CV**	c|t<ʈ<p<k
	VC	c|t|ʈ<k<p
W	**CV**	c<t|ʈ<p<k
	VC	c<t<p<ʈ|k*

Table 26. Summary of trends in slope and SD values according to trajectory period (VC, CV) with the exclusion of the LMM analysis.

Lang	**Measure**	**Trend**	***Sig.***
A	**slope**	VC=CV	*n.s.*
	SD	VC>CV	p<0.0001
B	**slope**	VC<CV	*sig. for DP*
	SD	VC=CV	*n.s.*
G	**slope**	VC<CV	*n.s.*
	SD	VC<CV	*n.s.*
W	**slope**	VC<CV	*sig. for KR*
	SD	VC<CV	p<0.0001

Table 27. Summary of trends in slope and SD values according to prosodic prominence in the vowel (S = Strong, W = Weak).

Lang	**Measure**	**Comment**
A	**slope**	For /ʈ p/, W>S, for /t c k/, W<S; but *n.s*.
	SD	W=S
B	**slope**	Mixed results but *n.s*.
	SD	W=S
G	**slope**	*n.s.* but for /c/, W<S
	SD	S>W for /t c k/
W	**slope**	*n.s.* but in CV, W<S
	SD	W=S

4.2.2 Results – Comparing retroflexes and palatals

This section reports on the coarticulatory effects of the phonemic retroflex stop and the palatal stop on preceding and following vowels in F1, F2 and F3. To investigate vowel transitions into and out of the consonants, F1 F2 and F3 were examined during the vowel, /a/, preceding and following alveolar, retroflex and palatal stops. Recall that the hypotheses, H2) and H3), were that in Arrernte, pre-palatalisation (indicated by a raising of F2 and F3 formant frequencies and by a lowering of F1 frequencies) occurs in /a/ preceding phonemic retroflex stops in word-initial contexts. The literature on pre-palatalisation in Arrernte was discussed in full in §1.2.1.3. In H7), F3 lowering was hypothesised to occur in vowels preceding the retroflex stop in Burarra, Gupapuyngu and Warlpiri.

The methodology was discussed in full in §3.4.1.2. To reiterate, Wilcoxon rank sum tests were applied to the measurement points, V_{MID} (0.5), V_{EQ} (0.7) and V_{OFF} (0.9) into the vowel preceding the relevant intervocalic consonant and V_{ON} (0.1), V_{EQ} (0.3) and V_{MID} (0.5) into the vowel following the relevant consonant. Full details of formant frequency means and SD values, and also word lists, are given in Appendix A. Each language group is discussed in turn.

4.2.2.1 Comparing retroflexes and palatals – Arrernte

Table 28 shows F3 minima in Arrernte word-initial (WI) and non-word-initial (NWI) vowels preceding the phonemic retroflex (VC) and in vowels following the retroflex (CV). These minima apply to the entire vowel period. For MM and VD, F3 minima are highest in the word-initial context and lowest in the non-word-initial VC context. In the word-initial context, F3 minima tend to occur within the first 20% for MM and VD and at the midpoint for TR. In the non-word-initial VC context, for MM and VD, these F3 minima tend to occur approximately 75% into the vowel. In the CV context, F3 minima tend to occur between V_{ON} and 40% into the vowel.

Table 28. Arrernte and Burarra F3 ($\bar{x}$) minima (Hz) in the entire vowel, /a/, preceding (VC) and following (CV) the (intervocalic) phonemic retroflex stop where WI = word-initial, NWI = non-word-initial. Averages ($\bar{x}$) are given in grey.

		VC		**CV**	$\bar{x}$
		WI	**NWI**		
A	**MM**	2469	2140	2345	2318
	VD	2214	2013	2172	2133
	TR	2000	N/A	N/A	N/A
B	**DP**	1872		2000	1936
	KF	1880		1714	1797
	MW	1800		1731	1765

Vowel preceding

Figure 15 and Figure 16 show Arrernte speakers' linearly time-normalised and averaged F1, F2 and F3 trajectories in low central vowels preceding alveolar (marked in blue), retroflex (red) and palatal (black) stops in word-initial and non-word-initial contexts, respectively. Wilcoxon rank sum test results for the VC condition are given in Table 29. In the word-initial context, Figure 15 shows that during the second half of the vowel, in F1, the retroflex and alveolar conditions differ for MM but the pattern does not reach significance for VD (MM, W=964, p<0.0001; VD, W=1002, p=0.006), while for both MM and VD, the alveolar is associated with higher formant frequencies than the palatal condition (MM, W=940, p<0.0001; VD, W=595, p<0.0055). In F2, all conditions differ for both MM and VD (Table 29); the retroflex condition is associated with *higher F2 formant frequencies* than the palatal condition, and with *higher F2 formant frequencies* than the alveolar condition, indicating strong pre-palatalisation. In the case of TR, the palatal condition is associated with higher F2 formant frequencies than the retroflex condition (W=73, p<0.0001). In F3, for MM and VD, the retroflex condition is associated with higher F3 formant frequencies than the alveolar condition, but this pattern merely approaches significance for VD (MM, W=246, p<0.0001; VD, W=458, p=0.007). For both speakers, the palatal condition is associated with higher formant frequencies than the alveolar condition (MM, W=72, p<0.0001; VD, W=204, p<0.0055), but the retroflex and palatal conditions do not differ for either MM or VD. For TR, the retroflex condition is associated with lower F3 frequencies than the palatal condition (W=19, p<0.0001). These findings for speaker TR indicate the absence of pre-palatalisation and the presence of F3 lowering in /aʈ/.

In the non-word-initial context (in which no /t/ tokens occur for any speaker and in which no tokens occur for TR), as Figure 16 illustrates, for MM and VD the retroflex is associated with a higher F1 than the palatal condition (/ʈ c/, MM, W=591, p<0.0055; VD, W=2410, p<0.001; see Table 30 for all results). In F2, for MM and VD, the retroflex condition is associated with lower F2 frequencies than the palatal condition after the midpoint (MM, W=186, p=0.001; VD, W=589, p<0.0001). For both speakers, the retroflex is associated with a lower F3 than the palatal condition (/ʈ c/, MM, W=11, p<0.0001; VD, W=267, p<0.0001), *i.e.*, F3 lowering is occurring.

Comparing word-initial and non-word-initial /aʈ/ formant frequencies for the Arrernte speakers, MM and VD (see Table 31; means and SD values are given in Appendix A), F1 is lower and F2 and F3 are higher in the word-initial than in non-word-initial contexts, *i.e.*, pre-palatalisation is occurring in the word-initial context but not in the non-word-initial context.

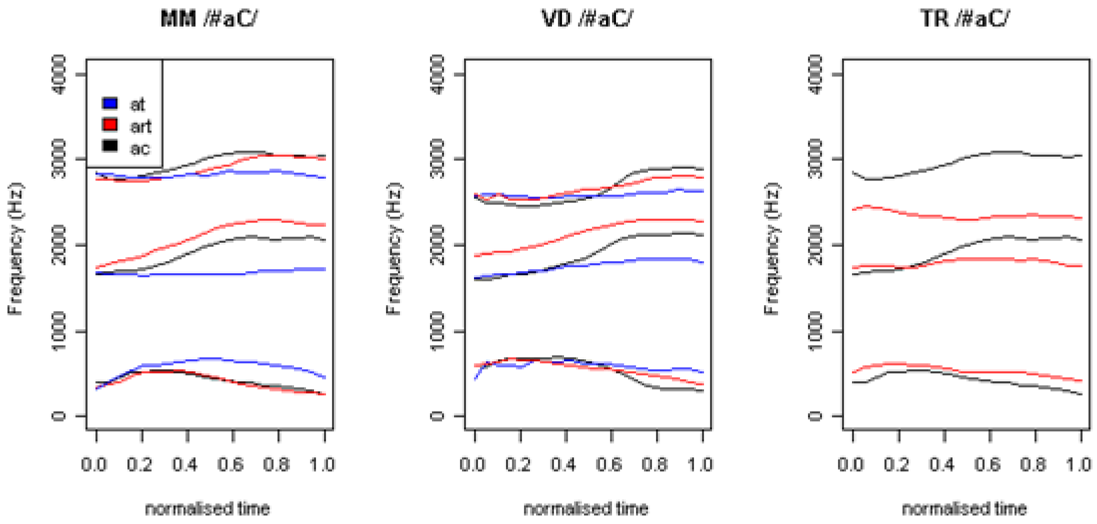

Figure 15. Averaged, linearly time-normalised F1, F2 and F3 trajectories for the Arrernte speakers for the entirety of the word-initial vowel /a/ preceding /t/ (blue), /ʈ/ (red) and /c/ (black) in the word-initial context. Here, 'rt' represents the retroflex stop.

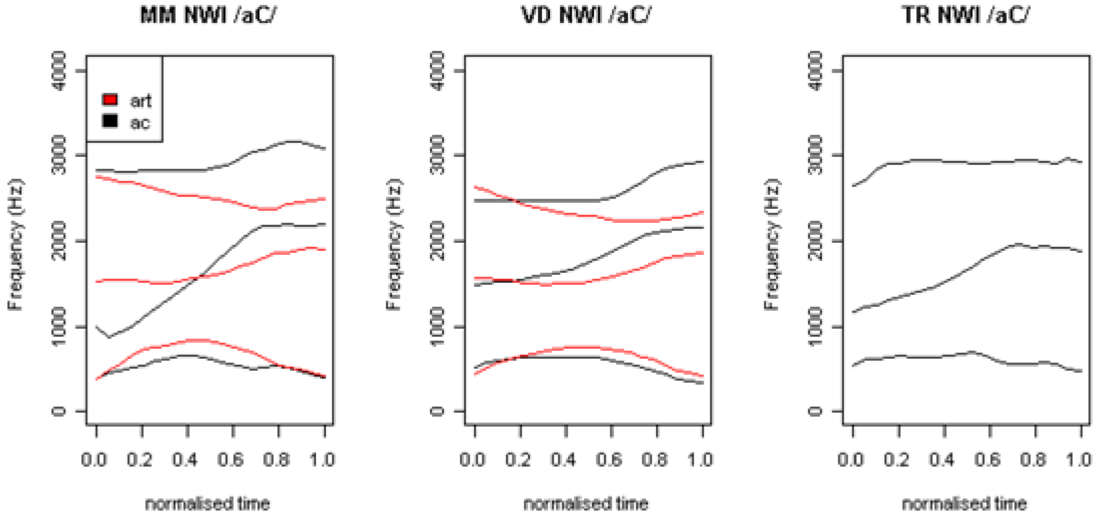

Figure 16. Averaged, linearly time-normalised F1, F2 and F3 trajectories for the Arrernte speakers during the entirety of the non-word-initial vowel /a/ preceding /ʈ/ (red) and /c/ (black). Here, 'rt' represents the retroflex stop.

Vowel following

Figure 17 shows the linearly time-normalised and averaged F1, F2 and F3 trajectories for MM and VD in low central vowels following alveolar, retroflex and palatal stops. (For TR, there are insufficient tokens.) Wilcoxon rank sum test results are given in Table 32. In F1, for MM and VD, the consonantal conditions tend to differ (with the exception of /t ʈ/ for MM, W=637, p=0.4), the palatal condition being associated with relatively low F1 formant frequencies during the first half of the vowel. In F2, the retroflex and alveolar conditions do not differ (MM, W=507, p=0.038; VD, W=2389, p=0.2). In F3, the retroflex condition is associated with lower F3 formant frequencies than both the alveolar and the palatal conditions (MM, /t ʈ/, W=1226, p<0.0001; /ʈ c/, W=290, p<0.0001; VD, /t ʈ/, W=3763, p<0.0055; /ʈ c/, W=5791, p<0.0055), while the alveolar and palatal conditions do not differ.

Table 29. Wilcoxon rank sum tests for the Arrernte speakers for /t ʈ c/ – VC in word-initial context in F1, F2 and F3 with W rounded down to the nearest whole number (W, p=* 0.0055, ** 0.001, *** 0.0001). Measurement points are V_{MID} (0.5), V_{EQ} (0.7) and V_{OFF} (0.9) into the vowel.

	F1			**F2**			**F3**		
	at-aʈ	**at-ac**	**aʈ-ac**	**at-aʈ**	**at-ac**	**aʈ-ac**	**at-aʈ**	**at-ac**	**aʈ-ac**
MM	964***	940***	1062	39***	94***	1887***	246**	72***	956
VD	1002	595*	962	217***	221*	1281***	458	204*	752
TR	N/A	N/A	245	N/A	N/A	73***	N/A	N/A	19***

Table 30. Wilcoxon rank sum tests for the Arrernte speakers for /ʈ c/ – VC in non-word-initial context in F1, F2 and F3 with W rounded down to the nearest whole number (W, p=* 0.0055, ** 0.001, *** 0.0001). Measurement points are V_{MID} (0.5), V_{EQ} (0.7) and V_{OFF} (0.9) into the vowel.

	F1	**F2**	**F3**
	aʈ-ac	**aʈ-ac**	**aʈ-ac**
MM	591*	186**	11***
VD	2410**	589***	267***
TR	N/A	N/A	N/A

Table 31. Wilcoxon rank sum tests for the Arrernte speakers – /Vʈ/ comparing word-initial (WI) and non-word-initial (NWI) contexts in F1, F2 and F3 with W rounded down to the nearest whole number (W, p=* 0.055, ** 0.001, *** 0.0001). Measurement points are V_{MID} (0.5), V_{EQ} (0.7) and V_{OFF} (0.9) into the vowel.

	F1	**F2**	**F3**
MM	115***	1422***	1418***
VD	590***	2218***	2147***
TR	N/A	N/A	N/A

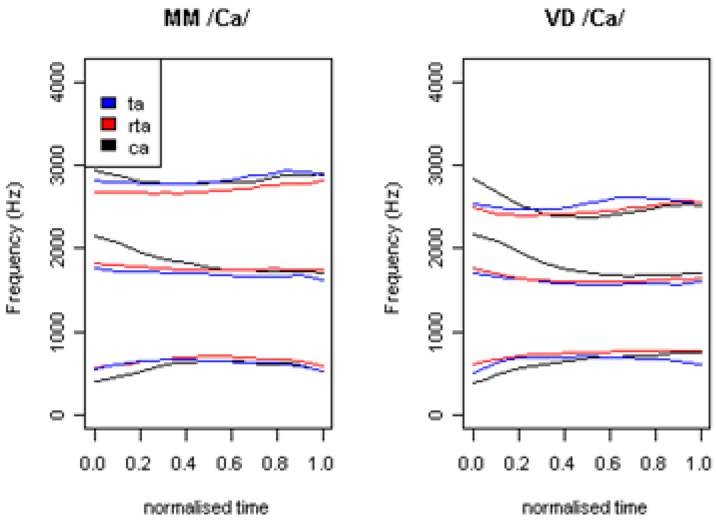

Figure 17. Averaged, linearly time-normalised F1, F2 and F3 trajectories for the Arrernte speakers MM and VD for the entirety of the vowel /a/ ~ [a] following /t/ (blue), /ʈ/ (red) and /c/ (black) in two contexts: upper, word-initial, lower, all word positions. Here, 'rt' represents the retroflex stop. The y-axis range is 0-4100Hz.

Summary - Arrernte

With regard to the VC trajectory period, for MM and VD, in the word-initial context, between V_{MID} and V_{OFF}, the phonemic retroflex condition is associated with a low F1 and a high F2 and F3 relative to the alveolar condition, as is the palatal condition. For these speakers, F2 formant frequencies are *higher* in the retroflex condition than in the palatal condition, *i.e.,* there is very strong pre-palatalisation. For VD, the pre-palatalised retroflex transition in F1 and F3 begins later in the vowel than is the case for MM at approximately 0.4 or 40% into the vowel. For both speakers, the F3 decline commences early in the vowel. In non-word-initial position, for MM and VD, the retroflex condition is associated with F1 raising and F2 and F3 lowering relative to the palatal condition, commencing between V_{ON} and V_{MID}, *i.e.* early in the vowel. These results indicate that pre-palatalisation is occurring for MM and VD in word-initial but not in non-word-initial VC environments. For TR, F3 lowering occurs in the vowel preceding the retroflex. With regard to the CV trajectory period, for the Arrernte speakers, in the first half of the vowel following the consonant, the retroflex condition is associated with higher F1 and lower F2 and F3 frequencies than the palatal condition.

These results indicate that while pre-palatalisation occurs in the word-initial context for MM and VD, it does not occur in the non-word-initial context for any speaker. In the latter context, there is F3 lowering indicating retroflexion. In the vowel following the retroflex stop, there is no evidence of palatalisation.

With regard to the palatal condition, this consonant is associated with an F2 increase that commences at or before V_{MID} and with a decrease in F3 that commences at or prior to V_{MID}. F1 is level or falling.

4.2.2.2 Comparing retroflexes and palatals - Burarra

As shown in Table 34, F3 minima are lower in the VC context than in the CV context for DP, but higher in the CV than the VC context for KF and MW. In the VC condition, F3 minima tend to occur between 80% into the vowel and vowel offset. In the CV condition, F3 minima tend to occur between the V_{ON} and V_{MID} for DP and KF, and between V_{MID} and V_{EQ} for MW.

Vowel preceding

Figure 18 shows the Burarra speakers' linearly time-normalised and averaged F1, F2 and F3 trajectories in low central vowels preceding alveolar, retroflex and palatal stops. All Wilcoxon rank sum test results for the VC condition are given in Table 33.

Table 32. Wilcoxon rank sum tests for the Arrernte speakers for /t ʈ c/ – non-word-initial CV in F1, F2 and F3 with W rounded down to the nearest whole number (W, p=* 0.0055, ** 0.001, *** 0.0001). Measurement points are V_{ON} (0.1), V_{EQ} (0.3) and V_{MID} (0.5) into the vowel.

	F1			**F2**			**F3**		
	ta-ʈa	**ta-ca**	**ʈa-ca**	**ta-ʈa**	**ta-ca**	**ʈa-ca**	**ta-ʈa**	**ta-ca**	**ʈa-ca**
MM	637	558*	1863***	507	65***	502**	1226***	313	290***
VD	1778*	2239***	13299***	2389	202***	1598***	3763*	1538	5791*

Table 33. Wilcoxon rank sum tests for the Burarra speakers for /t ʈ c/ – VC in F1, F2 and F3 with W rounded down to the nearest whole number (W, p=* 0.0083, ** 0.001, *** 0.0001). Measurement points are V_{MID} (0.5), V_{EQ} (0.7) and V_{OFF} (0.9) into the vowel.

	F1			**F2**			**F3**		
	at-aʈ	**at-ac**	**aʈ-ac**	**at-aʈ**	**at-ac**	**aʈ-ac**	**at-aʈ**	**at-ac**	**aʈ-ac**
DP	1143	1967***	5895***	1254	296***	987***	1805***	383***	790***
KF	1376	1259	2113	1067	227***	543***	1789***	106***	178***
MW	1311	2048**	8547***	1262	114***	799***	2576***	546***	711***

Table 34. Wilcoxon rank sum tests for the Burarra speakers for /t ʈ c/ – non-word-initial CV in F1, F2 and F3 with W rounded down to the nearest whole number (W, p=* 0.0083, ** 0.001, *** 0.0001). Measurement points are V_{ON} (0.1), V_{EQ} (0.3) and V_{MID} (0.5) into the vowel.

	F1			**F2**			**F3**		
	ta-ʈa	**ta-ca**	**ʈa-ca**	**ta-ʈa**	**ta-ca**	**ʈa-ca**	**ta-ʈa**	**ta-ca**	**ʈa-ca**
DP	1552	3003	16197***	1566	760***	5536***	1984	2134	9981*
KF	1737	1580	7645	1396	152***	1688***	1175**	547***	4987**
MW	1522*	2953	24058***	1874	853***	9212***	1844	1738*	13619***

In F1, during the second half of the vowel, for DP and MW, the palatal condition tends to be associated with lower F1 formant frequencies than the alveolar and retroflex conditions (DP, /t c/, W=1967, p<0.0001; /ʈ c/, W=5895, p<0.0001; MW, /t c/, W=4121, p<0.0001; /ʈ c/, W=12076, p<0.0001). For KF, no comparisons are significant. In F2, the alveolar and retroflex consonants do not differ for any speaker, while the palatal condition is associated with higher F2 frequencies than the alveolar and retroflex conditions (DP, /t c/, W=296, p<0.0001, /ʈ c/, W=987, p<0.0001; KF, /t c/, W=227, p<0.0001; /ʈ c/, W=543, p<0.0001; MW, /t c/, W=114, p<0.0001; /ʈ c/, W=799, p<0.0001). In F3, for every speaker, all conditions differ; the retroflex condition is associated with a lower F3 than the other conditions, especially after 0.4 or 40% into the vowel, while the palatal is associated with a higher F3 than the alveolar condition. In other words, there is retroflexion in the retroflex condition and a tendency towards F1 lowering and F2 and F3 raising – or palatalisation – in the palatal condition.

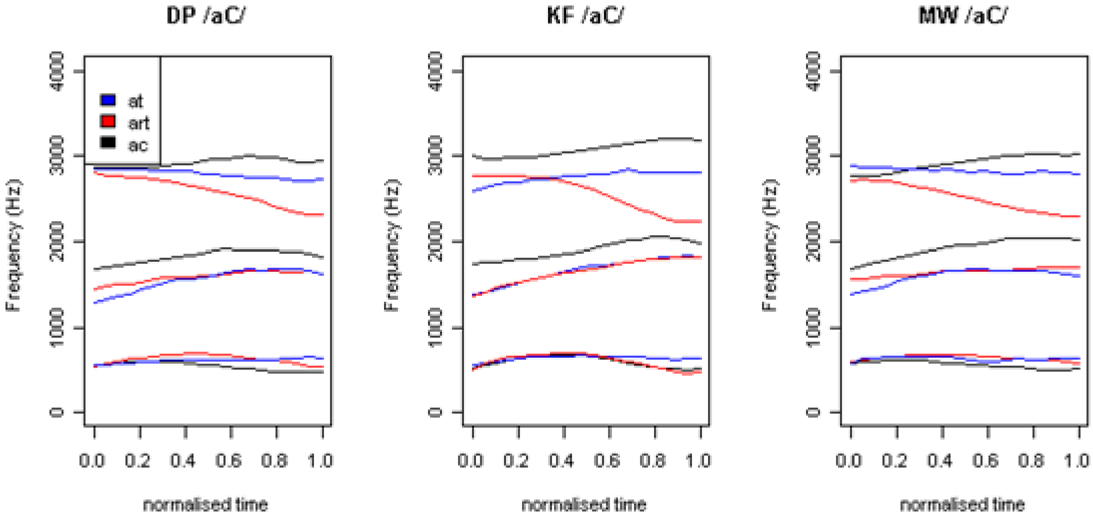

Figure 18. Averaged, linearly time-normalised F1, F2 and F3 trajectories for Burarra (upper) speakers during the entirety of the vowel /a/ preceding /t/ (blue), /ʈ/ (red) and /c/ (black). Here, 'rt' represents /ʈ/.

Vowel following

Figure 19 shows Burarra speakers' linearly time-normalised and averaged F1, F2 and F3 trajectories in low central vowels following alveolar, retroflex and palatal stops. All Wilcoxon rank sum test results are given in Table 34. In F1 between V_{ON} and V_{MID}, for DP and MW, the retroflex is associated with higher F1 formant frequencies than the palatal condition (DP, W=16197, p<0.0001; MW, W=24058, p<0.0001). In F2, for all speakers, the alveolar and retroflex conditions do not differ, while the palatal condition is associated with higher formant frequencies than the other conditions (DP, /t c/, W=760, p<0.0001; /ʈ c/, W=5536, p<0.0001; KF, /t c/, W=152, p<0.0001; /ʈ c/, W=1688, p<0.0001; MW, /t c/, W=853, p<0.0001; /ʈ c/, W=9212, p<0.0001). In F3, the retroflex and alveolar conditions tend not to differ, but for all speakers, the retroflex is associated with lower formant frequencies than the palatal condition (DP, W=9981, p<0.0083; KF, W=4987, p<0.001; MW, W=13619, p<0.0001) and for KF and MW, the alveolar is also associated with lower formant frequencies than the palatal condition (KF, W=547, p<0.0001; MW, W=1738, p<0.0083).

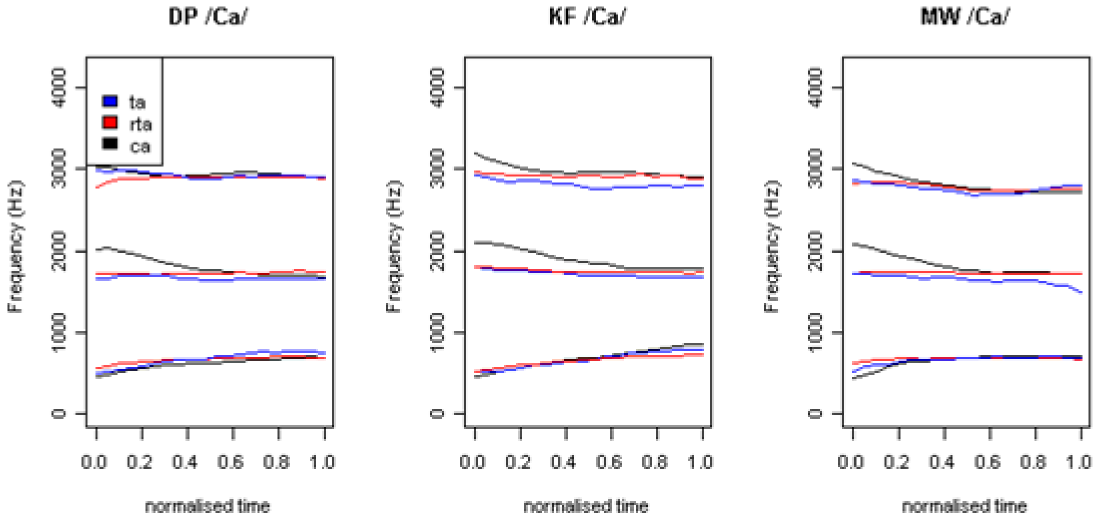

Figure 19. Averaged, linearly time-normalised F1, F2 and F3 trajectories for the Burarra speakers during the entirety of the vowel /a/ following /t/ (blue), /ʈ/ (red) and /c/ (black) in two contexts: upper, word-initial, lower, all word positions. Here, ’rt’ represents /ʈ/.

Summary - Burarra

For the Burarra speakers, in the VC trajectory period, the retroflex condition is associated with a strong F3 decline that commences early, at approximately 0.4 or 40% into the vowel, as was the case for the Arrernte speakers in the non-word-initial VC context. The F3 decline is also evident auditorily. The palatal condition is associated with a lowered F1 and raised F2 and F3 relative to the alveolar and retroflex conditions. In the CV trajectory period, the retroflex stop tends to be associated with relatively low F3 formant frequencies during the first half of the following vowel, but this F3 lowering is very small in magnitude in comparison to that occurring in the vowel preceding the stop. Typically, the palatal stop is associated with low F1 and high F2 and F3 formant frequencies in the first half of the following vowel. The F2 rise typically commences at vowel onset. In other words, there is retroflexion and not pre-palatalisation in the vowel preceding the retroflex. There is strong anticipatory palatal-to-vowel coarticulation. Carryover retroflex and palatal coarticulation is weaker than anticipatory coarticulation.

4.2.2.3 Comparing retroflexes and palatals – Gupapuyngu

According to Table 35, for the Gupapuyngu speakers, F3 minima are typically lower in the VC condition than the CV condition. In the VC condition, F3 minima tend to occur between 80% into the vowel and V_{OFF}. In the CV condition, F3 is fairly stable across the course of the vowel.

Vowel preceding

As shown in Figure 20, in Gupapuyngu the retroflex is associated with a decline in F3 formant frequencies from V_{ON} for BT and EG and from approximately 0.4 time-normalised or 40% into the vowel for AM, *i.e.*, transitions commence early in the vowel as in the case of Arrernte in non-word-initial position and in Burarra. The palatal stop is associated with relatively high F2 formant frequencies especially after V_{MID} in the preceding vowel. F3 rises somewhat across the course of the vowel, typically reaching its maximum prior to V_{OFF}.

Table 35. Gupapuyngu and Warlpiri F3 (mean) minima (Hz) in the entire vowel, /a/, preceding and following the (intervocalic) phonemic retroflex stop. Averages ($\bar{x}$) are given in grey.

		VC	**CV**	$\bar{x}$
G	**AM**	1783	1766	1774
	BT	1991	2390	2190
	EG	1856	2363	2109
W	**BP**	1880	1833	1856
	KR	1611	1820	1715
	RR	1792	2215	2003

Vowel following

Figure 21 shows Gupapuyngu speakers' linearly time-normalised and averaged F1, F2 and F3 trajectories of low central vowels following alveolar, retroflex and palatal stops. Wilcoxon rank sum test results are given in Table 37. In F1, during the second half of the vowel, the palatal condition is associated with lower formant frequencies than the retroflex and alveolar conditions (AM, /t c/, W=665, p<0.0083; /ʈ c/, W=1187, p<0.0083; BT, /t c/, W=685, p<0.001; /ʈ c/, W=1693, p<0.0001; EG, /t c/, W=196, p<0.0083; /ʈ c/, W=928, p<0.0001), but the retroflex and alveolar conditions do not differ. In F2, all conditions differ. As is clearly evident in the figure, the palatal is associated with relatively high F2 frequencies, the retroflex, with intermediate, and the alveolar with low frequencies. In F3, conditions tend not to differ.

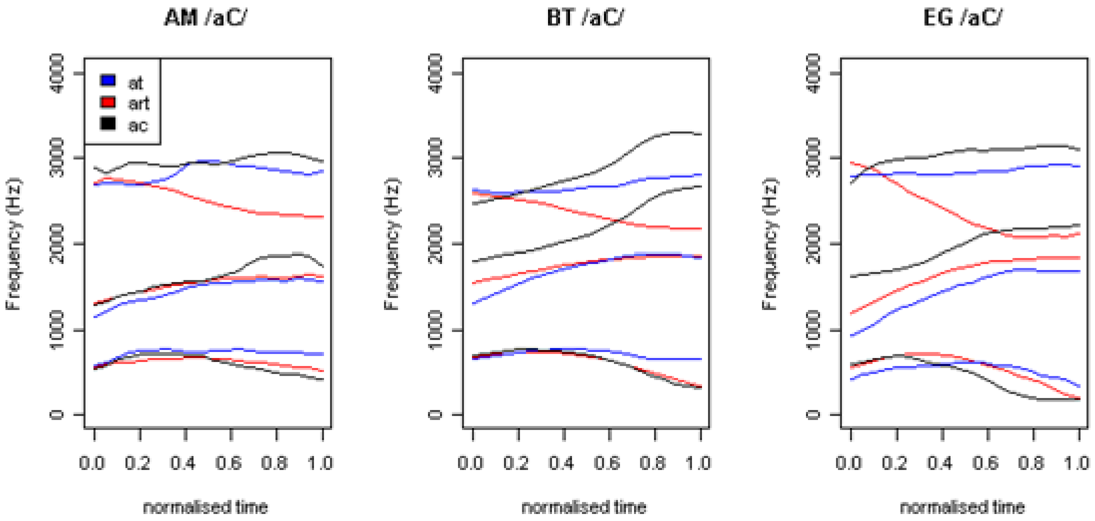

Figure 20. Averaged, linearly time-normalised F1, F2 and F3 trajectories for the Gupapuyngu speakers during the entirety of the vowel /a/ preceding /t/ (blue), /ʈ/ (red) and /c/ (black). Here, 'rt' represents /ʈ/.

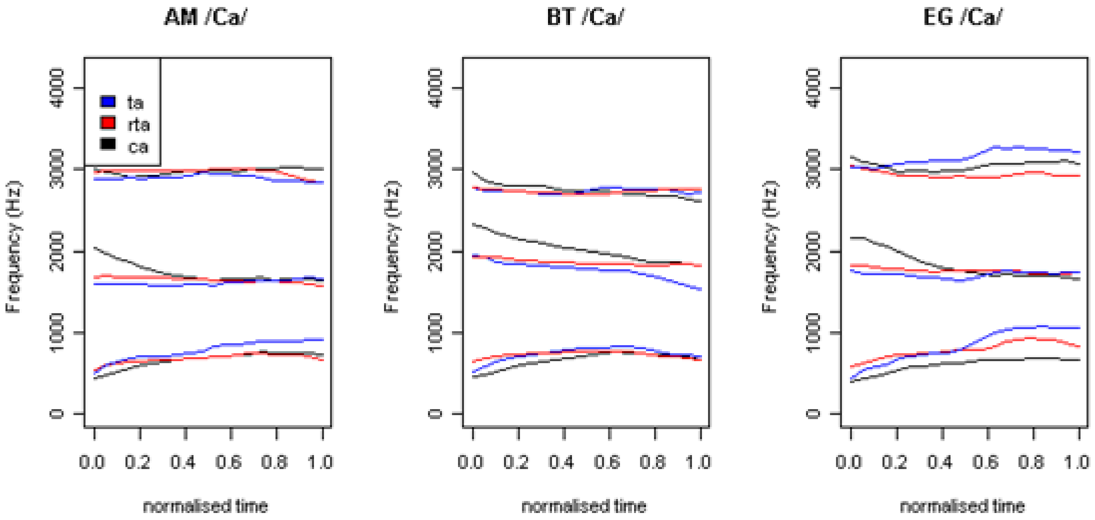

Figure 21. Averaged, linearly time-normalised F1, F2 and F3 trajectories for the Gupapuyngu speakers during the entirety of the vowel /a/ following /t/ (blue), /ʈ/ (red) and /c/ (black). Here, 'rt' represents /ʈ/. The y-axis range is 0-4100Hz.

Table 36. Wilcoxon rank sum tests for the Gupapuyngu speakers for /t ʈ c/ – VC in F1, F2 and F3 with W rounded down to the nearest whole number (W, p=* 0.0083, ** 0.001, *** 0.0001). Measurement points are V_{MID} (0.5), V_{EQ} (0.7) and V_{OFF} (0.9) into the vowel.

	F1			**F2**			**F3**		
	at-aʈ	**at-ac**	**aʈ-ac**	**at-aʈ**	**at-ac**	**aʈ-ac**	**at-aʈ**	**at-ac**	**aʈ-ac**
AM	375*	102**	377	149	19	193	388**	30	61***
BT	466*	61	250	305	0**	12***	563***	10	4***
EG	200	71*	252	37**	0***	4***	324***	0**	0***

Table 37. Wilcoxon rank sum tests for the Gupapuyngu speakers for /t ʈ c/ – non-word-initial CV in F1, F2 and F3 with W rounded down to the nearest whole number (W, p=* 0.0083, ** 0.001, *** 0.0001). Measurement points are V_{ON} (0.1), V_{EQ} (0.3) and V_{MID} (0.5) into the vowel.

	F1			**F2**			**F3**		
	ta-ʈa	**ta-ca**	**ʈa-ca**	**ta-ʈa**	**ta-ca**	**ʈa-ca**	**ta-ʈa**	**ta-ca**	**ʈa-ca**
AM	861	665*	1187*	286***	104***	480**	401*	368	1093
BT	1093	685**	1693***	801*	29***	157***	1199	312	721
EG	129	196*	928***	51**	24**	241**	186	106	361

Summary - Gupapuyngu

For the Gupapuyngu speakers, the retroflex stop is associated with retroflexion in the preceding vowel, while the palatal stop is associated with F2 raising (and some F3 raising) in the preceding vowel. The F2 increase typically commences at the vowel onset. In the following vowel, the retroflex tends not to be associated with significantly lower F3 formant frequencies than the alveolar and palatal conditions. The palatal condition is associated with some carryover palatal-to-vowel coarticulation in F1 and F2, but the magnitude tends to be weaker than that of anticipatory palatal-to-vowel coarticulation.

4.2.2.4 Comparing retroflexes and palatals – Warlpiri

Table 35 shows F3 (mean) minima in word-initial and non-word-initial preceding vowels and in following vowels. For the Warlpiri speakers, F3 minima are typically lower in the VC condition than the CV condition. In the VC condition, F3 minima tend to occur between 80% into the vowel and V_{OFF} while in the CV condition, minima tend to occur between V_{ON} and 40% into the vowel. However, F3 does not change substantially across the course of the vowel.

Vowel preceding

Figure 22 shows linearly time-normalised and averaged F1, F2 and F3 trajectories of low central vowels preceding retroflex, alveolar and palatal consonants in the tokens of Warlpiri speakers, BP, KR and RR. All Wilcoxon rank sum test results for the VC condition are given in Table 38. As shown by Figure 22, in both F1 and F2, during the second half of the vowel, the retroflex and alveolar conditions tend not to differ. In F1, the palatal tends to be associated with lower formant frequencies than the retroflex and alveolar conditions (BP, /t c/, W=591, $p<0.0001$; /ʈ c/, W=1620, p=0.035; KR, /t c/, W=890, $p<0.001$; /ʈ c/, W=3330, $p<0.0001$; RR, /t c/, W=451, p=0.02, /ʈ c/, W=2083, $p<0.001$). In F2, the palatal condition tends to be associated with higher formant frequencies than the other conditions (BP, /t c/, W=6, $p<0.0001$; /ʈ c/, W=74, $p<0.0001$; KR, /t c/, W=251, $p<0.0001$; /ʈ c/, W=181, $p<0.0001$; RR, /t c/, W=167, $p<0.0083$; /ʈ c/, W=674, $p<0.0001$). In F3, typically, all conditions differ; as seen in the figure, the retroflex is associated with relatively low formant frequencies, the alveolar, with intermediate, and the palatal, with higher formant frequencies. This F3 decline in the retroflex condition is particularly evident from V_{ON} for BP and KR and from approximately 0.4 for RR. In the palatal condition, F3 maxima tend to occur at approximately 0.75 time-normalised (or 75% into the vowel).

Vowel following

Figure 23 shows the Warlpiri speakers' time-normalised and averaged F1, F2 and F3 trajectories of formant frequencies in the vowel following the alveolar, retroflex and palatal stops. All Wilcoxon rank sum test results are given in Table 39.

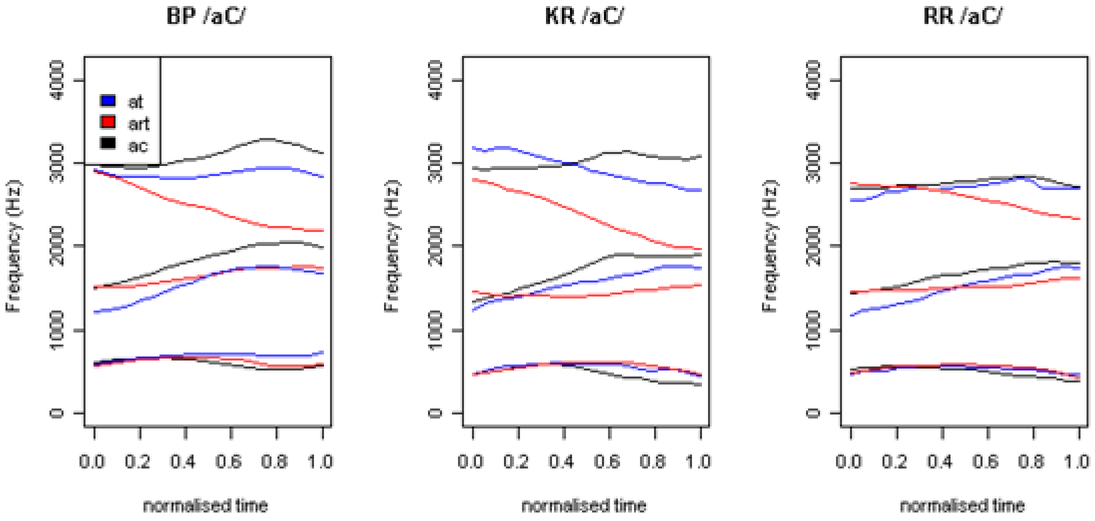

Figure 22. Averaged, linearly time-normalised F1, F2 and F3 trajectories for the Warlpiri speakers for /a/ preceding /t/ (blue), /ʈ/ (red) and /c/ (black). Here, 'rt' represents /ʈ/. y-axis is modified to include 0-4100Hz.

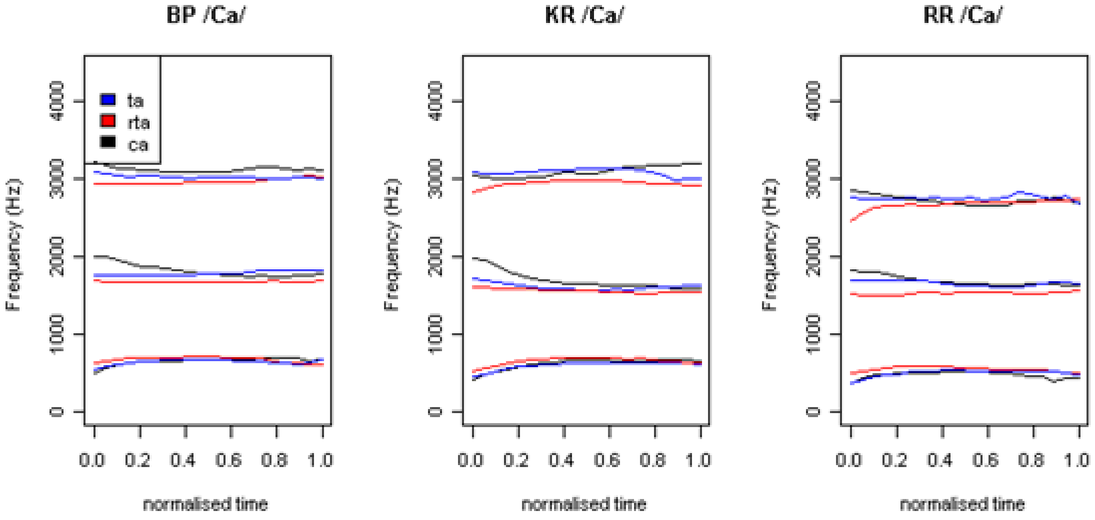

Figure 23. Averaged, linearly time-normalised F1, F2 and F3 trajectories for the Warlpiri speakers for /a/ following /t/ (blue), /ʈ/ (red) and /c/ (black) in two contexts: upper, word-initial, lower, all word positions. Here, 'rt' represents /ʈ/. y-axis is modified to include 0-4400Hz.

During the first half of the vowel following the word-medial consonant, in F1, the retroflex tends to be associated with higher formant frequencies than the alveolar and palatal conditions (BP, /t ʈ/, W=181, $p<0.001$; ʈ c/, W=882, $p<0.0083$; KR, /t ʈ/, W=772, $p<0.001$; /ʈ c/, W=1429, $p=0.09$; RR, /t /, W=171, $p=0.16$; /ʈ c/, W=1046, $p<0.0083$). In F2, the retroflex and alveolar conditions tend not to differ, while the palatal tends to be associated with higher formant frequencies than the other conditions (BP, /t c/, W=73, $p<0.0001$; /ʈ c/, W=107, $p<0.0001$; KR, /t c/, W=252, $p<0.0001$; /ʈ c/, W=453, $p<0.0001$; RR, /t c/, W=86, $p=0.2$; /ʈ c/, W=347, $p<0.001$). In F3, conditions tend not to differ.

Summary – Warlpiri

For the Warlpiri speakers, in the VC trajectory period, the retroflex condition is associated with relatively low F3 formant frequencies with a decline that commences early in the vowel and is particularly evident after 0.4 or 40% into the vowel as was the case for Arrernte (non-word-initial position only), Burarra and Gupapuyngu speakers. The palatal condition is associated with relatively low F1 and high F2 and F3 formant frequencies.

In the CV trajectory period, the retroflex condition is associated with higher F1 formant frequencies but not with significantly lower F3 formant frequencies than the alveolar and palatal conditions; there is a lack of clear retroflex cues at V_{ON} and thus as in Burarra and Gupapuyngu retroflex-to-vowel coarticulation in F3 appears to be weaker than that occurring in the vowel preceding the consonant. The palatal condition is associated with relatively high F2 frequencies, especially at V_{ON}.

Table 38. Wilcoxon rank sum tests for the Warlpiri speakers for /t ʈ c/ – VC in F1, F2 and F3 with W rounded down to the nearest whole number (W, p=* 0.0083, ** 0.001, *** 0.0001). Measurement points are V_{MID} (0.5), V_{EQ} (0.7) and V_{OFF} (0.9) into the vowel.

	F1			**F2**			**F3**		
	at-aʈ	**at-ac**	**aʈ-ac**	**at-aʈ**	**at-ac**	**aʈ-ac**	**at-aʈ**	**at-ac**	**aʈ-ac**
BP	1016**	591***	1620	523	6***	74***	1216***	41***	12***
KR	2154	890**	3330***	3958***	251***	181***	4099***	219***	95***
RR	617	451	2083**	881	167*	674***	1104**	252	565***

Table 39. Wilcoxon rank sum tests for the Warlpiri speakers for /t ʈ c/ – non-word-initial CV in F1, F2 and F3 with W rounded down to the nearest whole number (W, p=* 0.0083, ** 0.001, *** 0.0001). Measurement points are V_{ON} (0.1), V_{EQ} (0.3) and V_{MID} (0.5) into the vowel.

	F1			**F2**			**F3**		
	ta-ʈa	**ta-ca**	**ʈa-ca**	**ta-ʈa**	**ta-ca**	**ʈa-ca**	**ta-ʈa**	**ta-ca**	**ʈa-ca**
BP	181**	235	882*	615*	73***	107***	402	117*	397
KR	772**	514	1429	1560	253***	453***	1232	781	1414
RR	171	127	1046*	344	86	347**	304	139	615

4.2.2.5 Results - F3 phonemic retroflex consonant loci

F3 phonemic retroflex consonant loci are given in Table 40. In both VC and CV contexts, loci tend to approximate 2700Hz. Consonant loci tend to be slightly higher in the CV context, presumably reflecting the lack of F3 lowering effects associated with retroflexion. Additionally, loci are more consistent across language groups in this context.

Table 40. F3 phonemic retroflex loci (Hz) in VC and CV sequences or trajectory periods. Unrealistic values (>+/-6000Hz) are marked by *. Averages ($\bar{x}$) exclude unrealistic values and are given in grey.

		VC	**CV**	**$\bar{x}$**
A	**MM**	2373	2664	2518
	VD	2132	2437	2284
	TR	2251	3102	2676
B	**DP**	5616	2259	3937
	KF	1175	3132	2153
	MW	1652	3059	2355
G	**AM**	5146	2957	4051
	BT	2006	3132	2569
	EG	1956	3117	2536
W	**BP**	-21429*	3107	N/A
	KR	1318	9400*	N/A
	RR	3324	1735	2529
$\bar{x}$		2632	2791	

4.2.2.6 Summary – Comparing retroflexes and palatals

It has been shown that, while there are some similarities between speakers and languages in alveolar, retroflex and palatal stop production, there are also both speaker- and language-dependent acoustic differences, most importantly at the left edge of the stop. These similarities and differences are summarised in the following paragraphs.

Anticipatory apical coarticulation

As stated in H2) and H3), the acoustic cues to pre-palatalisation are relatively high F2 and F3 values and relatively low F1 values at and approaching the vowel offset in the VC trajectory period. It was hypothesised that pre-palatalisation would occur only for the Arrernte speakers in the VC period in word-initial context. For the Arrernte speakers, MM and VD, a lowering of F1 and a raising of F2 and F3 in word-initial contexts in prosodically weak /a/ preceding the stop is seen in words such as <artitye> /aˈʈica/ 'teeth' preceding /i/, but also in words such as <arteke> /aˈʈəka/ 'built', in which it precedes phonemic schwa and <artule> /aˈʈula/ 'plain' in which it precedes /u/. In these Arrernte results in word-initial context, the F3 lowering that is typically present in vowels preceding retroflex consonants cross-linguistically is absent. Rather, there is a raising of F2 and also F3 that is conventionally associated with palatal consonants, but this raising is *stronger* than that associated with palatal stops. There is also some F1 lowering before retroflex stops in this word-initial context, which approaches the F1 lowering observed in vowels preceding palatal stops in this context. Speaker TR shows F3 lowering and not pre-palatalisation in the word-initial context. In the non-word-initial VC context, speakers MM and VD show F2 and F3 lowering, and F1 raising, as is typically associated with a retroflex stop. Any retroflex-to-vowel coarticulation is very much weaker in the CV context.

For the retroflex, similar coarticulatory patterns occur in the non-word-initial VC period in Arrernte as in the VC period in Burarra, Gupapuyngu and Warlpiri. For the Burarra, Gupapuyngu and Warlpiri speakers, the retroflex appears to be inducing strong anticipatory C-to-V coarticulation involving a lowering of F3 formant frequencies. This F3 lowering tends to commences early, typically prior to V_{MID} in /aʈ/ for the Burarra, Gupapuyngu and Warlpiri speakers, and also for the Arrernte speakers in the non-word-initial VC context (although for Burarra speaker, KF, and Warlpiri speaker, RR, it commences at or around the midpoint). The primary acoustical cue that separates the retroflex from the alveolar and the palatal consonants appears to be this lower F3 minimum in the preceding vowel, and this F3 lowering is clearly audible during the vowel period (that is, vowels are rhotacised).

Carryover apical coarticulation

For the Arrernte speakers, in the low central vowel following the retroflex consonant, F2 is lower than in the palatal condition. For MM, the retroflex appears to be exerting weak carryover C-to-V coarticulation in the form of F3 lowering, which should be taken as evidence that for this speaker, the pre-palatalised apical is frequently produced with retroflexion. However, the magnitude of F3 lowering is small in magnitude in comparison to the non-word-initial VC context.

For Burarra, Gupapuyngu and Warlpiri, any carryover retroflex-to-vowel coarticulation is weak, particularly in the productions of the Burarra speakers and Gupapuyngu speakers, AM and BT. For Gupapuyngu speaker, EG, and for the Warlpiri speakers, the retroflex stop appears to be exerting weak F3 lowering (and F2 lowering in the case of Warlpiri speakers). For Burarra speaker, KF, and Gupapuyngu speakers, BT and EG, the retroflex stop is associated with higher F2 frequencies than the alveolar stop. It should be noted that in many cases, the vowel following the consonant is word-final (see §3.4.1.2), and hence, there would be some word-final or pre-boundary effects.

Anticipatory and carryover palatal coarticulation

With regard to anticipatory palatal stop-to-vowel coarticulation, for the Arrernte, Burarra and Gupapuyngu speakers, the palatal condition is typically associated with F1 lowering and F2 and F3 raising and for the Warlpiri speakers, with a raising of F2 and, additionally, a lowering of F1 and a raising of F3 for speaker BP and KR. In other words, there are strong anticipatory palatal effects for all speakers. There are some observable differences between the languages. For example, for the Arrernte and Burarra speakers, an F3 decline commences at or before the midpoint, whereas for the Gupapuyngu and Warlpiri speakers, F3 rises somewhat, typically reaching its maximum prior to vowel offset.

The most significant consonantal effects in the carryover condition are associated with the palatal stop, across languages. Consequently, as reported in §4.2.1, this place of articulation is relatively coarticulation aggressive (see §2.2 for a discussion of this term in the context of the DAC model). Carryover palatal- to-vowel coarticulation is strongest closest to the consonant boundary, at V_{ON}, and is predominantly associated with relatively high F2 frequencies in the following vowel. For the Arrernte speakers, especially for VD, the palatal is additionally associated with relatively low F1 and high F3 frequencies at the onset of the following vowel; the latter result may reflect the more anterior closure target and constriction location at the point of release in Arrernte than in the other languages (Tabain, 2008; 2012; Tabain *et al.*, 2011). For the other speakers, coarticulatory effects tend to be present in F1 and F3 at V_{ON} only. Nonetheless, these results demonstrate that the palatal stop is relatively coarticulation aggressive in these languages.

4.2.3 Results – Vowel-dependent velar coarticulation

It was found in §4.2.1 that the velar consonant tends to be associated with relatively higher slope values and high F2 variability in adjacent vowels. In this section, as is consistent with the literature, /k/ distribution is examined with following rather than preceding vowels. The relevant research questions are given in §2.5. The primary hypothesis, H4), is that F2 frequencies at V_{ON} by V_{MID} following velar consonants form three distinct groups according to three distinct targets in the vowels, /i a u/. In other words, the velar stop will be produced with a more front constriction in close front vowel contexts and with a more retracted (e.g., post-velar or more posterior) constriction in back vowel contexts. This hypothesis is tested by measuring F2 formant frequencies at V_{ON} and V_{MID} following the velar stop and comparing formant frequencies with regard to measurement point and to vowel quality. This measure is comparable to that of the LE. In the initial portion of this section, results will be reported for an LMM procedure on F2 formant frequencies in /kV/ sequences with the fixed factors of measurement point (two levels: V_{ON} and V_{MID}), vowel quality (three levels: /i a u/), language group (four levels: Arrernte, Burarra, Gupapuyngu and Warlpiri) and with the random factor of speaker. Subsequently, the results of Welch's two-sample t-tests on F2 formant frequencies in /kV/ sequences at V_{ON} and V_{MID} conducted per speaker and vowel quality will be reported. Full methodological details are given in §3.4.1.3. All individual speaker means and SD values, full details of the Welch-corrected t-test results and word lists are given in Appendix A. This section is divided into five subsections: a section per language and, in the final section, a summary of results.

4.2.3.1 Results – across speakers

Language groups do not differ with regard to vowel-to-velar stop coarticulation according to a Linear Mixed Model analysis with the fixed factors of language group, measurement point and vowel quality (F(3,4523)=1.661, p=0.17), when variability due to speaker-specific behaviour is excluded. Additionally, the difference between measurement points (V_{ON} and V_{MID}) is non-significant (F(3,4525)=0.545, p=0.55), *i.e.*, there is a high magnitude of vowel-dependent velar coarticulation, as demonstrated previously in §4.2.1. However, the difference between vowel qualities (three levels: /i a u/) is highly significant (F(3,4525)=5541, p<0.0001). According to Tukey's multiple contrasts, all vowel comparisons were highly significant at the p<0.0001 level (/i a/, z=62.42; /u a/, z=-65.96; /u i/, z=105.61). As revealed by Figure 24, the vowels are roughly equidistant, but the average distance between /i a/ is greater than between /a u/; vowel /i/ is associated with a mean across all groups of 2322Hz, /a/, $\bar{x}$=1621Hz, and /u/, $\bar{x}$=1089Hz. In order to investigate vowel-to-velar stop coarticulation in a more fine-grained manner, each language and speaker is now considered in turn.

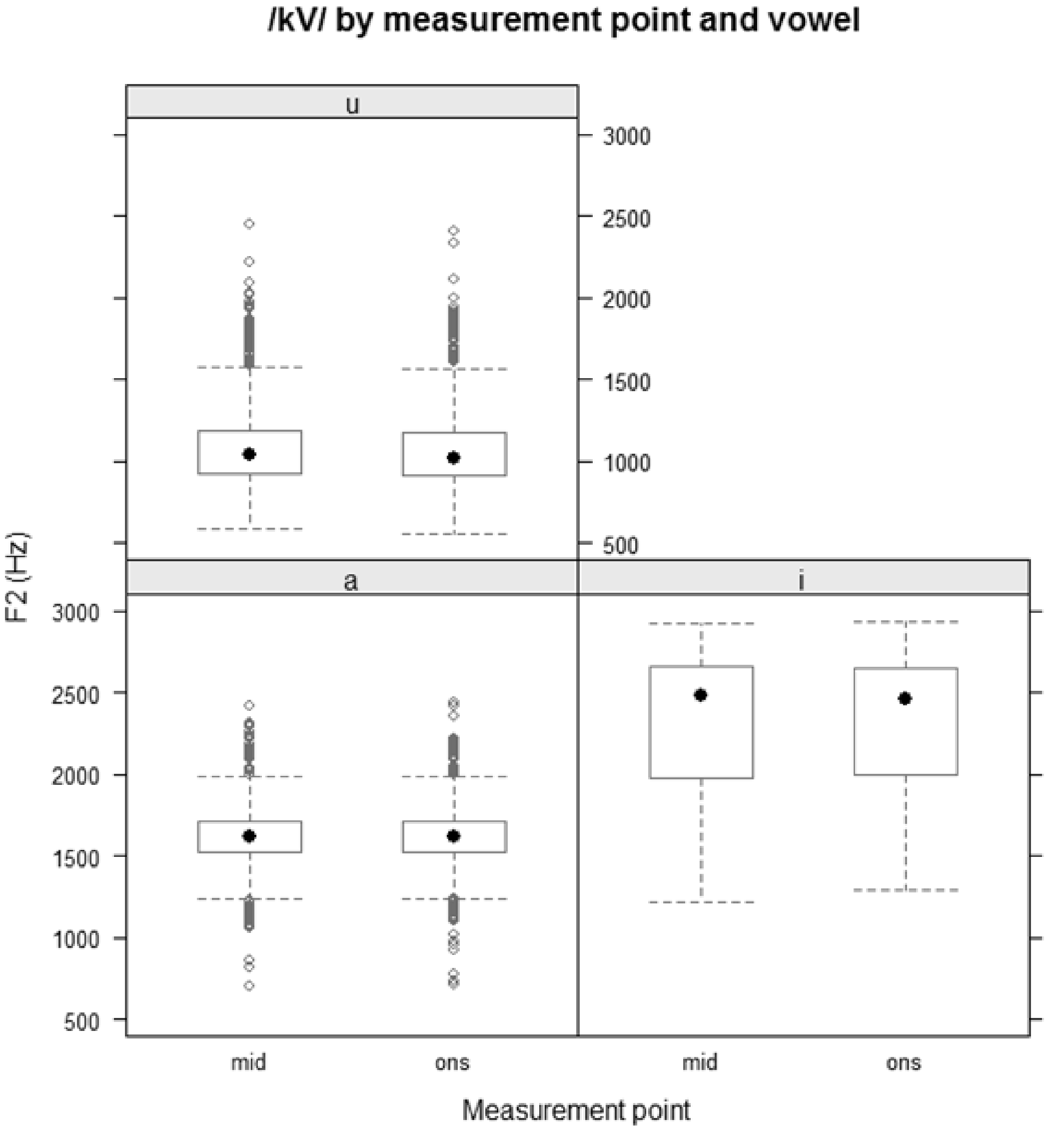

Figure 24. Velar distribution in the CV context in F2 (Hz) as a function of measurement point (x-axis, where 'ons' = V_{ON} 'mid'= V_{MID}) and vowel (/i a u/.

4.2.3.2 Velar coarticulation - Arrernte

For the Arrernte speakers, as shown in Figure 25 (upper panel), there is a clear separation of vowel contexts, especially at V_{MID}. The distribution and number of tokens is given in §3.4.1.3. For all speakers, there are few tokens associated with the close vowel contexts, especially /i/.

When means are calculated for the Arrernte speakers as a group, for /ka/, the mean F2 V_{ON} value is 1586Hz and V_{MID} value is very slightly higher at 1602Hz. For /ki/, the mean F2 V_{ON} value is 2380Hz and V_{MID} value is higher at 2501Hz. For /ku/, the mean F2 V_{ON} is 793Hz and V_{MID} is slightly higher at 858Hz. In other words, at both V_{ON} and V_{MID}, /ku/ is associated with low F2 values, /ki/ with high values and /ka/ with intermediate values. Formula frequency values are slightly *higher* at V_{MID}.

SD values tend to about 100Hz for speakers MM and VD, and this is reflected in a small amount of vowel context overlap for MM. For VD, there are a few /ka/ tokens that are high both at V_{ON} and V_{MID}, but not sufficiently high to overlap with the /i/ tokens. These tokens occur in the word <yweke> /j^{w}əka/ 'don't know', produced by this speaker as [jwəkaj].

The results of paired t-tests on F2 frequencies at V_{ON} and V_{MID} following /k/ are given in Table 41. With the exception of /ka/ for MM ($t(125)=-3.23$, $p<0.01$), for whom V_{MID} is associated with higher F2 frequencies than V_{ON}, all comparisons are non-significant, *i.e.*, coarticulation is maximal.

According to Table 42, comparing /ki/ and /ci/, F2 at V_{MID} in /ci/ is lower than the equivalent values in /ki/, while F2 at V_{ON} does not differ between conditions (at V_{ON}, the coefficient for VD approaches significance at $p=0.052$; however, note the low numbers of tokens).

These data suggest that the location of the velar constriction varies between a post-velar or even uvular location preceding the back vowel and a fronted location preceding the front vowel, with an intermediate constriction location preceding the central vowel.

Summary - Arrernte

For the Arrernte speakers, the distribution of F2 formant frequencies in plots of V_{ON} by V_{MID} following velar stops forms three groups, corresponding to /i a u/ vowel contexts (Figure 25). F2 formant frequencies at V_{ON} and V_{MID} tend not to differ, which should be taken as evidence that the velar is undergoing strong vowel-dependent coarticulation, as would be consistent with the results presented previously in §4.2.1. These results appear to reflect variation in the location of the velar constriction between post-velar or even uvular in the context of back vowels and fronted velar in the context of front vowels.

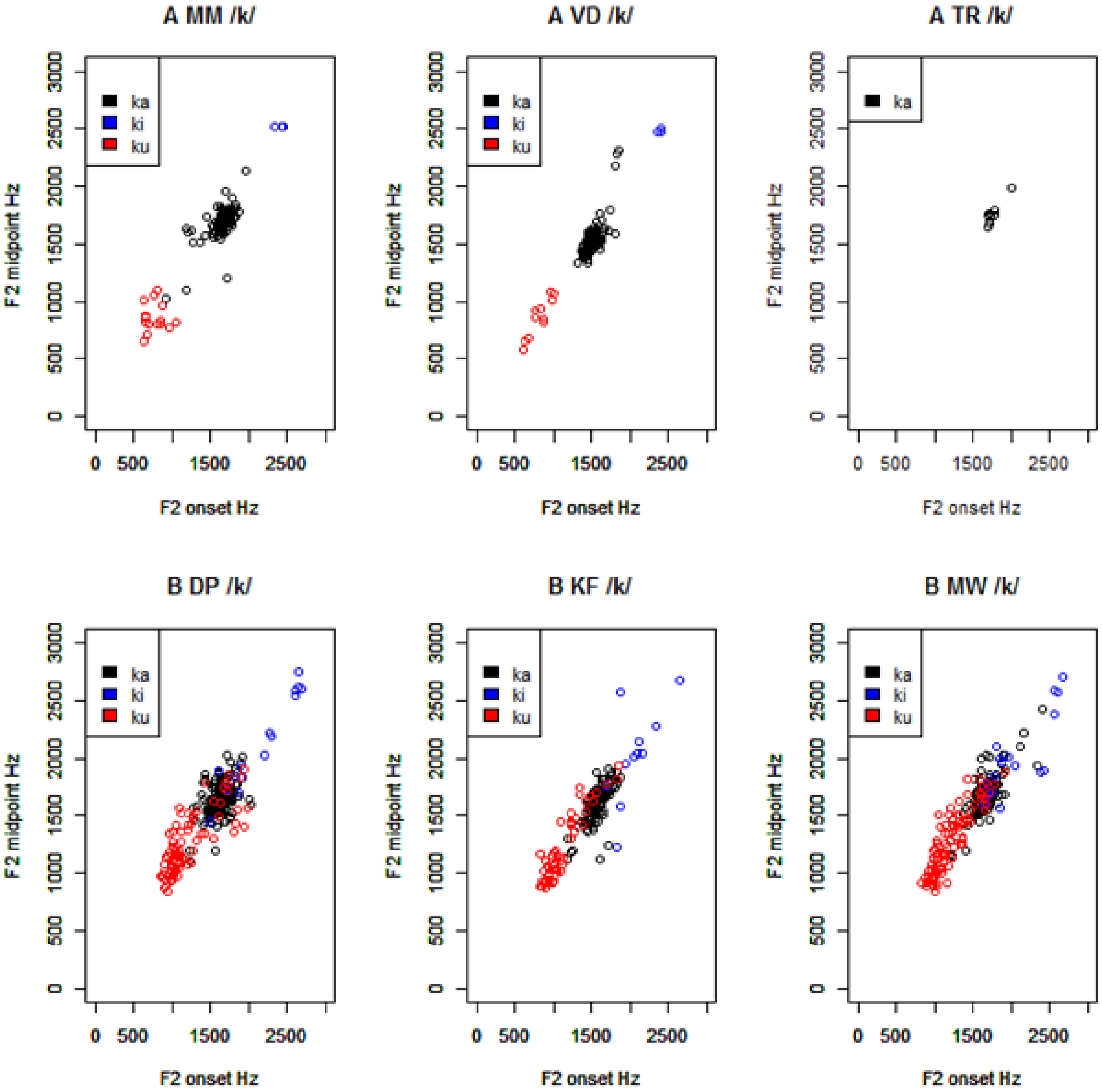

Figure 25. Velar distribution in the CV context for Arrernte and Burarra speakers in the F2 in the V_{ON} by V_{MID} plane. x-axis = F2 (Hz) at V_{ON}, y-axis = F2 (Hz) at V_{MID}.

Table 41. Welch's two-sample t-tests for /ka/, /ki/ and /ku/ conditions for Arrernte and Burarra speakers in F2 at V_{ON} and V_{MID} where * $p<0.01$, ** $p<0.001$, *** $p<0.0001$.

Lang	**Sp**	**ka**		**ki**		**ku**	
		t	**df**	**t**	**df**	**t**	**df**
A	**MM**	-3.23*	125	-3.2	2	-2.01	14
	VD	-0.58	152	-3.5	2	-1.5	10
	TR	0.6	10	N/A	N/A	N/A	N/A
B	**DP**	-2.4	178	0.39	15	-2.8*	81
	KF	-4.16***	127	0.35	10	-6.7***	53
	MW	-1.4	216	1.14	17	-5.67***	104

Table 42. Welch's two-sample t-tests for /ki/ and /ci/ conditions for Arrernte and Burarra speakers in F2 at V_{ON} and V_{MID} where * $p<0.01$, ** $p<0.001$, *** $p<0.0001$.

Lang	**Sp**	V_{MID}		V_{ON}	
		t	**df**	**t**	**df**
A	**MM**	5.76**	9	1.55	4
	VD	4.97**	10	3.159	7
	TR	N/A	N/A	N/A	N/A
B	**DP**	0.2794	24	0.29	29
	KF	-0.58	14	-0.9	22
	MW	-1.66	29	-1.22	26

4.2.3.3 Velar coarticulation - Burarra

Figure 25 (lower panel) shows that, for the Burarra speakers, there is a greater overlap of vowel contexts than is the case for the Arrernte speakers but there is still some separation. There is some overlap of /u/ and /a/ contexts, and /a/ and /i/ contexts. When /ku/ is associated with high V_{ON} and V_{MID} values, it is typically adjacent or near adjacent to a palatal articulation, or the vowel has undergone centralisation. Averaging across the speakers, for /ka/, the mean F2 V_{ON} value is 1621Hz. The mean F2 V_{MID} is very slightly higher at 1646Hz. For /ki/, the mean F2 V_{ON} is 2082Hz and V_{MID} is slightly lower at 2038Hz. For /ku/, the mean F2 V_{ON} is 1181Hz and V_{MID} is higher at 1234Hz.

In /ka/, for KF, V_{MID} is associated with significantly higher F2 formant frequencies than V_{ON} ($t(127)=-4.16$, $p<0.0001$). For all speakers, in /ku/, once again, V_{MID} is associated with significantly higher F2 formant frequencies than V_{ON} (DP, $t(81)=-2.8$, $p<0.01$; KF, $t(53)=-6.7$, $p<0.0001$; MW, $t(104)=-5.67$, $p<0.0001$). It is interesting to note that these results are very different from the Arrernte /ku/ results (Table 41). All other comparisons are non-significant.

When /ki/ and /ci/ are compared in Burarra, F2 formant frequencies do not differ at V_{ON} or V_{MID} (Table 42).

Summary – Burarra

For the Burarra speakers, while there is some separation of vowel contexts following the velar stop, there is an overlapping of /a u/ contexts, and of /i a/ contexts. In the back vowel context, F2 formant frequencies are higher at V_{MID} than V_{ON}, indicating sub-maximal coarticulation between the velar and the vowel (that is, V_{ON} reflects incomplete anticipation of V_{MID}). The location of the velar constriction appears to vary between post-velar or even uvular in the context of back vowels and a fronted velar articulation in the context of front vowels.

4.2.3.4 Velar coarticulation - Gupapuyngu

Figure 26 (upper panel) shows that for the Gupapuyngu speakers, there is a strong separation of vowel contexts for speakers BT and EG, and moderate separation of vowel contexts for speaker AM, with F2 frequencies for some tokens of /ki/ and /ku/ occurring in the region of /ka/. This occurs due to strong coarticulatory effects induced by neighbouring segments, including vowels and consonants.

F2 frequencies at V_{ON} and V_{MID} are highest for speaker BT and lowest for AM. Considering means for the group as a whole, for /ka/, the mean F2 V_{ON} is 1694Hz. The mean F2 V_{MID} is slightly higher at 1739Hz. For /ki/, the mean F2 V_{ON} is 2447Hz and the mean V_{MID} is slightly lower at 2415Hz. For /ku/, the mean F2 V_{ON} is 969Hz and the mean V_{MID} is higher at 1079Hz.

For AM, there is much greater variation in F2 at V_{ON} and V_{MID} for /i/ than for the other vowels. The relatively high EG /ku/ V_{MID} values appear to be due to palatal C-to-V coarticulatory effects in the words <gutjan> /gucan/ 'fem. subsec.' [gʉⁱcan] and <gudjuk> /guɟuk/ 'male subsec.' [gʉⁱɟⁱʉʔk] (where /u/ is centralised; see Chapter 5).

All Gupapuyngu speakers show significantly higher V_{MID} values than V_{ON} values in /ka/ and /ku/ (see Table 43), with the exception of /ka/ for BT. This pattern is especially evident in Figure 26 for /ku/. All other comparisons are non-significant. These results are similar to the Burarra results and are unlike the Arrernte results.

According to Table 44 in /ki/ and /ci/ at V_{ON} and V_{MID} in F2, all comparisons are non-significant; for EG, the comparison at V_{MID} approaches significance; F2 formant frequencies are somewhat higher in the /ci/ condition ($t(24)=-2.08$, $p=0.05$).

Table 43. Welch's two-sample t-tests for /ka/, /ki/ and /ku/ conditions for Gupapuyngu and Warlpiri speakers in F2 at V_{ON} and V_{MID} where p=* 0.01, ** 0.001, *** 0.0001 ***.

Lang	**Sp**	**ka**		**ki**		**ku**	
		t	**df**	**t**	**df**	**t**	**df**
G	**AM**	-4.8***	88	-2.4	35	-8.86***	90
	BT	-1.6	109	2.58	35	-11.2***	111
	EG	-5.75***	35	2.58	14	-4.48***	32
W	**BP**	-2.48	57	0.7597	32	-2.9*	40
	KR	1.27	125	5.06***	66	-5.21***	113
	RR	-2.98*	47	-0.75	37	-3.36*	49

Table 44. Welch's two-sample t-tests for /ki/ and /ci/ conditions for Gupapuyngu and Warlpiri speakers in F2 at V_{ON} and V_{MID} where * p<0.01, ** p<0.001, *** p<0.0001.

Lang	**Sp**	**V_{MID}**		**V_{ON}**	
		t	**df**	**t**	**df**
G	**AM**	-0.38	61	-1.9	60
	BT	-1.87	70	0.74	64
	EG	-2.08	23.7	-2.25	23
W	**BP**	4.95***	51	3.73**	49
	KR	-0.88	99	-0.71	91
	RR	-2.79*	61	-3.63**	61

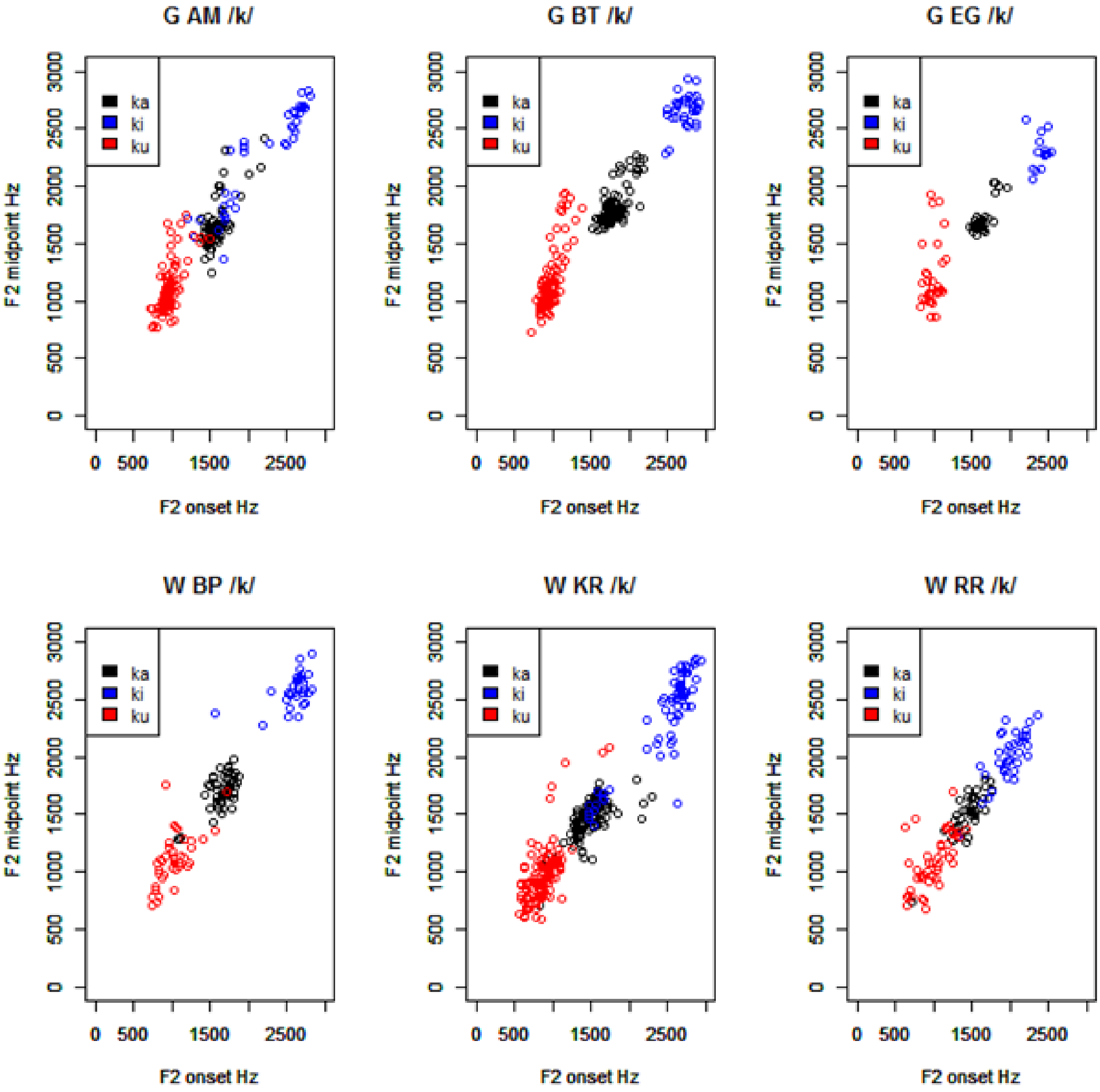

Figure 26. Velar distribution in the CV context for Gupapuyngu and Warlpiri speakers in the F2 in the V_{ON} by V_{MID} plane. x-axis = F2 (Hz) at V_{ON}, y-axis = F2 (Hz) at V_{MID}.

Summary - Gupapuyngu

There is a strong separation of vowel contexts for Gupapuyngu speakers, BT and EG, and a moderate separation of vowel contexts for speaker AM. The findings confirm that the location of the velar constriction varies according to the following vowel, as in Burarra, between a post-velar constriction in /ku/ and a fronted velar constriction in /ki/. In /a/ for two of the three speakers and in /u/, V_{MID} values are associated with significantly higher formant frequencies than V_{ON} values, indicating a more anterior constriction at V_{MID}.

4.2.3.5 Velar coarticulation - Warlpiri

For the Warlpiri speakers, there is some separation of vowel contexts for all three speakers. For speaker BP, there is slight overlapping of /ka/ and /ku/ values. For KR and RR, there is some overlapping of /ka/ and /ki/, and /ka/ and /ku/ values. When /ku/ is associated with high V_{ON} and V_{MID} values, this appears to be due to coarticulation by an adjacent or near adjacent palatal articulation. Lower /ka/ V_{ON} values for BP occur in /uka/ environments in the words <jukarra> /cukaɾa/ ‘tomorrow’ [c^{h}ukaɾa] and <mukarti> /mukaʈi/ [mʊk^{h}aɖe] and appear to be due to carryover V-to-V coarticulation. High values for /ku/ for KR are due to palatal C-to-V effects e.g., in <pujukuyuku> /pujukujuku/ ‘fog, mist’, e.g., [p^{h}ʉ^{i}j^{i}ʉkʉ^{i}jʉ^{i}k^{h}o] (where /u/ is centralised; see Chapter 5).

F2 frequencies at V_{ON} and V_{MID} tend to be highest for BP. Means across the speakers are for /ka/, at V_{ON}, $\bar{x}$=1524Hz, and at V_{MID}, $\bar{x}$=1537Hz. For /ki/, at V_{ON}, $\bar{x}$=2358Hz and at V_{MID}, $\bar{x}$=2293Hz. For /ku/, at V_{ON}, $\bar{x}$=945Hz and at V_{MID}, $\bar{x}$=1041Hz.

For all speakers, in /ku/, V_{MID} is higher than V_{ON} (BP,t(40)=-2.9, $p<0.01$; KR, t(113)=-5.21, $p<0.0001$; RR, t(49)=-3.36, $p<0.01$). Additionally for RR, in /ka/, F2 formant frequencies at V_{MID} are significantly higher than those at V_{ON} (t(47)=-2.98, $p<0.01$). For KR, in /ki/, V_{ON} is associated with higher frequencies than V_{MID} (t(66)=5.06, $p<0.0001$), suggesting the coarticulatory effects of segments after the vowel rather than a reduced magnitude of coarticulation between the velar and the front vowel. All other comparisons are non-significant. These results are similar to those of Burarra and Gupapuyngu and differ from those of Arrernte.

According to Table 44, when /ki/ and /ci/ are compared in F2 at V_{ON} and V_{MID}, there are strong inter-speaker differences. For BP, at both measurement points, /ki/ is associated with significantly higher F2 formant frequencies than /ci/, as for Arrernte speakers MM and VD at V_{MID}. For KR, the comparison is non-significant, as for the

Burarra and Gupapuyngu speakers. For RR, /ki/ and /ci/ differ at both measurement points; /ci/ is associated with higher F2 values.

Summary - Warlpiri

For the Warlpiri speakers, vowel contexts tend to be well separated. Apparent variation in constriction location tends to be similar to that in Burarra and Gupapuyngu. In /ku/, formant frequencies are higher at V_{MID} than V_{ON}, indicating sub-maximal coarticulation between the vowel and the velar stop. The same is true of /ka/ for RR and /ki/ for KR. For BP but not KR and RR, /ki/ is associated with higher F2 frequencies than /ci/ at both V_{ON} and V_{MID}.

4.2.3.6 Summary – Velar coarticulation

For the velar stop, there is robust evidence of variation in F2 formant frequency - and by extension in the location of the major constriction relative to the glottis according to the context of the following vowel - between a post-velar or even uvular location before /u/ and a fronted velar location before /i/.

At V_{MID}, for each language group, the different vowel contexts are typically associated with means that differ by 400Hz or more. Per group and vowel, V_{ON} and V_{MID} values typically differ by up to 65Hz, although for /ki/ for the Arrernte speakers, the measurement points differ by 121Hz on average and for /ku/ for the Gupapuyngu and Warlpiri speakers, the measurement points differ by about 100Hz. /ku/ is associated with higher V_{MID} values than V_{ON} values for the Burarra, Gupapuyngu and Warlpiri speakers.[38] The generality of this pattern concerning /ku/ suggests that it is caused by the interaction between the velar and the vowel and not by any neighbouring segments. There appears to be a shifting forward of the location of the constriction in the vocal tract from V_{ON} to V_{MID}, from a very back velar constriction to a somewhat centralised vowel, perhaps [ɵ] (on the subject of /u/ and a potential lack of lip rounding and protrusion, see Dixon, 1980, p. 130; Butcher, 2006). (Vowel production will be investigated fully in Chapter 5.) In the clas*sic* consonant locus diagrams (Delattre, Liberman, & Cooper, 1955), the velar stop is, associated with higher V_{ON} than V_{MID} values in the following vowel. This difference between the studies may reflect a less backed velar constriction in American English than in these Australian languages. It may be the case, as is consistent with the LE results reported in §4.2.1, that velar consonants are almost uvular with back vowels, as has been suggested for many Australian languages

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[38] This is also true for the Arrernte speakers but the difference does not reach significance, perhaps because of the very low number of tokens containing /ku/, or perhaps because of articulatory differences.

(e.g., Butcher, 2006). It was seen in §4.2.1.5 that, while the velar locus varies greatly in Burarra, Gupapuyngu and Warlpiri, the mean locus in the four languages is very low in comparison to the American English F2 'ideal' velar locus at 3000Hz presented by Delattre *et al*. (1955). When these results are compared to the velar loci presented in §4.2.1.5, the velar loci are typically similar to the mean F2 frequency values at V_{ON} and V_{MID} in /ka/, although for the Burarra speakers, the velar loci are lower, approaching the V_{ON} and V_{MID} values in the /ku/ sequences and for the Warlpiri speakers, the velar loci are similar to /ka/ (with regard to VC loci) and /ki/ (CV loci) values.

It was demonstrated that /i/ is exerting particularly strong coarticulatory effects in the velar given that there is evidence of maximal vowel-dependent coarticulation in the context of /ki/[39] but not in /ka/ for a number of speakers or in /ku/ for Burarra, Gupapuyngu and Warlpiri. In these data, velars occur much less frequently before front vowels than before central and back vowels (see §3.4.1.3) at between 2% (Arrernte and 28% in Warlpiri. This small number of /ki/ tokens may reflect the instability of the front velar phone or the marked nature of /i/ in these languages. For the majority of speakers, /ki/ and /ci/ sequences do not differ in F2 at V_{ON} and V_{MID}. For the Arrernte speakers and for Warlpiri speaker, BP, /ki/ is associated with higher F2 formant frequencies than /ci/, for the Arrernte speakers at V_{MID} only and for BP at V_{ON} and V_{MID}.

4.3 Discussion

This chapter has examined consonant-vowel coarticulation with special regard to vowel-dependent consonant coarticulation (§4.2.1), to retroflex-to-vowel coarticulation (§4.2.2) and to vowel-dependent velar coarticulation (§4.2.3). In Arrernte and Burarra, F2 variability tends to be small in magnitude when compared to that in Gupapuyngu and Warlpiri. This section comprises a summary and discussion of all results presented in this chapter. Conclusions follow.

4.3.1 Effect of consonant place of articulation on consonant-vowel coarticulation

The most important finding in this chapter is that most of the variation in the magnitude of consonant-vowel coarticulation appears to be dependent on the place of articulation of the consonant. These analyses show clear and consistent place of articulation effects on the magnitude of consonant-vowel coarticulation, in support of RQ1), regarding the

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[39] For Warlpiri speaker, KR, onset and midpoint F2 formant frequencies differ; however this difference appears to be due to a segment following the vowel inducing an F2 lowering effect (indicating a retraction of the constriction), rather than to sub-maximal coarticulation between the velar and the vowel.

relationship between consonant place and coarticulation. It was demonstrated in §4.2.1 that in these languages the velar stops undergo a high degree of vowel-dependent coarticulation, bilabial stops, slightly less coarticulation, and alveolar and retroflex stops, still less coarticulation, while palatal stops undergo a low degree of coarticulation (consistent with Lindblom, 1963; Lindblom *et al.*, 2007; Krull, 1989; Sussman *et al.*, 1991, 1993; Butcher, 1995; Recasens, 1985, 1999; Tabain & Butcher, 1999; Fowler & Brancazio, 2000; Tabain, 2000, amongst others). Slopes vary inversely with y-intercepts (Duez, 1992; Fowler, 1994).

The effects of consonant place of articulation on consonant-vowel coarticulation are clear and consistent in the four languages. However some evidence has also been presented in §4.2.1 of differences between the languages in slope values, and therefore in constraints on the magnitude of vowel-dependent coarticulation permitted by consonantal places of articulation. According to the DAC model, these acoustical differences may reflect articulatory differences. For example, it was found that Arrernte /p/, and Burarra /ʈ|ɖ/, undergo less vowel-dependent coarticulation than bilabial and retroflex stops in the other languages. With regard to consonant-dependent coarticulation, the effect of consonant place appears to be weakest in F3 in the CV trajectory period, and strongest in F2 in both trajectory periods but especially in the VC trajectory (and to be strong in VC in F3 with respect to the retroflex place).

Turning to the matter of vowel-dependent coarticulation, the peripheral stops are seen to behave very differently from the non-peripheral stops. The finding of a larger degree of vowel-dependent coarticulation for peripheral consonants than for non-peripheral (coronal) consonants is consistent with the results of e.g., Fowler and Brancazio (2000) for English. This finding supports the claim that the peripheral/non-peripheral distinction is an important one in Australian languages. Moreover, the magnitude of variation in the vowel at the vowel-consonant boundary appears to vary primarily according to peripheral/non-peripheral place of articulation. A general trend was observed towards relatively high variability associated with the peripherals (as observed by Fant (1973) for Swedish; Recasens, 1985, for Catalan; Tabain & Butcher, 1999, for Yanyuwa and Yindjibarndi) and relatively low variability associated with the palatal, as observed for Arrernte by Tabain and Rickard (2007, p. 503), and the retroflex.[40] Additionally, peripheral stops are associated with significantly lower

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[40] Unusually, for Arrernte speaker, VD, the retroflex stop was associated with intermediate to high variability. This is consistent with Tabain and Rickard (2007), in which some variability was found in Arrernte in the articulation of the retroflex stop, especially in the amount of anterior contact. It is also possible that some variation is associated with the de-retroflexion process that applies to

consonant loci than non-peripheral stops, as reported in §4.2.1.5; there is a trend across speakers towards a high locus for the palatal, fairly high loci for the coronals, and low loci for the bilabial and the velar, with a trend towards high variability in peripheral loci and especially in velar loci. However, as in previous studies, the locus for the velar was the least stable (e.g., Fant, 1973; Öhman, 1966), most likely because of a high magnitude of variation according to vowel context, as demonstrated in §4.2.3. This dissertation then provides acoustical evidence for an F2-locus (Delattre *et al.,* 1955) for each of the following places of articulation, /p t ʈ c k/, in the four Australian languages, supporting the view that consonant loci provide information to the hearer concerning place of articulation (Stevens & Blumstein, 1975), with some variation according to context (Öhman, 1966).

The finding of relatively poor separation of the apicals by LE slope values is in accordance with Tabain (2000) and Tabain and Butcher (1999) on Yanyuwa and Yindjibarndi. A similar finding was also reported by Krull *et al.* (1995). The finding of relatively poor separation of (*i.e.,* between) peripheral consonants is typical in the LE literature (e,g, Fowler, 1994; Brancazio & Fowler, 1998; Sussman *et al.*, 1991; Iskarous *et al*., 2010). These results for apicals may be due to more numerous coronal than peripheral place categories in these language. This coronal crowding may necessitate greater articulatory precision and thus increased coarticulation resistance on the DAC model and a restricted magnitude of contextual and non-contextual variation (Butcher, 1995; Manuel, 1990; 1999; Butcher & Tabain, 2004). They may also be due to word-initial apical neutralisation in some tokens (§1.2 and elsewhere; however, most tokens in the analysis included word-medial apicals). In general, these results are consistent with H1) on the relationship between place of coarticulation and slope values.

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consonants preceded by a dental or word-initial palatal (e.g., Tabain, 2009a). The results of the present study suggest optional de-retroflexion.

Table 45. Cross-study comparison of CV slope values of female speakers collapsed across voicing contrasts and speakers within language groups. The consonant and the vowel quality are given in the first two columns (L). Both prosodic conditions (S=Strong and W=Weak, where Weak indicates a lack of an F0 peak associated with the vowel) are given when possible. A RF=Arrernte speaker RF (Tabain *et al.*, 2004). Ya1=Yanyuwa and Yi1=Yindjibarndi (Tabain & Butcher, 1999), Ya2=Yanyuwa and Yi2=Yindjibarndi speaker KM (Tabain *et al.*, 2004). Au4=Australian English speakers, Ya3=Yanyuwa, Yi3=Yindjibarndi (Butcher & Tabain, 2004), AuE1=Australian English (Tabain, 1999), AuE2=Australian English (Tabain, 2000), AmE=American English (Sussman *et al.*, 1993), AmE1=American English speaker CB (Fowler & Brancazio, 2000), Th=Thai (Sussman *et al.*, 1993), Numbers are averaged and rounded so as to be comparable. The non-Australian indigenous languages are shown in grey.

		A	**B**	**G**	**W**	**A RF**	**Ya1**	**Ya2**	**Ya3**	**Yi1**	**Yi2**	**Yi3**	**AuE1**	**AuE2**	**AmE**	**AmE1**	**Th**
p|b	**S**	0.5	0.8	0.85	0.8	0.3	0.75	0.8	N/A	0.8	0.8	N/A	N/A	N/A	0.9	0.8	0.65
	W	0.75	0.8	0.9	0.8												
t|d	**S**	0.55	0.6	0.7	0.7	0.7	0.75	0.7	N/A	0.35	0.3	N/A	0.1	0.4	0.4	0.2	0.25
	W	0.75	0.7	0.7	0.6												
ʈ|ɖ	**S**	0.5	0.7	0.7	N/A	0.6	0.6	0.7	N/A	0.5	0.6	N/A	N/A	N/A	N/A	N/A	N/A
	W	0.9	0.5	0.7	0.6												
c|ɟ	**S**	0.4	0.6	0.7	0.6	0.2	0.5	0.4	N/A	0.5	0.4	N/A	N/A	N/A	N/A	N/A	N/A
	W	0.4	0.4	0.5	0.55												
k|g	**S**	1	1	1	1	0.8	1	0.9	1	1	1	1	0.7	0.8	0.75	0.3	N/A
	W	0.9	0.9	1	0.9												

Table 46. Cross-study comparison of VC slope values of female speakers collapsed across voicing contrasts and speakers within language groups. The consonant and the vowel quality are given in the first two columns (L). Both prosodic conditions (S=Strong and W=Weak, where Weak indicates a lack of an F0 peak associated with the vowel) are given when possible. A RF=Arrernte speaker RF, Ya2=Yanyuwa and Yi2=Yindjibarndi speaker KM (Tabain *et al.*, 2004). AuE3=Australian English. Numbers are averaged and rounded so as to be comparable. The non-Australian indigenous languages are shown in grey. * indicates that for at least one of the three speakers, n<10.

		A	**B**	**G**	**W**	**A RF**	**Ya2**	**Yi2**	**AuE3**
S	**p|b**	0.5	0.7	0.6	0.6	0.35	0.8	0.9	0.8
W		0.7	0.5	0.2	0.7				
S	**t|d**	N/A	0.7	0.5	0.6	0.4	0.8	0.2	0.55
W		0.5	0.55	0.4	0.6				
S	**ʈ|ɖ**	0.5	0.6	0.6	0.7	0.5	0.7	0.7	N/A
W		0.75	0.5	N/A	0.7				
S	**c|ɟ**	0.3	0.3	0.3	0.4	0.6	0.2	0.5	N/A
W		0.1	0.7	0	0.4				
S	**k|g**	0.9	0.8	0.4	0.7*	0.5	1	1	1
W		0.9	0.7	0.6	0.6*				

Table 45 shows slope value results reported for female speakers in previous studies in the CV context, while Table 46 shows slope results reported for female speakers in previous studies in the VC context. It can be seen LE slope values for alveolar consonants in the present study tended to be higher than those found for female speakers of Australian and American English and Thai, and in fact, Yindjibarndi, indicating that the alveolar consonants in the languages in the present study undergo greater vowel-dependent coarticulation (although of course, consonant and vowel inventories differ). Additionally, the mean LE slope values for velar consonants in the present study tended to be higher than those found for female speakers of Australian and American English and Thai, indicating that the velar consonants in the languages in the present study undergo greater vowel-dependent coarticulation, as is supported by the results reported in §4.2.3. Moreover, for the American English speakers, the velar is associated with slopes that are lower than or similar to those of the bilabial, but in Australian languages such as those in the current study, velar slopes tend to be higher than bilabial slopes. Overall, the slope results of the present study tend to be consistent with those of previous studies of Australian languages, as shown in Table 45 and Table 46. In §4.3.1.1, §4.3.1.2 and §4.3.1.3, the results relating to the retroflex, palatal and peripheral places of articulation will be discussed in detail, with regard to the literature.

4.3.1.1 Retroflex place of articulation

In this chapter, it was shown that the retroflex undergoes a low to intermediate degree of vowel-dependent coarticulation (LE measure). This may occur both for articulatory and perceptual reasons: a typical retroflex stop in these languages involves dorsum raising and a complex and precise tip/blade articulation (e.g., Henderson, 1998; Butcher, 1995). Furthermore, as it is situated in a crowded section of the inventory, it is necessary that strong perceptual cues be present, as was also clearly evident in the F3 trajectories reported in §4.2.2 and discussed in §4.2.2.6.

H2) and H3) posited that pre-palatalisation occurs in /a/ preceding the phonemic retroflex stop in Arrernte and is greater in magnitude word-initially than elsewhere. It was observed that two of the three Arrernte speakers, MM and VD, show strong evidence in support of H3) of word-initial pre-palatalisation of the (phonemic) retroflex stop in a preceding word-initial low central vowel (consistent with Breen, 2001, p. 52) with the retroflex being realised phonetically as a retroflex or an alveolar (as discussed in, e.g., Butcher, 1990; Tabain 2009a), e.g., <artitye> /aʈic(a)/ [æʲʈɪca] 'teeth'.[41] This finding is inconsistent with the hypothesis that the pre-palatal sequence is the realisation of 'a distinct coronal place of articulation' (Harvey, 2011, p. 95). This pre-palatalisation may be the cause of the relatively high retroflex locus variability that was reported in §4.2.1.5 and was not present in the other languages. One of the interesting results of this chapter is that in the pre-palatalised vowel there is a raising of F2 and also F3 that is greater in magnitude than that associated with actual palatal stops.

The variable results concerning the apparent place of articulation of the word-initial context retroflex stop for the Arrernte speakers support the claims by Henderson (1998) and Breen (2001) that this pre-palatalised stop does not constitute a third apical place of articulation distinct from the retroflex and alveolar stops (§1.2.1.3), consistent with Butcher's 1995 claims regarding neutralisation in Australian languages. Neutralisation of the apical contrast in word-initial position 'is common typologically, since ... the main cue to retroflexion – namely a lowered F3 and/or F4 – occurs before consonant closure, and the perceptual cues available at release are similar for retroflexes and front apicals (Steriade, 1995; 2000; reported in Tabain, 2009a). That is, the perceptibility of the contrast appears to require the presence of the preceding vowel (see, e.g., Tabain & Breen, 2011, p. 70). So, in

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[41] Harvey (2011) suggests that sequences in which a high front vowel follows the apical consonant are 'probably not the only source of pre-palatals in Arandic ... there is evidence for pre-palatals deriving from retroflexes, regardless of the nature of the following vowel.' (p. 94)

view of the above, F3 lowering in the non-word-initial context for MM and VD should be taken as evidence that the consonant is here realised more consistently as a (phonetic) retroflex stop.

It is suggested that the articulatory realisation of the pre-palatalisation is a raising and fronting of /a/, and this can be observed auditorily. Butcher (*pers. comm.*, reported in Tabain, 2009a,b) suggests that just as the low F3 [of the retroflex] of the VC transitions brings F2 and F3 near one another, so does [j]; therefore, pre-palatalisation of the retroflex may be enhancing the acoustical effects of dorsum fronting (and raising) typically involved in retroflexion in Arrernte. The word-initial phonemic retroflex and palatal plosives – and the vowel-consonant transitions – are clearly perceptually distinct (as supported by Gavan Breen, *pers. comm.*) even if this distinctiveness is achieved in an unexpected way.

For speaker TR, the results indicate retroflex-to-vowel coarticulation in the form of F3 lowering rather than pre-palatalisation. Arrernte speakers then utilise different strategies in ‘cueing’ the retroflex stop. For the Burarra, Gupapuyngu and Warlpiri speakers, the retroflex consonant is associated with F3 lowering or ‘rhotacisation’ primarily in the preceding vowel (that is, this pre-palatalisation is confined to the Arrernte language). This F3 lowering tends to commence before the midpoint, as in other Australian languages, such as Wubuy (Bundgaard-Nielsen *et al.*, 2009), supporting an analysis of retroflexion as an autosegment (Evans, 1995, pp. 739-740). Retroflex consonants are widely known to exert prominent anticipatory coarticulation, regardless of manner (e.g., American English: Boyce & Espy-Wilson, 1997; Catalan: Recasens, 1986). The predominence of anticipatory effects is predictable given that the release phase of retroflex stops is known to involve an alveolar-like, tip up articulation (e.g., Ladefoged & Maddieson, 1996, p. 28). It should be noted that the strong retroflexion of /a/ preceding intervocalic retroflexes in Warlpiri does not support Jagst’s (1975) claim that the degree of retroflexion in this language varies between vowels, although this variability may occur in other retroflex consonants not considered in this study, e.g., in different manners of articulation.

TR is reported to be between ten and twenty years younger than MM and VD. It is possible that pre-palatalisation in this word-initial /aʈ/ context is produced by older speakers of Arrernte more frequently than younger speakers. This is consistent with the finding by Tabain (2009a,b) in her study of a mother and daughter speaker of Arrernte that the mother adopted the pre-palatalised variant (after /a/ but not /ə/) in many instances (with the retroflex being realised as an alveolar), e.g., <artepe> /aʈəp/ [æʲtəp] ‘back’ (2009a, p. 491; see also, Tabain &

Breen, 2011). The daughter, who was aged in her 30s, like TR in the present study, did not. However, this 'age hypothesis' is merely a suggestion and other factors may be involved, e.g., schooling or exact location of residence (Jenny Green & Gavan Breen, *pers. comm.*).

4.3.1.2 Palatal place of articulation

In the present study, palatals are associated with the lowest slope values (as was shown by e.g., Recasens 1984a,b; Fowler & Brancazio, 2000), indicating a high magnitude of resistance to vowel-dependent coarticulation, presumably due to the large amount of predorsum and jaw raising (Tabain, 2009b; Recasens, 2012) and strong coupling between the primary articulator and other tongue regions, as reflected in the high consonant loci (see Tabain, 1996, p. 155) and as predicted by the DAC model (Recasens, 1999; 2012).[42] The palatal is resistant to coarticulation by adjacent vowels in these languages (as has been shown by Tabain & Butcher, 1999; Tabain & Rickard, 2007; Fletcher *et al.*, 2008; Tabain *et al.*, 2011, and others), it is coarticulation aggressive, and for some speakers, such as Arrernte speakers, MM and VD, it tends to permit relatively little variation in adjacent vowels, indicating low context-sensitivity.

RQ2) proposed that languages differing in the number of coronal contrasts may differ in coronal coarticulatory patterns. Given that Arrernte and Gupapuyngu possess both (alveolo-)palatal and dental consonants, it might be predicted that the palatal stop is more constrained in these languages than in Burarra and Warlpiri (after Tabain *et al.*, 2011). The particularly low slope values and low variability associated with the palatal stop for Arrernte speakers (especially when a weak vowel precedes the consonant) may be caused by a very retracted and highly controlled articulation; Tabain *et al.* (2011) suggest that the Arrernte palatal 'may be a more 'extreme' version that is recruited when a contrast must be maintained with the more forward lamino-dental' (capitals removed; p. 277). Further, in §4.2.2, some evidence was provided of greater palatal-to-V coarticulation in VC and CV trajectory periods in Arrernte than in Warlpiri.

While slope values for the palatal are typically low across language groups, there are a few exceptionally high values. Likewise, there are a few exceptionally high Burarra and Gupapuyngu SD values in the VC trajectory, reflecting a high magnitude of variability at the vowel-consonant boundary and this high context-

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[42] The alveolopalatal and the dorso-palatal are known to differ in the extent of dorso-palatal contact and by extension in the magnitude of coarticulatory influence from preceding and following vowels (e.g., Recasens, 1984a,b, on Catalan); dorso-palatals involve greater linguo-palatal contact and hence are more coarticulation resistant.

sensitivity. These findings may reflect reduced and more variable linguo-palatal contact during the simultaneous alveolar and palatal closure. It is worth noting that Fletcher *et al.* (2007a), in an EPG study on Warlpiri, found some variability in the amount of anterior contact associated with palatals in consonant clusters and singletons. The extent of contact anterior to the pre-palatal region is also known to differ for Arrernte speakers (Butcher, 1995).

On the subject of coarticulation aggressiveness, it was demonstrated in §4.2.2 that the palatal stop differs from alveolar and retroflex stops in its effects on adjacent vowels. The palatal stop was seen to induce coarticulatory effects, especially in the form of F2 raising, in both preceding and following vowels (as found by Tabain & Breen, 2011, for Arrernte), but especially in preceding vowels. For some speakers, the palatal is also associated with a lowering of F1 and a raising of F3 in adjacent vowels. Carryover effects appear to be not only smaller in magnitude but also more temporally limited (when proportional, or linearly normalised, timing is considered), as shown in the plots presented, but they are stronger than any carryover effects associated with the other coronal consonants. The relative strength of the carryover component may reflect the strong dorsal component of the articulatory gesture (e.g., Recasens, 1999).

4.3.1.3 Bilabial and velar places of articulation

In the present study, it appears that the bilabial involves relative independence between different articulators (as shown in the slope results reported in §4.2.1 and the consonant locus results reported in §4.2.1.5), whereas in the velar, the dorsum is relatively free to move in the horizontal dimension, as is reflected in the large degree of F2 variation[43] (shown in the SD results presented in §4.2.1 and particularly in the results presented in §4.2.3) and the jaw is generally low but is context-sensitive (Keating, Lindblom, Lubker & Kreiman, 1994; Tabain, 2009b; Recasens, 2012).

The bilabial and velar stops are associated with a high degree of vowel-dependent coarticulation (high LE slope values), high context-sensitivity (high variability in vowels at the vowel-consonant boundary), and, by extension, low coarticulation resistance. It appears that velar slopes are particularly high because these consonants are strongly influenced by /i/ (§4.2.3) and are fronted in this

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[43] This claim draws on the understanding that the two articulatory factors that are most involved in F2 variation are, firstly, tongue dorsum backing and the degree of tongue dorsum (or linguo-palatal) contact and secondly, lip rounding (e.g., Fant, 1960). It seems unlikely that a transfer of lip rounding from the vowel to the consonant is involved in the difference between the vowel-onset and –midpoint given that lip rounding in /u/ is said to be weak (see §4.2.3.6).

context, as in Gupapuyngu <gikina> [gʲikʲina] ‘tooth’, or are post-velar or almost uvular with non-front vowels as in Gupapuyngu <gulku> [k̠olk̠o] ‘lots’ (see also Gooniyandi: McGregor, 1990, p. 52; Arrernte and Warlpiri: Fletcher *et al.*, 2007a, and Tabain *et al*., 2011). It was demonstrated in §4.2.1 and §4.2.3 that the velar stop varies in F2 according to the quality of the following vowel (/i a u/), in support of H4). Moreover, it was demonstrated statistically that there are three distinct targets (as argued by Butcher & Tabain, 2004). Consonants such as velars and bilabials are thus more contextually variable (as reflected in variability in adjacent vowels at vowel-consonant boundaries), whereas consonants that are higher in coarticulation resistance, such as palatals, are less variable and place stronger constraints on adjacent segments (Recasens & Espinosa, 2009a). See further, §4.2.3. The large F2 variability in velars can be related to ‘allophonic’ variation, as shown very clearly in §4.2.3. This variation is not allophonic in the strict sense of the word, but rather ‘a type of free variation resulting from standard coarticulatory processes’ (Tabain & Breen, 2011). These velar ‘allophones’ are roughly equidistantly spaced and members of each ($V_{ON,}$ V_{MID}) pair are closely aligned when inter-speaker variation is removed. /ki/ is associated with higher F2 formant frequencies than /ci/ for the Arrernte speakers and for Warlpiri speaker, BP, consistent with the claim of a fronted constriction and low velar resistance to coarticulation by front vowels (*cf.* American English: Sussman *et al.*, 1991; Fowler, 1994).

When speakers were examined individually, in Burarra, Gupapuyngu and Warlpiri, it was found that there was sub-maximal anticipation (by the velar) with a rising transition from vowel-onset to midpoint, suggesting an advancing of the tongue body from the velar into the vowel midpoint[44] in support of the notion that the velar consonants are blending with the adjacent back vowels (see Recasens & Espinosa, 2006b; see also Mooshammer, Hoole & Kühnert, 1995). It remains unclear why the stop would be articulated further back than the vowel target, but the claim that the stop target is more retracted than the vowel target is plausible given some lower velar loci in Gupapuyngu and Warlpiri than in Arrernte (see Figure 14). Nonetheless, on the whole, there is minimal difference between F2 frequencies at the vowel-onset and –midpoint (as indicated by LMM results and as illustrated by Figure 24), in accordance with Butcher and Tabain’s (2004) claim that

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[44] The consistency of this result for /ku/ in Burarra, Gupapuyngu and Warlpiri is particularly striking because one would expect any consonants following the sequence to exert some coarticulatory effects on V_{MID} if not V_{MID} and V_{ON} based on the other results presented in this chapter.

coarticulation between vowel onsets and midpoints is maximal for all three point vowels in Australian languages.

Arrernte /ku/ means are approximately 150-200Hz lower on average than those of the other languages, while /ka/ means are similar across the four languages. In /ku/, in Arrernte, at V_{ON} $\bar{x}=790$Hz, in Burarra, $\bar{x}=1180$Hz, in Gupapuyngu, $\bar{x}=970$Hz, and in Warlpiri, $\bar{x}=945$Hz. These results might be seen to suggest that the velar is a somewhat backed articulation in Arrernte and a similar or slightly more forward articulation in Warlpiri, but any fronting of the constriction in Warlpiri does not appear to be reflected in reduced slope values or reduced variation at consonant edges. and there is inter-speaker variation (Butcher, 1993; Butcher & Tabain, 2004; Tabain *et al.*, 2011).[45] There are no phonemic uvular consonants in Arrernte (or in Warlpiri) and accordingly it can be argued that the velar place may be pulled back, perhaps to strengthen cues to consonant identity, without causing confusion. Presumably the backed articulation in Arrernte of both the velar and the palatal (Tabain *et al.*, 2011) reflects the 'double-laminal' status of Arrernte (Arrernte includes two laminal categories); speakers might be expected to maximise the laminal contrast by producing a more back articulation in the palatal. However, note that when inter-speaker variation was excluded (in the LMM analysis; see §4.2.3.1), there was no difference in between the languages in F2 frequencies in vowels following velar stops (at vowel-onset and –midpoint).

As shown very clearly in Figure 24, velars do not resist the coarticulatory influence of adjacent vowels very strongly and can in fact be 'pulled from their place of articulation' (Fowler, 1994, p. 600). According to Ladefoged and Maddieson (1996), cross-linguistically, 'since the active articulator [in the velar stop] is the body of the tongue and this is also involved in the front/back contrasts in vowels, the effect on vowel environment on velar stops is different from that seen with other places ... the location of the constriction itself is affected.' (p. 33) These findings are supported by those reported in §4.2.3 (and consistent with previous work in, e.g., Swedish: Öhman, 1966; American English: Kent & Moll, 1972; Dembowski *et al*., 1998; Arrernte, Yanyuwa and Yindjibarndi: Butcher & Tabain, 2004; Warlpiri: Fletcher *et al.*, 2007a; Catalan: Recasens, 1991; 2009b). Moreover, the Warlpiri results are consistent with F2 onset results presented in Butcher and Tabain (2004) for (their) Warlpiri speaker, BP. The Warlpiri results, and in fact all of the languages' results, are also consistent with the findings of Fletcher *et al.*, (2007a), who present evidence of apparent vowel-dependent variation in Warlpiri in

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[45] Furthermore, palatograms reported by Butcher and Tabain (2004), which represent linguo-palatal contact during /aka/ sequences for Warlpiri speaker, CW, and their Arrernte speaker, MM, do not show any major difference as far as the forward edge of contact is concerned.

velars in consonant clusters (preceded by a nasal consonant); the velar is realised with a very backed constriction in the low vowel environment and with a more forward constriction in the front vowel environment. In some of the word-initial velar consonants, there may also be lenition, perhaps due to aerodynamic constraints (see, e.g., Butcher, 2006; Butcher & Tabain, 2004), such that the consonant coarticulates even more readily with the following vowel than a non-lenited velar consonant.

In Recasens' (1990a; 1991) study of C-to-V coarticulation in Catalan, he found that '[k] with back vowels is produced with a velar place of articulation; thus a very retracted tongue position for the consonant causes some retraction during the vowel when compared to its neutral configuration in the pVp environment.' (1990a, p. 145) In the present results, the velar in the /ku/ environment is associated with a very retracted articulation, particularly in the case of Arrernte but also in Gupapuyngu and Warlpiri, but the vowel appears to be slightly less retracted, especially in Gupapuyngu and Warlpiri (see Chapter 5).

Typically, a high F2 at vowel-onset for the velar is considered important as a cue to velar place, and a rise from vowel-onset to midpoint in the back vowel context is potentially confusable for a bilabial place.[46] As Butcher and Tabain (2004) state,

> 'the falling VELAR transition should not be too extensive in order to avoid confusion with the ALVEOLAR, and this is best achieved if the VELAR is relatively back – at least behind the [F3-F2-] changeover point. In the case of the Australian languages, *the back VELAR allophones can be very retracted and in some cases the transition may end up level or rising*.'
>
> (2004; emphasis added)

Frequently, in front vowel contexts, there is a level or a slightly falling transition between vowel-onset and –midpoint in /ki/, which would serve to distinguish front velar 'allophones' from palatal ones. Additionally, as Keating (1988) points out, the fronting of a velar 'does not turn it into a palatal' (p. 83; see also Keating & Lahiri, 1993, and Recasens, 1990b); palatograms for female Warlpiri speakers of velar and palatal stops in the front-vowel context show differences in

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[46] In keeping with Butcher and Tabain (2004), in the current corpus, there is an apparent swapping of cavity affiliations for the velar in F2 and F3 (*i.e.*, an F3-F2 changeover point) at approximately 2000Hz (20 ERB). Mean F2 /i/ values are below 2000Hz for Warlpiri speaker, RR (especially in the onset condition). Additionally, there are some data points that fall below 2000Hz for the other Warlpiri speakers, Burarra speakers and Gupapuyngu speaker, AM. In Butcher and Tabain (2004), all front vowel articulations are higher than 2000Hz at onset and midpoint. The authors note that a low F2 onset for an anterior velar stop may make it confusable for an alveolar (see, e.g., Plauché, Delogu and Ohala, 1997) (given that the spectra of the stop bursts of /k/ and /t/ are generally similar). There may be in these data, therefore, acoustical instability in the F3~F2 crossover point.

patterns of linguo-palatal contact.[47] Further, it could be hypothesised that the perceptual distinction is aided by a manner distinction: the front-velar and the palatal can be distinguished by the affrication typically associated with /c/ in these languages (see Butcher & Tabain, 2004; Tabain *et al.*, 2011, p. 278). Of course, this phonetic parameter is free to be used to supplement formant transition information because there is no fricative or affricate series in these languages. This spirantisation should not be seen as a form of weakening - as is made clear by a recent articulatory study of Arrernte jaw dynamics in which the jaw target for the palatal stop appeared to be timed to coincide with the fricative portion of the release (Tabain, 2012) - but rather a consequence of the biomechanics of the production (the large mass of the active articulator, and the difficulty involved in forming a complete constriction). (See further, Butcher & Tabain, 2004, p. 47.)

Several findings reported in §4.2.3 support the claim that /i/ is more coarticulation resistant that /a/ or /u/; there is evidence that /i/ is associated with less variability between the vowel-onset and –midpoint when following the velar stop than /a u/. Further, the Euclidean distance between /i a/ is often greater than between /a u/, suggesting /i/ is particularly coarticulation resistant and finally, for some speakers, /ki/ appeared to be associated with a fronted (perhaps medio- or postpalatal) constriction location (see Recasens, 1990b, p. 276 and elsewhere). /ki/ and /ci/ tended not to differ in F2 (consistent with the findings of Butcher & Tabain, 2004), with the exceptions of the productions of the Arrernte speakers, and particularly of Warlpiri speaker, BP, in which /ki/ was associated with higher F2 frequencies than /ci/. RQ1) with regard to vowels is strongly supported by these results. These results are consistent with a claim that perceptual differentiation of consonant places of articulation is more important at the left edge of the consonant than at the release in these languages, as will be discussed further in the next section.

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[47] A palatogram for a female Warlpiri speaker, CW, in Tabain and Butcher's (2004) dorsals study, which represents tongue contact throughout the word <piki> /piki/ 'pig', shows that while the velar gesture is fronted, central contact extends only into the medio-palatal region, with lateral contact extending forward into the post-alveolar region and back into the front velar region (p. 33). An averaged palatogram sampled at the midpoint of the palatal stop in the front vowel context, for another female Warlpiri speaker, their BP, shows central contact much further forward , with lateral contact extending back at least to the hard-palate/soft-palate juncture (Tabain *et al*., 2011, p. 274). (See also Recasens, 1990b, p. 275.) Butcher and Tabain (2004) do not provide an equivalent front-velar palatogram for their Arrernte speaker, MM, but Tabain *et al*. (2011) provide evidence of a palatal or alveolar/post-alveolar articulation for their mother and daughter Arrernte speakers, ST and JT (who are also referred to in §4.3.1.1).

4.3.2 Effect of trajectory period on consonant-vowel coarticulation

Hypotheses H5), H6) and H7) relate to the effects of trajectory period (whether the vowel precedes or follows the consonant) on consonant-vowel coarticulation. Overall, in the present study, cues to consonant identity appear to be either similarly controlled in the VC and CV trajectory periods or more present in the VC period.

Greater vowel-dependent coarticulation is observed when the vowel follows the consonant (in the CV trajectory period), with the possible exception of Arrernte. H5) on slope values being higher in the CV context can therefore be confirmed. Such a tendency towards greater V-to-C anticipatory than carryover coarticulation on the slope measure is thought to indicate planned, active coarticulation (see Recasens, 1989). Recall that in §2.1, the literature addressing directionality in V-to-C coarticulation was discussed. Many studies have shown an effect of factors such as place of articulation, specifically, the constriction location and related biomechanical properties associated with place. Studies such as that of Modarresi, *et al*. (2004) have shown an effect of trajectory period on LE slope value, but the consonant places still differed in the expected way. While there is some evidence of an effect of place of articulation on the predominant direction of both vowel-to-consonant and consonant-to-vowel coarticulation, in accordance with the predictions of the DAC model, this interaction did not reach significance in the case of the LMM analysis of slope values (see §4.2.1). It is possible that this non-significant interaction indicates an additional factor that plays a role in determining whether there is greater anticipatory or carryover coarticulation: (language-specific) perceptual constraints, and therefore differences in articulatory organisation. As Byrd (1996) suggests with regard to directionality in consonant cluster overlap, '[s]peakers may make less of an effort to preserve less robust perceptual cues.' (p. 235) Hence, in this context, speakers appear to be making an effort to preserve all word-medial consonant place cues.

Across the languages of this study, there was a predominance of anticipatory V-to-C coarticulation. This pattern is particularly interesting given findings of an avoidance of (synchronic) anticipatory coarticulation in Australian languages (discussed in §1.4 and §2.1.2) and is a clear point of divergence from the Arrernte, Yanyuwa and Yindjibarndi results presented by Tabain *et al.* (2004), who argued that VC and CV trajectory periods are not differentiated in Arrernte and other Australian languages on a phonetic level.[48] By extension, it could be argued that the left edge of the consonant is more protected than the right edge (release)

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[48] However, there is likely to be little vowel-to coronal stop coarticulation except that exerted by the high front vowel - as suggested by the findings in §4.2.3 - given the large set of place contrasts, and this may indicate a problem with the locus equation procedure.

from the coarticulatory effects of adjacent vowels, consistent with numerous phonological phenomena in the Australian context (§2.1.2.3) but antithetical to arguments by Ohala and Kawasaki (1984) and Steriade (1989; 1991) that (initial) CV transitions are more salient than VC transitions, and that the right edge (or release) of the consonant is perceptually more salient. Their arguments appear to be true for languages such as English and French but not for Australian languages. In this bias towards anticipatory V-to-C coarticulation, there is some evidence that stops have increased coarticulation resistance word-medially (the consonants in VC sequences are more likely to be word-medial than those in CV sequences; see §3.4.1.1; recall that the word lists are given in Appendix A) .

Turning now to the effect of trajectory period on variability or variance, as stated in §4.2.1.6, in this study, variability appeared to be more dependent on consonant place of articulation than on trajectory period. Nonetheless, for the Arrernte speakers, the difference between VC and CV conditions was not in accordance with H6), *i.e.*, greater variance occurred in the VC condition, indicating higher consonantal context-sensitivity to preceding vowels, which is inconsistent with the finding of an equivalent degree of vowel-dependent coarticulation in both trajectory periods for this language. There are no clear explanations at this stage for why there should be an inconsistency between the slope and variability measures.[49] Interestingly, in the study of Tabain *et al.* (2004), variability was slightly higher in the VC context for the Yanyuwa and Yindjibarndi speakers but not their Arrernte speaker, RF. For the Warlpiri speakers, the difference between conditions was in the opposite direction (there is greater variance in CV); this is consistent with the result for speaker KR and with the overall finding of greater vowel-dependent coarticulation in the CV condition.

With regard to H7) and the retroflex stop in particular, for the Burarra, Gupapuyngu and Warlpiri speakers and for Arrernte speaker, TR, for MM and VD in the non-word-initial context, the primary cue to the retroflex consonant in preceding vowels appears to be F3 lowering in the VC transition. That is to say, anticipatory retroflex-to-vowel coarticulation is predominant. Therefore, in all languages, there is evidence further to that given in §4.2.1 in the finding of greater CV than VC vowel-dependent coarticulation of an enhancement of retroflex stop cues at the left edge of the consonant. This is not inconsistent with the finding of reduced vowel-dependent coarticulation in the VC condition (on the LE measure). It is known that the retroflex has an alveolar-like final phase of production (Tabain,

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[49] However, it is important to note, again, that the SD value (and the variance measure) includes both contextual and non-contextual variability, unlike the LE. Non-contextual variability (e.g. variability due to token and speaker; Recasens & Espinosa, 2006a) may be acting as a confounding factor.

2009a,b) and so typically the release transitions of alveolars and retroflexes are not distinctive (e.g., Wubuy: Bundgaard-Nielsen *et al.*, 2009). This asymmetry is said to underlie the occurrence of apical neutralisation (see §4.2.2) in word-initial contexts, as in Arrernte and Warlpiri (see, e.g., Steriade, 2000). Tabain *et al.* (2004) argue that, in Arrernte,

> 'it is likely that the [word-initial] vowel is simply a means of increasing the number of cues to the 'real' initial phoneme, the consonant, in this language with so many places of articulation. The presence of a vowel adds cues such as VC transition and stop closure duration to cues such as stop burst duration and CV transition.'
>
> (p. 194)[50]

With regard to the issue of the underlying syllable, recall that Tabain *et al.* (2011) predicted that unlike English, the VC unit in Arrernte, Yanyuwa and Yindjibarndi would be a more protected unit, with less vowel-dependent coarticulation and less variability at the vowel-consonant boundary. They therefore predicted higher slope values and greater variability in the CV context. The authors instead found a similarity between CV and VC contexts across slope and F2/F3 variability at consonant release measures. As predicted, the English speakers' slope values tended to be higher in the VC context, indicating a fundamental difference in the gestural activation patterns underlying consonant-vowel coarticulation between the two language groups. Tabain *et al.* (2004) suggest that a dispreference for vowel-dependent VC coarticulation in the Australian languages may relate to the large number of consonant places (after Butcher, 2006) and also the presence of a retroflex series, as was shown very clearly in the results reported in §4.2.2:

> 'tight control of both the CV and VC transitions is a necessary constraint on consonant production in languages which have multiple places of articulation. [...] Following Steriade (2000), we may suggest that the presence of the retroflex consonant (=apico-postalveolar) in these languages motivates greater control of the VC sequence.'
>
> (p. 194)

Breen and Pensalifini (1999) suggested that an Australian language with pre-stopped nasals, such as Arrernte, is more likely to have a VC syllable (see §1.2.1.5). As was noted by Tabain *et al.* (2004), while for Arrernte there is some phonological evidence in the literature of an underlying VC syllable, there was none

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[50] It can be hypothesised that the apical following the pre-palatalised vowel behaves similarly to the neutralised word-initial apical; there is inter-speaker variation, apicals can be more or less canonical alveolar or retroflex stops, and there is variation according to the degree of hyper-articulation (Butcher, 1995; Anderson V. B., 2000; Gavin Breen *pers. comm*. reported in Tabain, 2009, p. 494).

preceding the authors' study for Yanyuwa and Yindjibarndi. Nor is there prior evidence for an underlying VC structure in Burarra, Gupapuyngu and Warlpiri. The LE slope results of the present study - in combination with those in Tabain *et al.* (2004) - might be considered to challenge claims regarding the universal unmarked nature of (underlying) CV syllables or the CV planning unit, because LE slope values were typically higher in the CV trajectory period than in the VC period (Butcher, 2006; Butcher & Harrington, 2003). However, some scholars would argue that the structure of the (surface) syllable is revealed primarily in the kinematics rather than the acoustics of speech, although the kinematics are revealed in the acoustics (e.g., Browman & Goldstein, 1987; 2000; Goldstein, Chitoran, & Selkirk, 2007). Similar consonant driven patterns are found in cases of post-tonic gemination, lengthening and strengthening in other languages, such as so-called 'syllable-timed' Romance languages, for which a VC syllable has not been posited (see, e.g., Blevins, 2007). It is known that coarticulation resistant consonants tend to be longer in duration (e.g., Fowler & Brancazio, 2000). These ideas are preliminary, but they suggest that further acoustical and articulatory studies of consonant-vowel coarticulation should be conducted in Australian languages.

4.3.3 Effect of prosodic prominence on consonant-vowel coarticulation

Regarding the effect of prosodic prominence on slope and SD values, an initial cross-linguistic analysis identified that there was an interaction of consonant place of articulation and prosodic prominence on LE slope values in support of H8). However, there was no clear separation of lingual and non-lingual stops according to the difference in slope values between prosodic conditions (*cf.* Lindblom *et al.*, 2007). Further, there was no significant interaction between prosodic prominence and trajectory period across speakers but a weak (non-significant) tendency towards lower slope values was observed for Burarra speakers and for Warlpiri speakers in the CV trajectory period when the vowel is prosodically weak. There is therefore insufficient evidence for the suggestion in RQ3) regarding prosodically prominent vowels being more likely to exert coarticulation (derived from findings by Farnetani, 1990, and de Jong *et al.,* 1993, amongst others). Hence, these results are unlike those reported by Lindblom *et al.* (2007) for English in that there are no consistent differences in locus equations due to stress (although prosodic prominence is not emphatic stress in this study).

With regard to the effects of prosodic prominence on F2 variability, the hypothesis, H8), was, in part, that SD values are higher when the vowel is prosodically weak. This is because a weak vowel is predicted to be less resistant (more context-sensitive) than a prominent vowel to the coarticulatory effects of adjacent segments. There is no clearly observable trend regarding prosodic effects on variability, hence, there is insufficient evidence for H8) with regard to variability.[51] If there *is* hyper-articulation due to the effects of prosodic prominence in these languages, it may be that it occurs on consonants rather than vowels, as suggested by the findings of Butcher and Harrington for Warlpiri (2003). This issue will be addressed further in Chapter 5.

4.4 Conclusions

In the results reported in this chapter, it has been demonstrated that the magnitude of consonant-vowel coarticulation in a given word is largely dependent on consonant place of articulation. Peripherals were seen to undergo greater vowel-dependent coarticulation than non-peripherals. Consonant-vowel coarticulation was found to be higher in magnitude in the CV condition, *i.e.*, consonants underwent greater vowel-dependent coarticulation in the anticipatory direction. Pre-palatalisation of retroflexes in the word-initial context was seen to occur for two of the three Arrernte speakers while the other ten Australian language speakers showed F3 lowering associated with retroflexion, or 'r-colouring'. Moreover, in all languages, velars were seen to vary in F2 formant frequency according to the quality of the following vowel. In general, as would be predicted, it appears that the more coarticulation resistant the consonant, the more it induces coarticulation in the vowel (*cf.* Cho 2001; 2004) and, specifically, the greater the amount of place of articulation information that is carried in the vowel. For example, it was demonstrated that the palatal stop is relatively coarticulation resistant (typically undergoing little vowel-dependent coarticulation) and tends to exert strong C-to-V coarticulation, particularly in F2.

As was found by Recasens (1985), when the results of LE and variability (SD) calculations are compared, for the most part, for a given consonant place of articulation, there is a positive correlation between the two, such that when a slope value is higher, a higher SD value can be predicted.The question of whether there is a link between coarticulation resistance and the LE can therefore be answered affirmatively; these results support the claim of Brancazio and Fowler *et al.* regarding a meaningful relationship between LE slope values and coarticulation resistance. By extension, these results support the uniform coarticulation resistance hypothesis (Brancazio & Fowler, 1998; Fowler, 1998; Fowler & Brancazio, 2000), which states that coarticulation resistance underlies the linear relationship between

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[51] However, for the Arrernte and Warlpiri speakers, there is a weakly discernible trend towards reduced variability in the vowel at the vowel-consonant boundary when the vowel is weak.

F2 at V_{MID} and the vowel at the vowel-consonant boundary ('CV transition starting point', in Recasens' terms), rather than Sussman's 'orderly output constraint' (§2.1.2). The positive correlations between the LE and SD results are consistent with the findings of Fowler and Brancazio (2000) and with Tabain's (2000) claim that a consonant that exhibits little variability will show little (anticipatory) coarticulation with the following vowel, whereas a consonant that exhibits great variability will show more coarticulatory influence from the vowel (p. 145). (Identical results would not be expected, however, as the SD cannot distinguish between contextual and non-contextual variability, whereas the LE slope value is intended to quantify merely contextual variability.) Moreover, the LE method appears to have produced results (*i.e.*, the results summarised in the previous paragraph) consistent with those generated by other means, e.g., examination of F1, F2 and F3 frequencies in neighbouring vowels in the case of retroflexes and F2 frequencies at the onsets and midpoints of following vowels in the case of velars. However, it has been noted that the LE is not highly robust to great irregularity in vowel distribution, nor is it highly robust to the coarticulatory effects of neighbouring segments (as noted by Löfqvist, 1999).

The various measures in combination have allowed research questions RQ1) to RQ3) and hypotheses H1) to H8) to be addressed. The results reported in this chapter are broadly consistent with those in the Australian experimental phonetic literature, in particular with the results of studies conducted by Tabain and Butcher and colleagues (e.g., Tabain, 2000; Butcher, 2006; Tabain & Butcher, 1999; Tabain *et al.*, 2004). Arguably, slope values associated with alveolar and retroflex consonants were poorly separated in the present study. Hence, the retroflex-to-vowel coarticulation results presented in §4.2.2, were important in contributing further information regarding interactions between such consonants and vowels.

As it was found in this chapter that there is some clear 'allophonic' variation associated with velars and other places of articulation in different vowel contexts, it is important that vowel realisation is explored further to inform the analysis of vowel-dependent coarticulation and to see the full extent of variation in vowels in different trajectory periods and in different prosodic contexts, which occur in different place of articulation environments. This will be undertaken in the next chapter.

5 Vowel variability and dispersion

5.1 Introduction

The previous chapter examined consonant-vowel coarticulation between consonants and vowels. It became apparent that there are vowel quality effects on consonant-vowel coarticulation in addition to consonant place of articulation and trajectory period effects. Additionally, there was an interaction between consonant place of articulation and prosodic prominence on LE slope values, but as a whole, prosodic effects were equivocal. Vowel categories were collapsed in the LE analyses in §4.2.1, while only low central vowels were considered in the pre-palatalised and retroflex consonant analysis in §4.2.2 and only point vowels /i a u/ were considered in the vowel-dependent velar coarticulation analysis in §4.2.3.

The present chapter examines vowel variability and dispersion in the four languages, which have relatively small vowel inventories, with regard to the effects of vowel quality, prosodic prominence and word position on F1 and F2 formant frequencies in CV1CV2 words. The qualities of these vowels were outlined in §1.2 and are reiterated briefly in §5.1.2. The results will inform the subsequent chapter on V-to-V coarticulation, Chapter 6, in which the relationship between formant transitions in target vowels and flanking vowel identity is considered in CV1CV2 words. A full discussion of the methodology employed in this chapter is provided in §3.4.2.

The analysis of vowel acoustics in the F2 x F1 plane presented in this chapter has four aims. The first is to determine how phonemic vowels in these languages differ in F1 and F2. The second, related, aim is to determine whether vowels are affected by neighbouring word-medial consonant place of articulation and whether a given vowel differs according to word position and prosodic prominence in the CV1CV2 word. Recall that in these words, V1 is prosodically prominent or 'strong', while V2 is prosodically weak. The third aim is to measure the magnitude of variability in each vowel quality in F1 and F2. The fourth is to determine the magnitude of vowel space dispersion within a given speaker's vowel space. This analysis is relevant to several research questions, including the question of whether the quality of a vowel determines the extent to which it is coarticulated by an adjacent segment (RQ1)), whether language-specific inventory-related differences explain some differences in coarticulation and resistance to coarticulation in these vowels (RQ2)), and whether prosodically prominent vowels are more likely to exert coarticulation and less likely to undergo coarticulation, all else being equal (RQ3)), factoring in the findings in the previous chapter.

The structure of this chapter is as follows: in §5.2, results are given per language group. The results for Arrernte are presented in §5.2.1, for Burarra, in

§5.2.2, for Gupapuyngu, in §5.2.3, and for Warlpiri, in §5.2.4. Within each of these sections, there are subsections relating to vowels in the F2 x F1 plane, which include an analysis of the effects of word-medial consonant place, prosodic condition and word position on vowel formant frequencies, an analysis of vowel variability and, finally, a Euclidean distance analysis, which addresses the effects of prosodic condition and word position on distances. A general discussion is undertaken in §5.3. This discussion addresses the hypothesis that there is an effect of word-medial consonant place on F1 and F2 formant frequencies in vowels, the hypotheses relating to the effect of vowel quality on variability and peripherality (§5.3.1), to vowel system distinctiveness and the effect of language on vowel space dispersion (§5.3.2), and to the effects of prosodic prominence and word position on vowel variability, vowel space dispersion and vowel peripherality (§5.3.3).

5.1.1 Hypotheses

The relevant research questions have been discussed in full in Chapter 2 and include RQ2) on the effect of language-specific inventory-related differences on coarticulation and coarticulation resistance. Specifically in this context, does the size of the vowel system affect the range, distribution and degree of dispersion and variability in vowels in the F2 x F1 plane (Lindblom, 1986)? The following hypotheses relate to vowel variability, vowel space dispersion and prosodic and word positional effects.

Firstly, it is proposed that some variability in the vowel space will reflect consonant-dependent coarticulatory effects (as can be inferred from the place of articulation imperative, e.g., Butcher, 1995; 2006; see RQ1)):

H9) F1 and F2 frequencies extracted from vowel midpoints show an effect of word-medial consonant place of articulation. This effect is stronger in F2 (after, e.g., Fant, 1960; Purcell, 1979; Recasens, 1984a).

In view of earlier findings for other languages that there is a relationship between vowel variability and context sensitivity (e.g., American English and Hindi: Stevens & Blumstein, 1975; Stevens, 1980; German: Hoole *et al.*, 1990), H10) states:

H10) Vowels /i u/, and especially /i/, are associated with less variability (smaller SD values, suggesting weaker context-sensitivity) and more peripherality (larger Euclidean distance or ED values) than /a/ regardless of the mutual articulatory compatibility of these vowels and adjacent segments.

Thus, it can be argued that the close vowels are more coarticulation resistant than /a/ (see §2.1.2). This behavior is due to close and close-mid vowels possessing stronger articulatory requirements than mid or low vowels.

The hypotheses relating to vowel space dispersion or the limits of the vowel space and the effects of language group and prosodic prominence comprise H11), H12) and H13) (see §2.3.1). The rationale for H11) is that a small, compact vowel space may be associated with a prioritising of consonant place of articulation rather than vowel quality contrasts.

H11) The languages display minimal distinctiveness in their vowel spaces; vowel spaces are compact and dispersion (ED values) associated with a language with a smaller vowel inventory is not greater than that associated with a language with a larger inventory (after Butcher, 1994; Recasens & Espinosa, 2009c).

A further rationale for H11) and a rationale for H13) is that the previous literature on non-Australian languages indicates that prosodic prominence has effects on vowel variability and dispersion or peripherality – typically, variability is decreased (thus, vowels become less context-sensitive) and dispersion is increased in prominent vowels – and therefore on the extent to which vowels undergo and exert coarticulation (as discussed in §2.4). Additionally, measuring variation (in the form of SD values) provides information about vowel reduction and centralisation.

H12) According to the localised hyper-articulation model, F1 and F2 variability (SD values) is lower in the VC, prosodically prominent, condition (after, e.g., de Jong, 1995; Koopmans-van Beinem, 1980). However, on the basis of the results reported in §4.2.1 and on the basis of previous studies of Australian languages, clear and consistent prosodic effects are not predicted.

H13) According to the localised hyper-articulation model, vowel space dispersion (in the form of ED values) is greater in the VC, prosodically prominent, condition (after, e.g., de Jong, 1995; Koopmans-van Beinem, 1980). Relatedly, after Vayra and Fowler (1992), Cho (1999; 2004) and Lindblom *et al.* (2007), vowels are thought to be associated with more extreme F1 and F2 means when prosodically prominent, e.g., prosodically prominent /i/ is associated with lower F1 frequencies and higher F2 frequencies than non-prominent /i/ and prominent /a/ is associated with higher F1 and lower F2 frequencies than non-prominent /a/ (after Cho, 1999). However, once again, on the basis of previously reported results, a clear and consistent relationship between prosodic prominence and vowel space dispersion and vowel peripherality is not predicted.

5.1.2 Methodology

Full methodological details and details of the distribution of the vowel categories in this corpus have been provided in Chapter 3. The vowel inventories are discussed in full in §1.2. The corpus for the experiments reported in the present chapter comprises all CV1CV2 words (the most common word type) in the four languages (see the core word list in Appendix A and the supplementary word list in Appendix B). Each vowel in the V1 condition is prosodically prominent and each vowel in the V2 condition is not, e.g., in the Gupapuyngu word <gapu> /'gapu/, 'water', only /a/ is prominent. For a discussion of how prosodic prominence is identified, see §3.3.1. Previous studies conducted by Recasens and Espinosa have utilised similar methods (e.g., 2009c).

F1 and F2 frequencies (Hz) are extracted from the vowel midpoint ($V1_{MID}$ and $V2_{MID}$) and plotted in the F2 x F1 plane per word/prosodic prominence condition with standard deviation ellipses (SD=2, CI=95%). Plotting all vowels in an inventory in an F2 x F1 plane with standard deviations provides an indication of both the magnitude of variation in a vowel and the plane(s) in which variation occurs (see, e.g., Harrington, 2006). V_{MID} is assumed to be least affected by adjacent segments (§3.4.2). F1 and F2 means are given as class centroids (marked by the vowel label). All plot labels except 'X', which marks the grand centroid, are phonemic (with the exception of the word-final vowel in Arrernte, see §1.2.1). In other words, the average position of each vowel category is marked with the corresponding symbol. For a clear graphical representation of vowel variability, standard deviations are plotted in the F2 x F1 plane per V1/V2 labelled by vowel and speaker (identified by initials and colour). Recall that significance levels have frequently been modified according to Bonferroni correction procedures and may differ between languages because of differences in the number of comparisons (see §3.4.2.1).

As discussed in §1.2.1, for the Arrernte speakers, vowel distribution (phonotactics) differs between V1 and V2; whereas the full range of Arrernte vowels occurs in V1, in V2 only a central vowel occurs and this vowel is not phonemic. /u/ does not occur in this corpus for speaker TR. In these CV1CV2 words, a stressed mid central vowel, /ɘ/, can occur in V1 position; see §1.2.1.5 and §3.3.1.

5.2 Results

In Figure 27, vowel spaces are summarised per language group as a function of word position and prosodic prominence. V1 (VC) is always prominent in this subsection of the corpus (CVCV words). It is apparent that there is more variability in F2 than in F1.

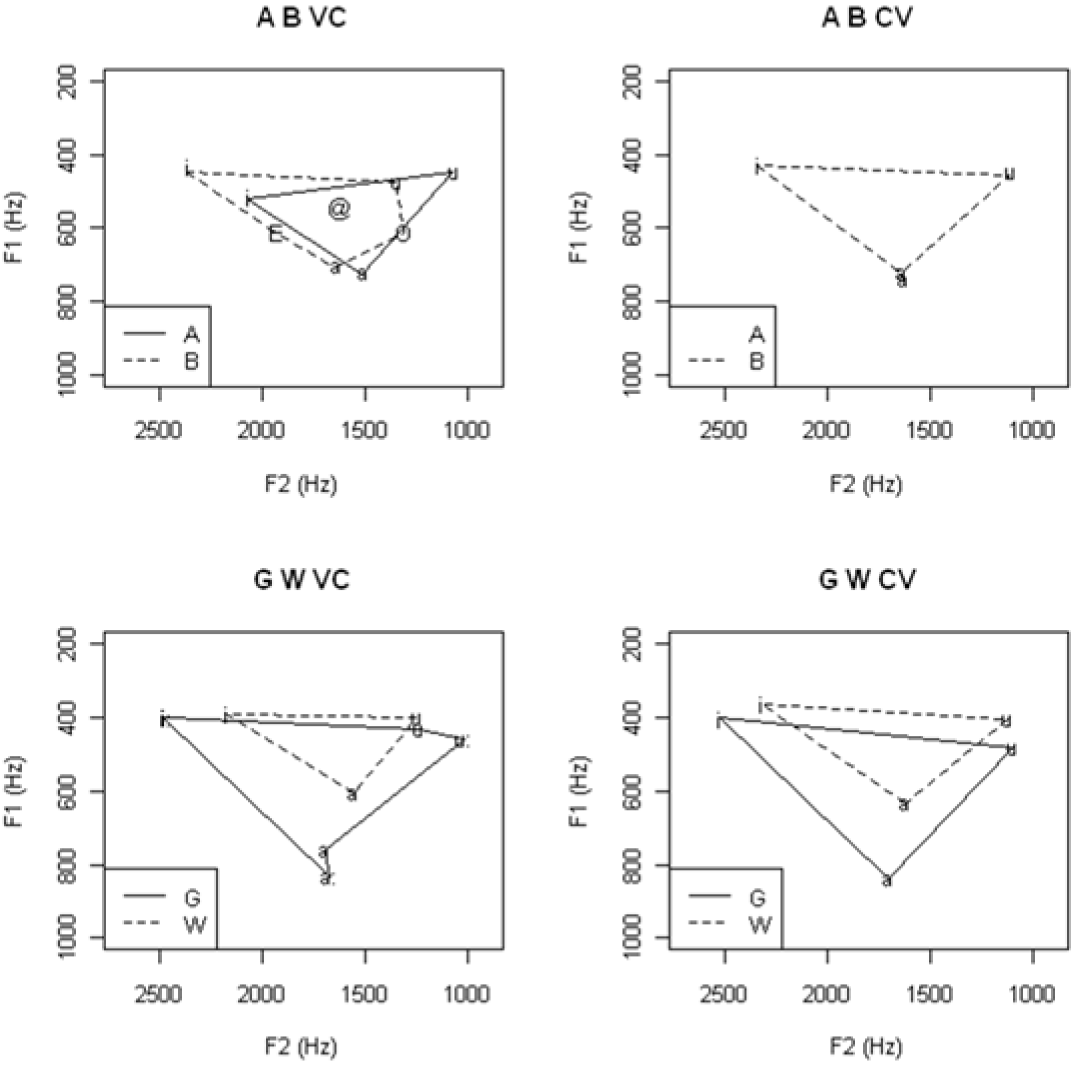

Figure 27. All vowels in the F2 x F1 plane (95% CI) for V1 (VC, left) and V2 (CV, right) contexts in CV1CV2 words for (upper) A (Arrernte, solid), B (Burarra, dashed), (lower) G (Gupapuyngu, solid) and W (Warlpiri, dashed), where '@' represents /ə/. Data are extracted at the temporal midpoint of the vowel. The average position of each vowel category is marked with the corresponding symbol. Prosodic prominence is on V1. In the CV2 context, the Arrernte vowel is [a].

Linear Mixed Model (LMM) procedures were used to investigate the effect of word-medial consonant place and language group on F1 and F2 formant frequencies at V_{MID} (vowels preceding and vowels following the word-medial consonant) in CVCV words (fixed factors: F1, F2, vowel quality, word-medial consonant place, language group; random factor: speaker). Four separate procedures were conducted for F1 and F2, and for VC and CV conditions. In the CV and F1 condition, there were main effects on V_{MID} of language group (F(3,8)=7.7, p<0.01), vowel quality (F(2,1620)=1376, p<0.0001) and word-medial consonant place (30, 1620)=3.13, p<0.0001). In F2, there was no effect of language group (F(3,8)=0.2, p=0.89), but there was an effect of vowel quality (F(2,1620)=4669, p<0.0001) and of word-medial consonant place (F(30,1620)=12.67, p<0.0001). In the VC and F1 condition, there were main effects of language group (F(3,8)=5.1, p<0.05), vowel quality (F(8,16140=536, p<0.001) and word-medial consonant place (F(30, 1614)=3.91, p<0.0001). In F2, once again there was no effect of language group (F(3,8)=0.18, p=0.9) but there were effects of vowel quality (F(8,1614)=758, p<0.0001) and word-medial consonant place (F(30, 1614)=15.5, p<0.0001).

While the effect of language group was only significant in F1 (relating to vowel height), the effects of word-medial consonant place were always significant, *i.e.*, the word-medial consonant exerts coarticulatory effects onto neighbouring vowel (at their midpoints). F values were higher in the F2 condition, which suggests that there are stronger effects of consonant place in F2 than in F1, as would be anticipated. Additionally, F values were slightly higher in the VC condition, which may suggest that there is greater anticipatory consonant-dependent coarticulation than carryover coarticulation. Importantly, when the factor of word-medial consonant place was removed from the LMM models, the goodness of fit was greatly reduced (CV and F1, χ^2(30,38)=93, p<0.0001; CV and F2, χ^2(30,38)=349, p<0.0001; VC and F1, χ^2(30,44)=116, p<0.0001; VC and F2, χ^2(30,44)=419, p<0.0001).[52]

In order to observe whether there was a cross-linguistic effect of prosodic prominence and word position (a V1/V2 effect) on raw F1 and F2 frequencies in vowels, LMM procedures were run on F1 and F2 formant frequencies with the effects of speaker and group excluded. In the LMM analysis of F1 formant frequencies (fixed factors: vowel quality, prosodic prominence/word position (V1, V2), random factors: language group, speaker), there was a main effect of vowel quality (F(8,3321)=674, p<0.0001) and prosodic prominence/word position

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[52] It is worth noting that an R^2 analysis indicated that the proportion of variability in the data set that is accounted for by a statistical model including only the independent variable of word-medial consonant place ranges from 0.07 to 0.09 (7 to 9%) in F1 and from 0.1 to 0.16 (10 to 16%) in F2. In the VC condition in F1, for the factor of vowel quality, R^2=0.67, and medial consonant place, R^2=0.07, for F2, vowel quality, R^2=0.7, medial consonant place, R^2=0.16. In the CV condition in F1, for vowel quality, R^2=0.61, medial consonant place, R^2=0.09, for F2, for vowel quality, R^2=0.8, and for medial consonant place, R^2 = 0.1. Given the F values associated with the relevant LMM results, it could be said that the factor of medial consonant place explains a significant proportion of variance in F1 and F2 at vowel midpoints.

($F(1,3321)=21$, $p<0.0001$).[53] F1 was higher in V2 (V2 was more open). When the F1 distribution associated with individual vowel qualities was examined, the F1 raising effect was most present in /a/, less clearly present in /u/, and not present in /i/.[54] In the same procedure in F2, there was again a main effect of vowel quality ($F(8,3321)=1159$, $p<0.0001$) but prosodic prominence/word position did not reach significance ($F(1,3321)=0.07$, $p>0.05$). Presumably, the larger F value associated with vowel quality in the F2 procedure indicates that vowels are better differentiated in F2 (backing) than F1 (height) in these languages (although Arrernte may be an exception). The four languages will now be discussed in turn.

Table 47. Mean Arrernte formant frequencies and standard deviations of all vowels in the VC context (upper) and CV context (lower), in which the vowel is prosodically prominent. Unusually low (<20Hz) or high values (>250Hz) are marked with an asterisk. In this and subsequent tables and figures, '@' =/ə/.

V1												
	MM				**VD**				**TR**			
	F1		**F2**		**F1**		**F2**		**F1**		**F2**	
	x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**
a	735	115	1581	197	730	89	1420	126	910	194	1675	125
ə	505	93	1604	339	565	97	1626	373*	638	53	1594	159
i	484	131	2040	163	498	75	2207	86	550	12*	1886	13*
u	449	66	1346	398*	434	107	867	186	N/A	N/A	N/A	N/A
V2												
	MM				**VD**				**TR**			
	F1		**F2**		**F1**		**F2**		**F1**		**F2**	
	x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**
a	543	131	1643	171	543	131	1643	171	543	131	1643	188

5.2.1 Vowel variability and dispersion - Arrernte

Figure 27 and Figure 28 show Arrernte vowels in the F2 x F1 plane at $V1_{MID}$ (V1 or VC) and $V2_{MID}$ (V2 or CV) conditions in CV1CV2 words, e.g., <kele> /kəl(a)/ 'alright'; <thipe> /t̪ip(a)/ 'bird'. Means and standard deviations are reported in Table 47. Euclidean distances are plotted in Figure 29 and tabulated in Appendix B. Statistical tests on standard deviations cannot be run due to widely differing sample sizes (see §3.4.2). Euclidean distances are calculated only for the V1 context, as only one vowel quality occurs in word-final position.

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[53] There was some difference according to the inclusion or exclusion of the factor of language group for F1 ($\chi^2(2,15)=6.68$, $p<0.05$) but not for F2 ($\chi^2(2,15)=1.19$, $p=0.4$), but this difference related to the factor of vowel quality and not vowel position (VC, CV), which was the focus of the procedure.

[54] Interaction effects could not be examined using the LMM procedure because of the presence of singularities (6 out of 18 effects), due to differing vowel inventories. However, an interaction is likely given differences in statistical distribution.

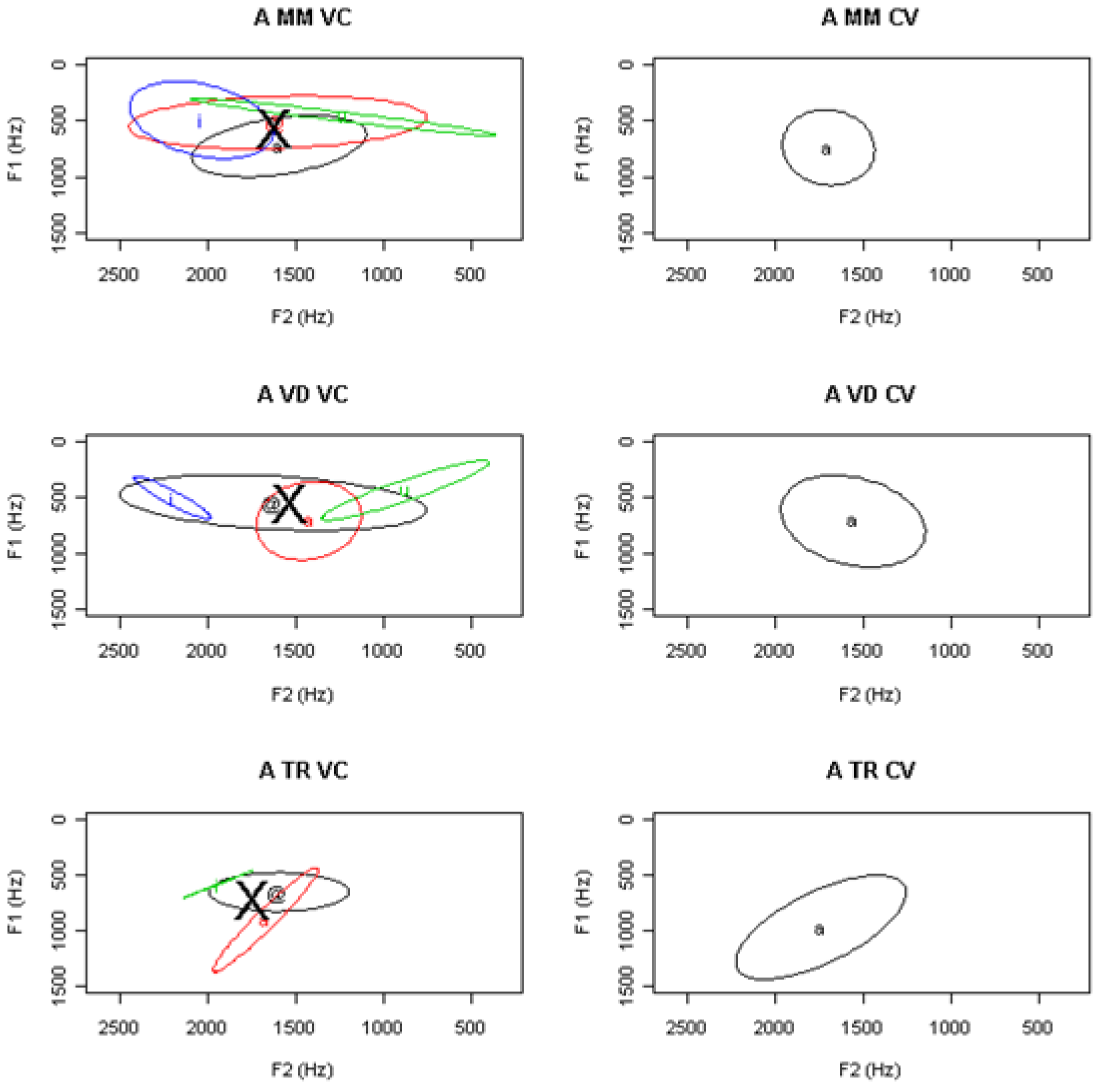

Figure 28. Arrernte vowels in the F2 x F1 plane (95% CI) in V1 (VC, left) and V2 (CV, right) conditions in CV1CV2 words. Data are extracted at the temporal midpoint of the vowel. The average position of each vowel category is marked with the corresponding symbol. Prosodic prominence is on V1. In the V2 condition, the centroid for the overall space is identical to the class centroid, here termed ‘a’. ’@’ represents /ə/. The x-axis range is 300-2600Hz. The y-axis range is 0-1500Hz.

According to Figure 28, in V1, Arrernte vowel ellipses are extensively overlapped and the central vowel, /ə/, is particularly variable in the F2 dimension. /u/ is often associated with F2 values greater than 1000Hz, indicating that it can be centralised and that lip rounding can be weak or absent, hence the back vowel can be produced as [ɵ] or [ə]. For MM and TR, the mid central vowel and /a/ are separated in F1 (tongue height) more than F2 (fronting), *i.e.*, /ə/ is produced with a closer constriction. As shown in Figure 28, in V2, in which the vowel is prosodically weak, only the (low) central vowel occurs. Across speakers, /a/ is higher in F1 and lower in F2 in V1 than is the vowel in V2, indicating a less open and more back vowel in the V1 context.

When the low open vowel was compared in V1 and V2 contexts, it was not seen to differ in F1 according to word/prosodic condition at ɑ=0.01 (MM, t(76)=-0.51, p=0.62; VD, t(95)=-0.20, p=0.84; TR, t(5)=-0.63, p=0.56). In F2, for MM and VD, /a/ is associated with lower frequencies in V1 (MM, t(42)=-2.82, p<0.01; VD, t(111)=-5.49, p<0.0001), indicating a more back constriction. For TR, word/prosodic conditions do not differ in the low open vowel (t(8)=-0.90, p=0.4), perhaps due to the small number of tokens (VC, n=4; CV, n=17).

Prosodically prominent /ə/ is associated with lower F1 frequencies (and is therefore less open) than the word-final vowel (MM, t(104)=-10.57, p<0.0001; VD, t(161)=-7.84, p<0.0001; TR, t(21)=-5.97, p<0.0001), as is evident in Figure 28. In F2, the difference approaches significance for speaker TR (t(20)=-1.987, p=0.06), for whom the smallest sample exists; F2 is higher in the word-final position. The difference is not significant for speakers MM and VD (MM, t(42)=-1.7, p=0.095; VD, t(69)=1.42, p=0.16).

With regard to variability in the mid central vowel, as was seen in Figure 28, and as tabulated in Table 47, variability is greater in F2 than F1 for the majority of vowel qualities. The mid central vowel varies moderately in F1. There tends to be more F2 variability in the mid central vowel than in /i a/, which may indicate greater coarticulatory sensitivity in the mid central vowel to consonant place (although consonant place is not controlled for here). High F2 variability in V1 in /ə u/ appears to be due to C-to-V coarticulation exerted by palatal, bilabial, labio-velar and velar consonants (see §4.2).

Across the V1 and V2 contexts, the low central vowel, /a/, is highly variable in F2, and for TR (but not for MM and VD) there is more F1 variability in /a/ than in /i ə/, presumably because for this speaker /a/ is more sensitive to variability in jaw and dorsum height or because of differing sample sizes. In V2, the central vowel varies similarly in F2 for the three speakers. In F1, it varies little for VD and greatly for TR (as in V1).

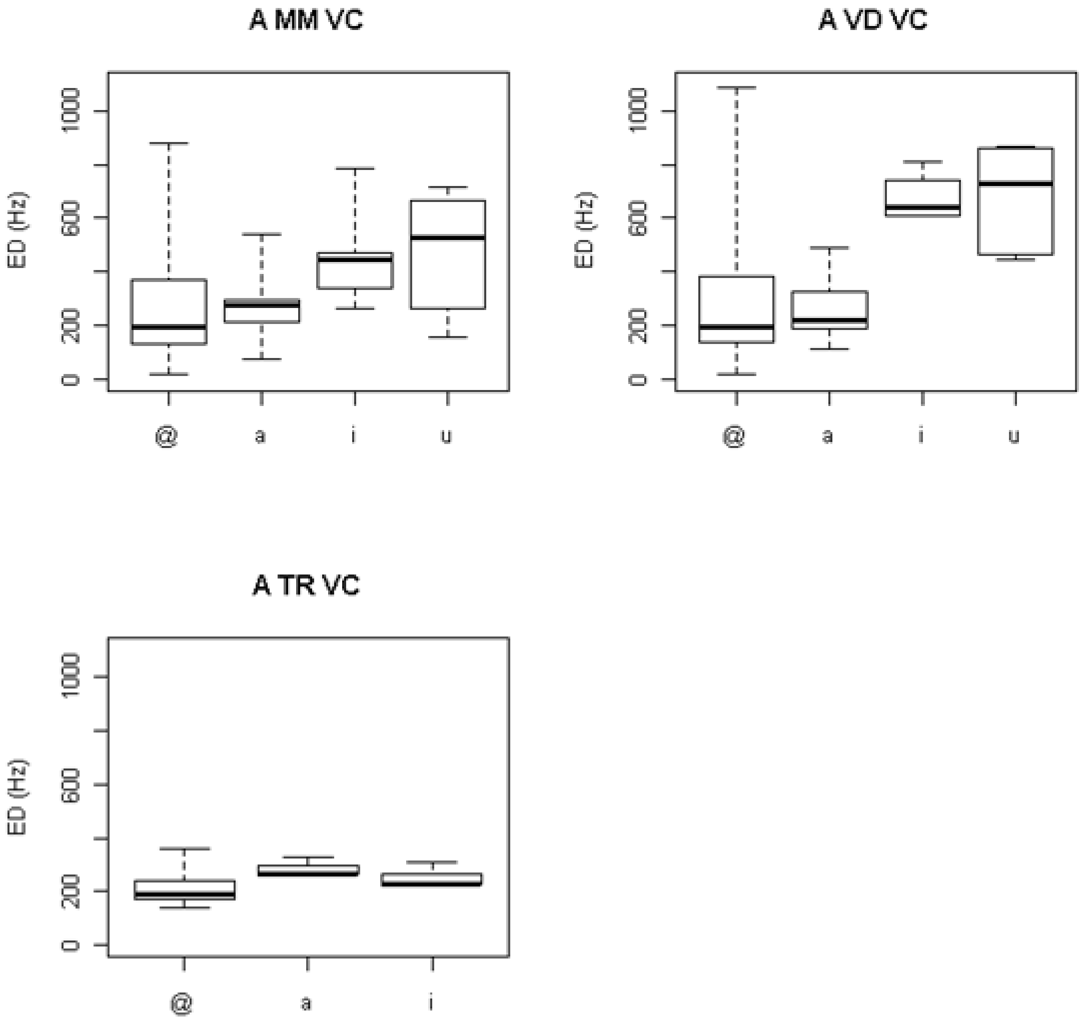

Figure 29. Boxplots of Euclidean distances to the centroid (Hz) for Arrernte speakers for vowels in the V1 condition in CV1CV2 words, where '@' represents /ə/. Distances are given in Hz. The y-axis range is 0-1100Hz.

Regarding the phonemic close vowels, in /i/, for MM, there is slightly more F1 variability than for /ə a u/, suggesting that while /i/ can be centralised it is usually realised as a somewhat close vowel (*i.e.*, it shows some coarticulation resistance). In the close back vowel, /u/, for VD, there is more F1 variability than for /i a ə/. For MM and VD, /i/ varies little in F2, while /u/ varies greatly.

With regard to Euclidean distances, for speakers MM and VD, the central vowels are between 250 and 289Hz from the overall F1 by F2 or 'grand' centroid (recall that the term 'grand centroid' refers to the centroid of the entire vowel space, marked by 'X' in Figure 28, whereas the term 'class centroid' refers to the centroid of an ellipse associated with a single vowel quality). It is clear from the presence of some zero values associated with /ə/ in Figure 29 that this vowel is functioning as the pivot or anchor in V1 (consistent with Figure 28). The close vowels, /i u/ are further from the centroid than the central vowels, as would be anticipated, at 459 and 542Hz, respectively, for MM, and 675 and 673Hz, respectively, for VD. The vowels thus separate into two groups (central and close vowels) with respect to Euclidean distances, as shown in Figure 29 and also with respect to the acoustic vowel space, as shown in Figure 28. The ED values of speaker TR differ from those of MM and VD due to the lack of /u/ tokens.[55]

5.2.2 Vowel variability and dispersion - Burarra

Figure 30 and Figure 27 show Burarra vowels in the F2 x F1 plane in $V1_{MID}$ (VC) and $V2_{MID}$ (CV) conditions in CV1CV2 words. Means and standard deviations are reported in Table 48 and Table 49. Euclidean distances are plotted in Figure 31 and tabulated in Appendix B. Note that in V2, there are few tokens containing /u/ for DP and MW and containing /i/ for MW. Statistical tests cannot be applied to standard deviations because of widely differing sample sizes (see §3.4.2).

There is great similarity between the Burarra speakers, much more so than for the Arrernte speakers, especially in V1. As is demonstrated by vowel space plots in Figure 30 and by Euclidean distance plots in Figure 31, across V1 and V2 conditions, /a/ appears to be functioning as the anchor or pivot. In the V1 context, grand centroids (indicated by ‘X’ in Figure 30) are located at 575 by 1690Hz for speaker DP, as was indicated in Figure 30, at 555 by 1685Hz for speaker KF and 570 by 1760Hz for speaker MW. V2 grand centroids are 550 by 1790Hz for speaker DP, 585 by 1970Hz for speaker KF and 505 by 1730Hz for speaker MW.

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[55] For speaker TR, no /u/ tokens occur in this V1 context, and this strongly affects the Euclidean distance results. For this speaker, the mid central vowel is closest to the grand centroid at 218Hz. The low central vowel, /a/, is furthest from the grand centroid at 280Hz and the close vowel /i/ is intermediate in distance at 252Hz. There is small and roughly even spacing between the three vowels.

Table 48. Burarra formant frequency means and standard deviations of all vowels in the V1 context, in which the vowel is prosodically prominent. Unusually low (<20Hz) or high values (>250Hz) are marked with an asterisk.

	DP				**KF**				**MW**			
	F1		**F2**		**F1**		**F2**		**F1**		**F2**	
	x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**
a	703	92	1606	112	725	112	1690	194	721	74	1654	104
ɛ	615	79	1873	88	589	67	2017	60	632	64	1940	90
i	441	65	2323	247	418	34	2385	219	449	38	2403	147
o	610	76	1320	148	595	65	1202	216	630	69	1352	238
u	517	52	1344	239	450	48	1200	251*	450	44	1410	346*

Table 49. Burarra formant frequency means and standard deviations of all vowels in the V2 context, in which the vowel is prosodically weak. Unusually low (<20Hz) or high values (>250Hz) are marked with an asterisk.

	DP				**KF**				**MW**			
	F1		**F2**		**F1**		**F2**		**F1**		**F2**	
	x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**
a	706	107	1635	160	719	120	1651	224	725	61	1649	85
i	417	24	2242	160	457	50	2298	210	385	46	2449	38
u	506	44	1116	18*	N/A	N/A	N/A	N/A	403	19*	1099	59

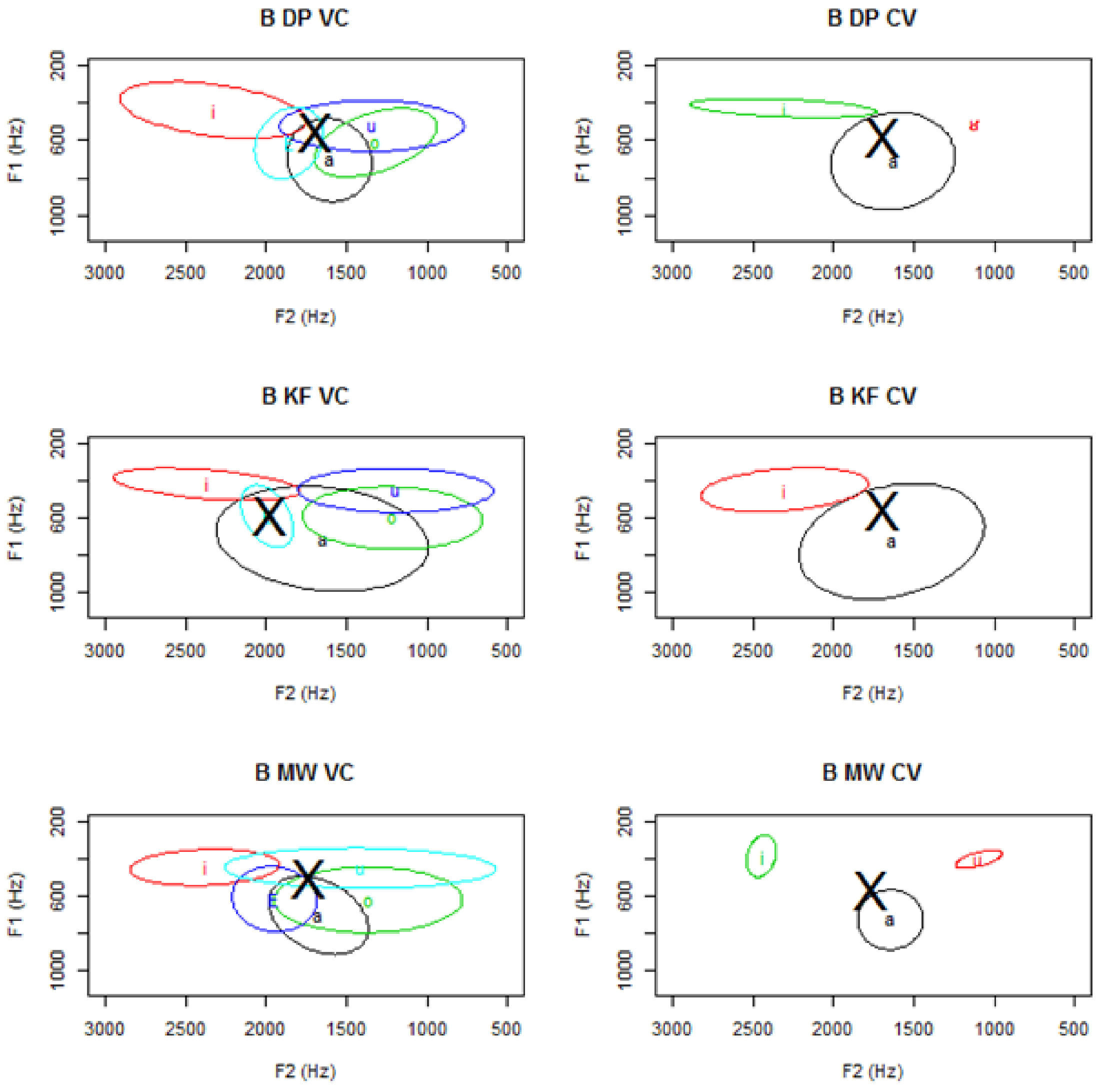


Figure 30. Burarra vowels in the F2 x F1 plane (95% CI) for V1 (VC, left) and V2 (CV, right) contexts in CV1CV2 words. Data are extracted at the temporal midpoint of the vowel. The average position of each vowel category is marked with the corresponding symbol. Prosodic prominence is on V1. ‘E’ represents /ɛ/. The x-axis range is 500-3000Hz. The y-axis range is 200-1100Hz.

Figure 30 shows that in the V1 context, in the prosodically prominent vowel, the vowel spaces are very overlapped (with the exception of /i/), as was the case for the Arrernte speakers. /i/ is realised with high F2 formant frequencies relative to the other front vowel, /ɛ/, while /u/ is typically no more peripheral in the F2 dimension than the other back vowel, /o/. /o ɛ/ do not differ in F1, *i.e.*, they are similar in height. /u/ is often centralised and is likely to lack lip rounding and protrusion in many contexts, as for the Arrernte speakers. It is evident that /a/ can be realised with a fairly forward constriction, for example as [ɛ] in <yarta> /jaʈa/

[jɛʈa] 'for a short time', presumably due to the coarticulatory influence of the palatal approximant. /o/ appears to be realised in a manner approximating [ɔ] or [o] for DP and KF, and with a slightly lower constriction for MW, [o̞]. In the V2 context, vowel ellipses are minimally separated for DP and KF, and well separated for MW, for whom there is little variability.

For those vowels that occur in both V1 and V2 positions, comparisons of F1 and F2 frequencies in the two positions can be made. In /a/, F1 and F2 frequencies do not differ significantly across V1 and V2 for the Burarra speakers at $\beta=0.025$ (F1, DP, t(162)=0.33, p=0.74; KF, t(65)=0.86, p=0.39; MW, t(130)=-0.77, p=0.44; F2, DP, t(221)=-1.87, p=0.06; KF, t(59)=-1.28, p=0.2; MW, t(160)=0.78, p=0.43; see §3.4.2.1 for a discussion of the adjusted significance level). In /i/, both F1 and F2 frequencies do not differ across positions (F1, DP, t(20)=0.7, p=0.48; KF, t(20)=-1.89, p=0.07; MW, t(5.5)=2.7323, p=0.037; F2, DP, t(5.6)=0.16, p=0.88; KF, t(28)=0.84, p=0.41; MW, t(24)=-1.47, p=0.15). Finally, in /u/, F1 frequencies do not differ between V1 and V2 conditions (DP, t(1.6)=0.4445, p=0.7; MW, t(3.66)=3.6355, p=0.026). In F2, for DP and MW, the V1 condition is associated with higher formant frequencies (DP, t(9.7)=4.54, p<0.005; MW, t(18.1)=5.08, p<0.0001), indicating a less retracted constriction. For KF, there are insufficient observations.

With specific regard to variability in the form of SD values, as shown in Table 48 and Table 49, across V1 and V2 contexts, the low central vowel tends to be the most variable (although variability in F1 remains low even for /a/). This was evident in Figure 30 in the V2 condition for the three speakers and in the V1 condition for speaker KF. In the V2 context (also shown in Table 40), the spread of F2 values in /a/ is particularly large for speaker KF at 870 to 2103Hz (the higher values occurring in the environment of palatal consonants). Close vowels, especially /i/, vary least in the F1 dimension, and /ɛ/ varies least in the F2 dimension (although *n* is small, see Table 18). For DP, when /i/ is associated with F2 frequencies lower than 2000Hz, the vowel is adjacent to retroflex consonants, e.g., <mirdi> /miɖi/ 'strong'. The back vowels can be seen not only to differ in raw F1 formant frequencies (Figure 30) but also in the magnitude of F2 variability. The close-mid vowels are similar in F1 variability, but differ in F2 variability; /o/ is more variable. With regard to speaker MW, the finding of more F2 variability for /u/ than for, say, /a/, is due in part to sensitivity to consonantal effects; the higher F2 frequencies in /u/ occur adjacent to palatal and retroflex consonants and indicate C-to-V coarticulation (see §4.2.1.2), e.g., <nuya> /nuja/ 'ant sp.' and <yunya> /juɲa/ 'to sleep, be lying down'.

Turning to the issue of vowel space dispersion, as shown in Figure 31, for speakers DP and MW, significantly greater dispersion occurs in V1 than V2 (Wilcoxon test for paired samples, DP, V=8844, $p<0.005$; MW, V=11386, $p<0.0001$), that is, in the word-initial, prosodically prominent vowel. The same pattern approaches significance for speaker KF (V=3072, $p=0.06$). Of the three speakers, KF's vowels are associated with relatively high ED values, hence, greater dispersion (and also high variability in /a/ in V1 and in /i a/ in V2). In the V1 context, /a ɛ/ and /o u/ are not well separated whereas /i/ is very well separated from the other vowels; /i/ is furthest from the grand centroid at 657Hz for DP, 705Hz for KF and 641Hz for MW, indicating a relatively close vowel in the word-initial context. For speakers DP and MW, /ɛ/ and /a/ are closest to the grand centroid at 187 and 193Hz, respectively, for DP and 202 and 215Hz, respectively, for MW. Similarly, for speaker KF, in this context, /a/ is closest to the grand centroid, followed by /ɛ/, at 246 and 331Hz respectively. /o/ and /u/ are intermediate in distance at 381 and 379Hz, respectively, for DP, 503 and 522Hz, respectively, for KF and 434 and 451Hz, respectively, for MW. /u/ is very much a close-mid rather than a close vowel, possibly best described as [ʊ], and is often centralised.

In the V2 context, for DP and MW, there are three class centroids, /a/, /i/, and /u/ (while for KF there are merely two, /a i/, due to differences in vowel distribution in the corpus). /a/ is closest to the grand centroid (DP, 235Hz from the grand centroid; KF, 394Hz; MW, 238Hz). /i/ tends to be furthest from the grand centroid (DP, 636Hz; MW, 728Hz), indicating a fairly close vowel. /u/ tends to be closer to /i/ than /a/ (DP, 564Hz; MW, 641Hz); /u/ appears to be close-mid. Hence, the vowels separate into central and close/close-mid categories.

In summary, comparing the V1 and V2 vowel spaces, while there is more vowel overlap in V1, both spaces are compact or sufficiently dispersed. The low central vowel is acting as anchor or pivot. /u/ tends to be more retracted in V1 than in V2. With regard to variability, the low central vowel is most variable and close vowels tend to vary more in the F2 dimension than the F1 dimension while /a/ tends to vary more in the F1 dimension than in the F2 dimension. Greater dispersion tends to occur in the prosodically prominent V1.

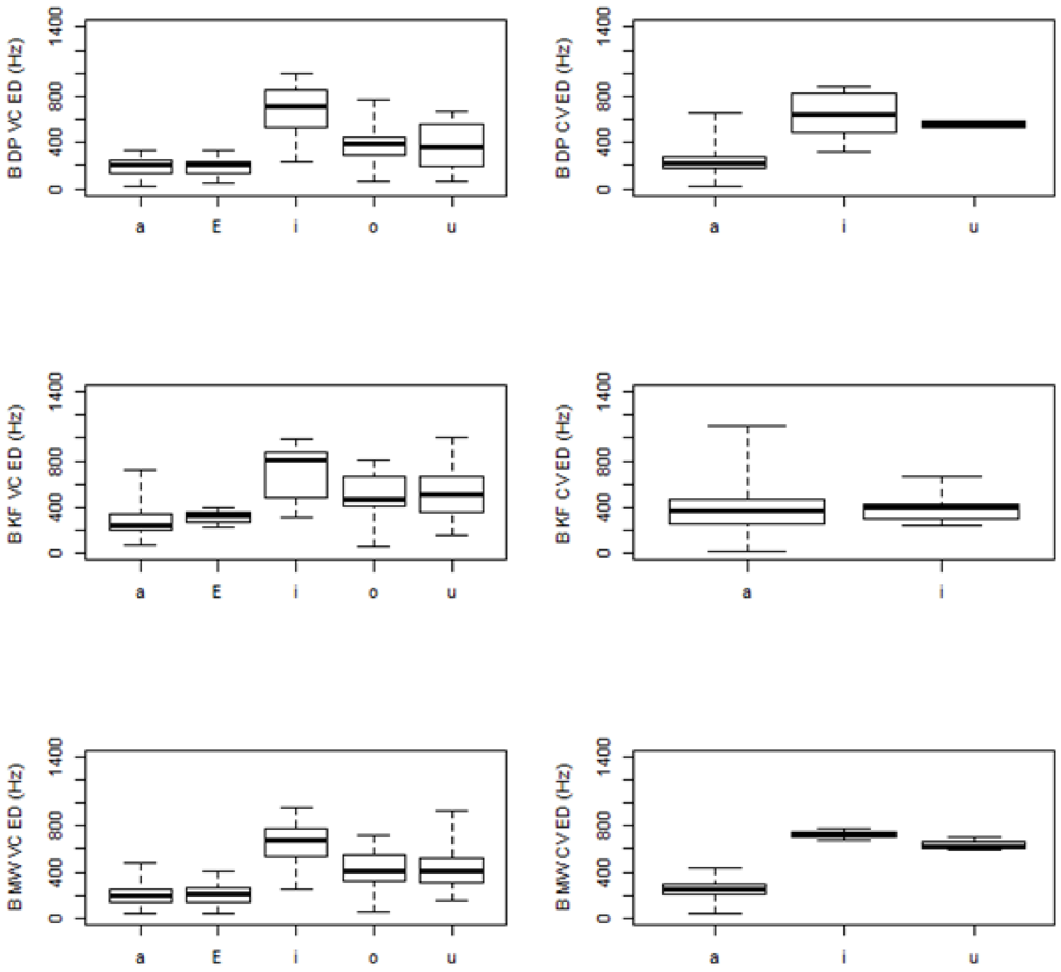


Figure 31. Boxplots of Euclidean distances to the centroid (Hz) for Burarra speakers for vowels in V1 (VC, left) and V2 (CV, right) conditions in CV1CV2 words. Distances are given in Hz. 'E' represents /ɛ/.

5.2.3 Vowel variability and dispersion - Gupapuyngu

Figure 32 and Figure 27 show vowels in the F2 x F1 plane for Gupapuyngu speakers in V1 (VC) and V2 (CV) conditions in CV1CV2 words. Means and standard deviations are given in Table 50 and Table 51. Euclidean distances are plotted in Figure 33 and tabulated in Appendix B. The vowel length distinction is restricted to the initial vowel (and syllable) in the word, as discussed in §1.2.3.2. Note that for speaker EG there are fewer tokens than for AM and BT (as was shown in Table 18 in §3.4.2).

Table 50. Gupapuyngu formant frequency means and standard deviations of all vowels in the VC context, in which the vowel is prosodically prominent. Unusually low (<20Hz) or high values (>250Hz) are marked with an asterisk.

	AM				**BT**				**EG**			
	F1		**F2**		**F1**		**F2**		**F1**		**F2**	
	x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**
a	783	120	1602	153	764	56	1780	212	720	114	1648	159
a:	815	84	1586	69	839	54	1776	60	851	98	1596	45
i	395	24	2317	221	205	52	2624	187	400	N/A	2454	N/A
i:	394	19*	2241	207	402	29	2728	168	N/A	25	N/A	149
u	430	44	1114	196	424	48	1343	345*	442	47	1139	193
u:	460	58	1013	157	456	36	1043	143	474	57	971	74

Table 51. Gupapuyngu formant frequency means and standard deviations of all vowels in the CV context, in which the vowel is prosodically weak. Unusually low (<20Hz) or high values (>250Hz) are marked with an asterisk.

	AM				**BT**				**EG**			
	F1		**F2**		**F1**		**F2**		**F1**		**F2**	
	x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**
a	822	125	1656	167	801	66	1765	119	892	155	1669	89
i	420	31	2339	260*	378	42	2706	96	430	42	2426	107
u	467	66	1090	148	476	67	1106	142	543	127	1109	209

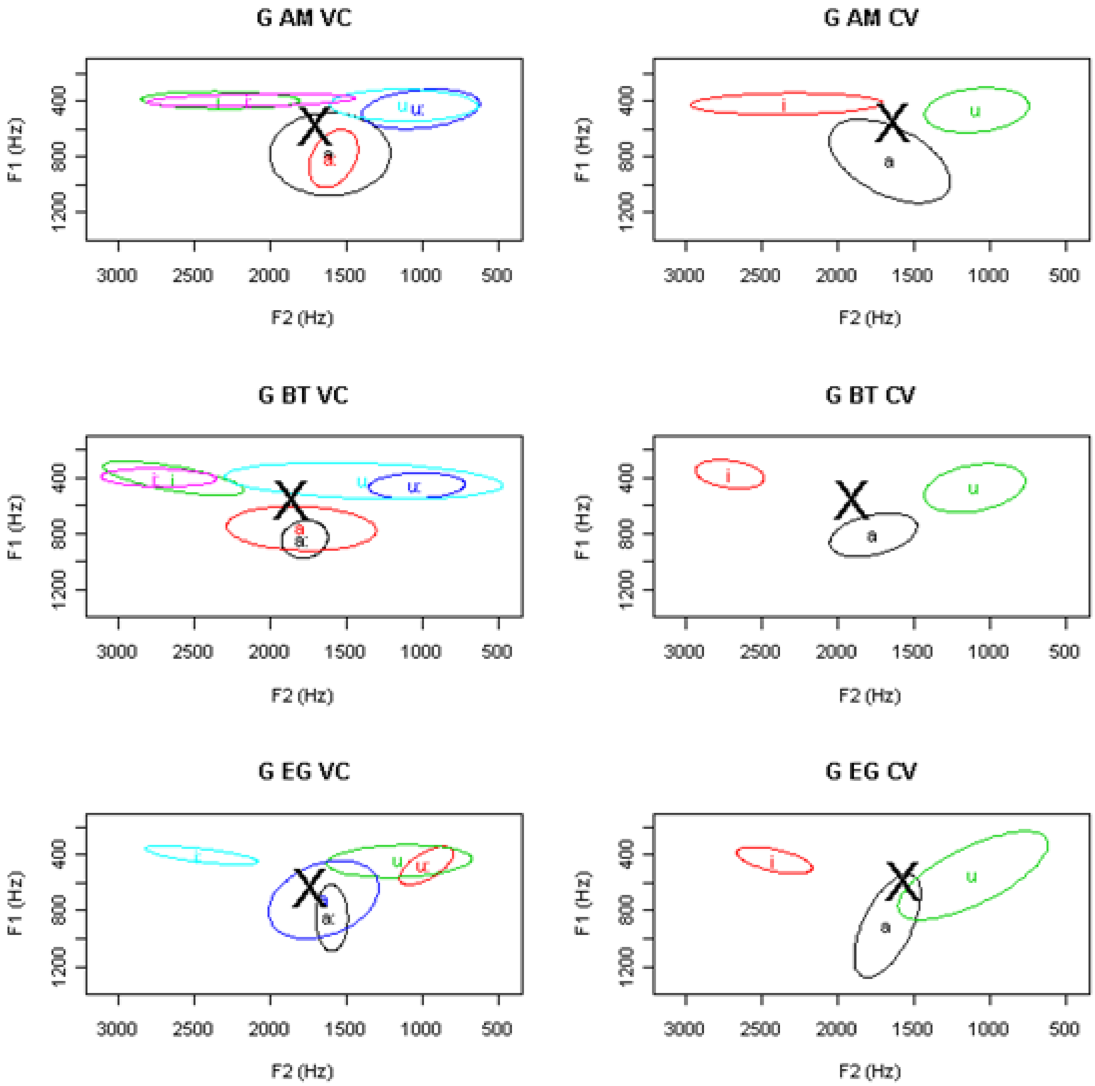


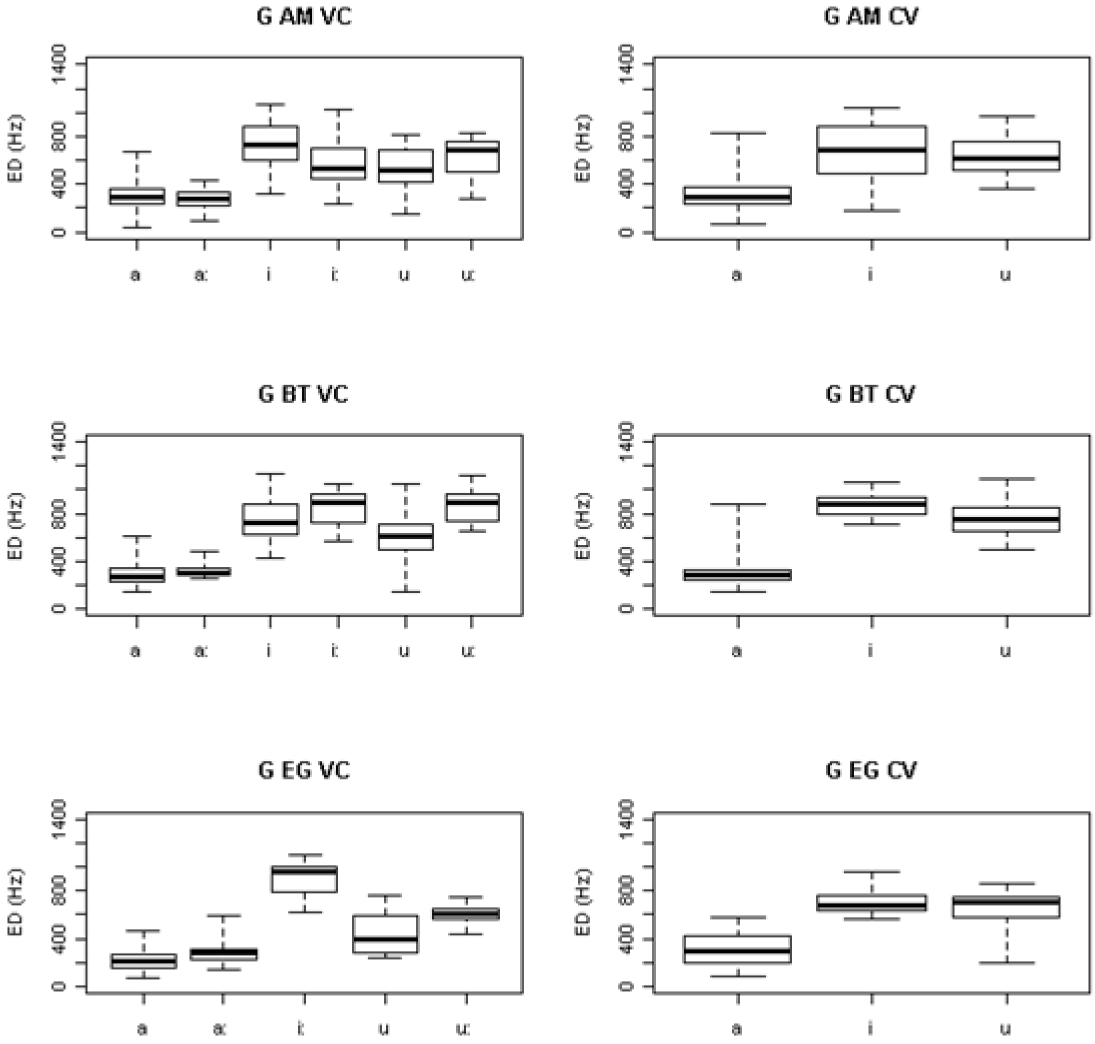
Figure 32. Gupapuyngu vowels in the F2 x F1 plane (95% CI) for V1 (VC, left) and V2 (CV, right) contexts in CV1CV2 words. Data are extracted at the temporal midpoint of the vowel. The average position of each vowel category is marked with the corresponding symbol. Prosodic prominence is on V1. The x-axis range is 450-3100Hz. The y-axis range is 150-1350Hz.

In V1, grand centroids are 550 by 1655Hz for speaker AM, 540 by 1865Hz for speaker BT and 580 by 1565Hz for speaker EG. In V2, the grand centroid is 570 by 1680Hz for speaker AM, 515 by 1795Hz for speaker BT and 635 by 1735Hz for speaker EG. In V1, phonemic vowel ellipses are well separated for speaker BT, but /u/ is often centralised, as for Arrernte and Burarra speakers, being realised as [ɵ] or [ɔ]. There is minimal overlap for speakers AM and EG. It is evident that long vowel class centroids tend to be more peripheral than short vowel centroids; formant frequency means associated with long vowels are, in F1, similar to their short vowel counterparts or slightly higher, and in F2, slightly higher in /i:/ and slightly lower in /u/ (with the exception of the /i i:/ pair for speaker AM). Overall, /u u:/ do not differ in F1 (height) but do differ in F2 (backing), while /i i:/ and /a a:/ do not differ in F2 but differ in F1. In V2, vowel ellipses are well separated.

Now, comparing the short vowels only, in /a/, F1 frequencies are lower in V1 at β=0.0167 (AM, t(128)=-2.53, p<0.0167; BT, t(127)=-4.58, p<0.0001; EG, t(65)=-6.37, p<0.0001). For all speakers V1 and V2 do not differ in F2 (AM, t(127)=-1.99, p=0.04; BT, t(86)=1.1, p=0.27; EG, t(35)=-0.87, p=0.39). In /i/, for AM, F1 is lower in word-initial, prosodically prominent V1, indicating a relatively close vowel (t(57)=-3.84, p<0.0005), while for BT the difference merely approaches significance and is in the opposite direction, *i.e.*, F1 is lower in V2 (t(38.5)=2.64, p=0.018; see §3.4.2.1 for a discussion of the adjusted significance level). In F2, positions do not differ (AM, t(56)=-0.12, p=0.9; BT, t(28)=-1.76, p=0.09). For EG, there are insufficient observations. Finally, in /u/, for every speaker, as is the case for /a/, F1 is lower in the V1 than in the V2 context (AM, t(109)=-3.34, p<0.005; BT, t(116)=-4.59, p<0.0001; EG, t(28.5)=-3.55, p<0.005); *i.e.*, /u/ is associated with a narrower (more close) constriction in the V1 (word-initial and prosodically prominent) context, indicating a relatively close vowel. In F2, speakers vary; AM and EG do not show a difference between positions (AM, t(68)=1.03, p=0.31; EG, t(41)=0.68, p=0.5), while for BT, F2 is higher in the V1 (word-initial, prosodically prominent) condition (t(54)=4.99, p<0.0001), indicating a relatively fronted constriction.

In sum, as Figure 32 illustrates, for the central and back vowels, F1 is lower in the V1 condition, indicating a relatively narrow constriction in the word-initial and prosodically prominent environment, or alternatively, a more open weak V2. In /i/, for AM, V1 is a more close vowel than V2. There are no other significant /i/ effects. In F2, there is no effect of prosodic prominence with the exception of /u/ for BT; BT's results suggest a fronted (centralised) /u/ in the V1 condition.

Acoustic variability in vowels has been shown in Figure 32. Inspection of vowel ellipses suggests that variability in close vowels tends to affect F2 rather than F1, as was observed for Arrernte and Burarra, which could indicate that these vowels are specified more for height than anteriority. For /a/, there is relatively high F1 variability for all three speakers and low to moderate F2 variability, as was shown previously for Arrernte and Burarra speakers. In /i/, there is relatively low F1 variability for the three speakers, but in F2, there is relatively high variability for AM and low to moderate variability for BT and EG. This particularly high F2 variability for AM in /i/ is likely to reflect consonant-dependent coarticulation (as indicated by the LMM results presented early in §5.2). For /u/, there tends to be relatively low F1 variability and high F2 variability. High variability in /a/, as stated, may be due to greater coarticulatory sensitivity to variability in jaw and dorsum height, which is generally associated with this vowel in many languages.



G AM VC

G AM CV

G BT VC

G BT CV

G EG VC

G EG CV

Figure 33. Boxplots of Euclidean distances to the centroid (Hz) for Gupapuyngu speakers for vowels in V1 (VC, left) and V2 (CV, right) conditions in CV1CV2 words. Distances are given in Hz.

In the prosodically weak, word-final V2, /a/, there is a tendency towards relatively high F1 variability and low F2 variability. In /i/, there tends to be relatively low F1 and F2 variability. In /u/, there tends to be low F1 variability and high F2 variability. Across the speakers, high variability in close vowels often occurs when the vowel is adjacent to bilabial, labio-velar, rhotic and lateral consonants, e.g., in e.g., <bolu> /bu:lu/ ‘bamboo’. Word-final /a/ tends to be retracted when adjacent or near adjacent to bilabial (indicating both anticipatory and carryover C-to-V coarticulatory effects for this consonant), rhotic or velar consonants and fronted when adjacent to palatal consonants for these speakers, e.g., for AM, <gapu> /gapu/ ‘water’, and for BT, <waku> /waku/ ‘woman’s child’.

According to modified t-tests (Table 52), when vowel categories are collapsed, standard deviations do not differ according to prosodic and word positional condition. However, for AM, in F2, standard deviations are larger in V2 (t(2)=-9.5529, p<0.05), indicating that more variability exists in the prosodically weak, word-final vowel, as would be predicted. All other comparisons are non-significant.

Table 52. Standard deviation modified t-test results comparing short vowels across V1 (VC) and V2 (CV) for Gupapuyngu where p<0.05 *, p<0.001**, p<0.0001***.

		df	**t**	**p**
AM	**F1**	2	0.4592	0.7
	F2	2	-9.5529	0.01*
BT	**F1**	2	-1.25	0.34
	F2	2	1	0.42
EG	**F1**	2	-0.93	0.45
	F2	2	-2.64	0.12

With regard to Euclidean distances, Figure 33 shows that in both V1 (VC) and in V2 (CV) the non-central vowels are associated with larger Euclidean distances than the central vowel for Gupapuyngu speakers. Longer vowels tend to be slightly more peripheral, as shown in Figure 32. There is relatively little inter-speaker variability. For these speakers, ED values do not differ according to word position/prosodic prominence (Wilcoxon test for paired samples, AM, V=9987, p=0.18; BT, V=15791, p=0.67; EG, V=2221, p=0.47), which indicates a lack of vowel space expansion in V1 relative to V2.

In the V1 context, /a a:/ are closest to the grand centroid (AM, 311 and 299Hz from the grand centroid, respectively; BT, 326 and 317Hz; EG, 219 and 281Hz), while /i i:/ tend to be most distant (AM, 700 and 677Hz, respectively; BT, 771 and 817Hz: EG, /i:/ only, 907Hz) and /u u:/ tend to be somewhat less distant (AM, 570 and 653Hz; BT, 609 and 834Hz; EG, 441 and 660Hz). /i i:/ appear to be relatively close. /u u:/ appear to be close-mid back vowels (although /u/ can be centralised). Long vowels tend to be more peripheral than short vowel counterparts. In V1, vowels /u:/ and /a a:/ tend to differ markedly from each other in ED values, as do /i i:/ and /a/.

In V2, there is a clear anchoring of the vowel space by the low central vowel, as was also suggested by Figure 32. As in V1, across the speakers, /a/ tends to be closest to the grand centroid (AM, 315Hz from the grand centroid; BT, 287Hz; EG, 306Hz), while /i/ is furthest (AM, 672Hz; BT, 906Hz; EG, 710Hz) and /u/ is slightly less distant (AM, 619Hz; BT, 697Hz; EG, 650Hz), as will be seen for the Warlpiri speakers.

5.2.4 Vowel variability and dispersion - Warlpiri

Figure 34 and Figure 27 show vowel ellipses in the F2 x F1 plane for Warlpiri speakers in V1 (VC) and V2 (CV) contexts in CV1CV2 words. Means and standard deviations are reported in Table 53 and Table 54. Euclidean distances are plotted in Figure 35 and tabulated in Appendix B.

The V1 grand centroid is 535 by 1835Hz for speaker BP, 440 by 1635Hz for speaker KR and 440 by 1570Hz for speaker RR. The V2 centroid is located at 555 by 1815Hz for speaker BP, 425 by 1680Hz for speaker KR and 440 by 1605Hz for RR.

Table 53. Warlpiri formant frequency means and standard deviations of all vowels in the VC context, in which the vowel is prosodically prominent. Unusually low (<20Hz) or high values (>250Hz) are marked with an asterisk.

	BP				**KR**				**RR**			
	F1		**F2**		**F1**		**F2**		**F1**		**F2**	
	x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**
a	660	125	1692	182	609	100	1547	257	555	116	1505	221
i	456	36	2391	208	364	58	2216	324*	376	76	2032	194
u	483	26	1421	263*	369	72	1064	304*	392	92	1144	339*

Table 54. Warlpiri formant frequency means and standard deviations of all vowels in the CV context, in which the vowel is prosodically weak. Unusually low (<20Hz) or high values (>250Hz) are marked with an asterisk.

	BP				**KR**				**RR**			
	F1		**F2**		**F1**		**F2**		**F1**		**F2**	
	x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**	**x̄**	**SD**
a	700	149	1691	163	713	128	1600	157	573	117	1565	195
i	460	36	2519	152	310	55	2382	213	351	94	2099	120
u	507	53	1227	193	351	82	1026	358*	419	102	1141	238

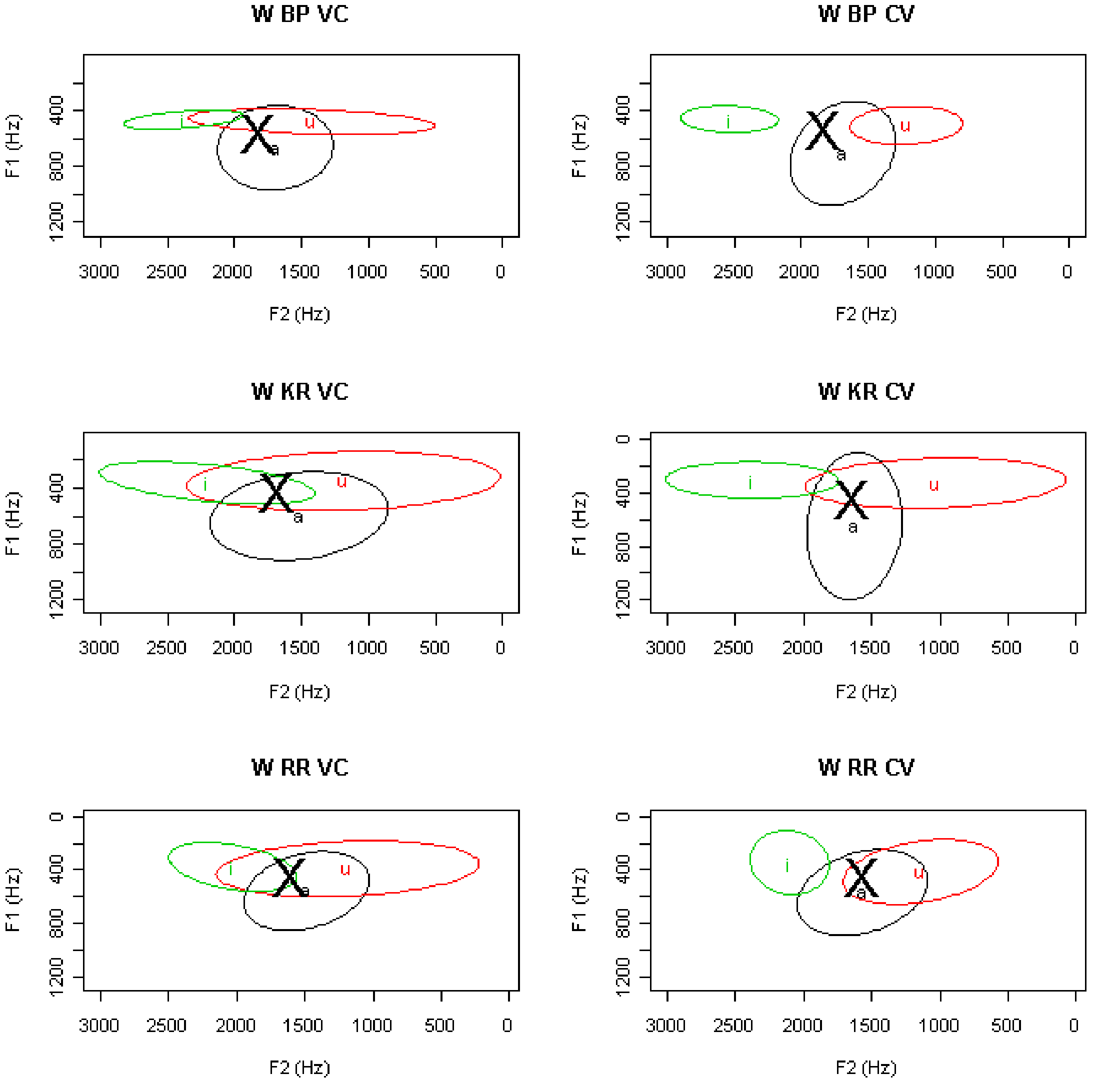


Figure 34. Warlpiri vowels in the F2 x F1 plane (95% CI) for V1C (left) and CV2 (right) contexts in CV1CV2 words. Data are extracted at the temporal midpoint of the vowel. The average position of each vowel category is marked with the corresponding symbol. Prosodic prominence is on V1. The x-axis range is 50-3000Hz. The y-axis range is 0-1250Hz.

Across contexts, there is a tendency towards extensive overlapping of /a/ and /u/ - as observed for the Arrernte and Burarra speakers, and Gupapuyngu speaker EG - and less overlapping of /a/ and /i/; as for all other language groups, /i/ tends to be the best separated of the vowels. /u/ is often centralised, as has been shown for the other language groups. There is extensive ellipse overlap in the centre of the vowel space in V1 and less overlap in V2. Overall, vowels are similar in F1 and F2 across V1 and V2. In /a/, word/prosodic conditions do not differ in F1 at $\beta=0.0167$ (BP, $t(90)=-1.46$, $p=0.15$; KR, $t(123)=-1.72$, $p=0.088$; RR, $t(136)=-0.499$, $p=0.62$). In F2, for KR, /a/ in (prosodically prominent) V1 is associated with relatively low formant frequencies ($t(138)=-3.29$, $p<0.005$), indicating a relatively back vowel and for RR, the difference approaches significance in the same direction (t(136)=-2.37, p=0.019) but for BP, positions do not differ (t(103)=0.21, p=0.83). /i/ as produced by KR is associated with lower F1 frequencies in V2 (t(70)=4.21, p<0.0001), but for BP and RR, word/prosodic conditions do not differ (BP, t(51)=0.39, p=0.7; RR, t(73)=1.69, p=0.09). BP and KR produce lower F2 frequencies in V1 (BP, t(42)=-3.33, p<0.005; KR, t(66.5)=-2.53, p=0.014 (approaching β); RR, t(69)=-2.08, p=0.04), *i.e.*, in /i/, the Warlpiri speakers tend to produce a relatively fronted vowel in prosodically weak V2. (There is also less variation in V2.)

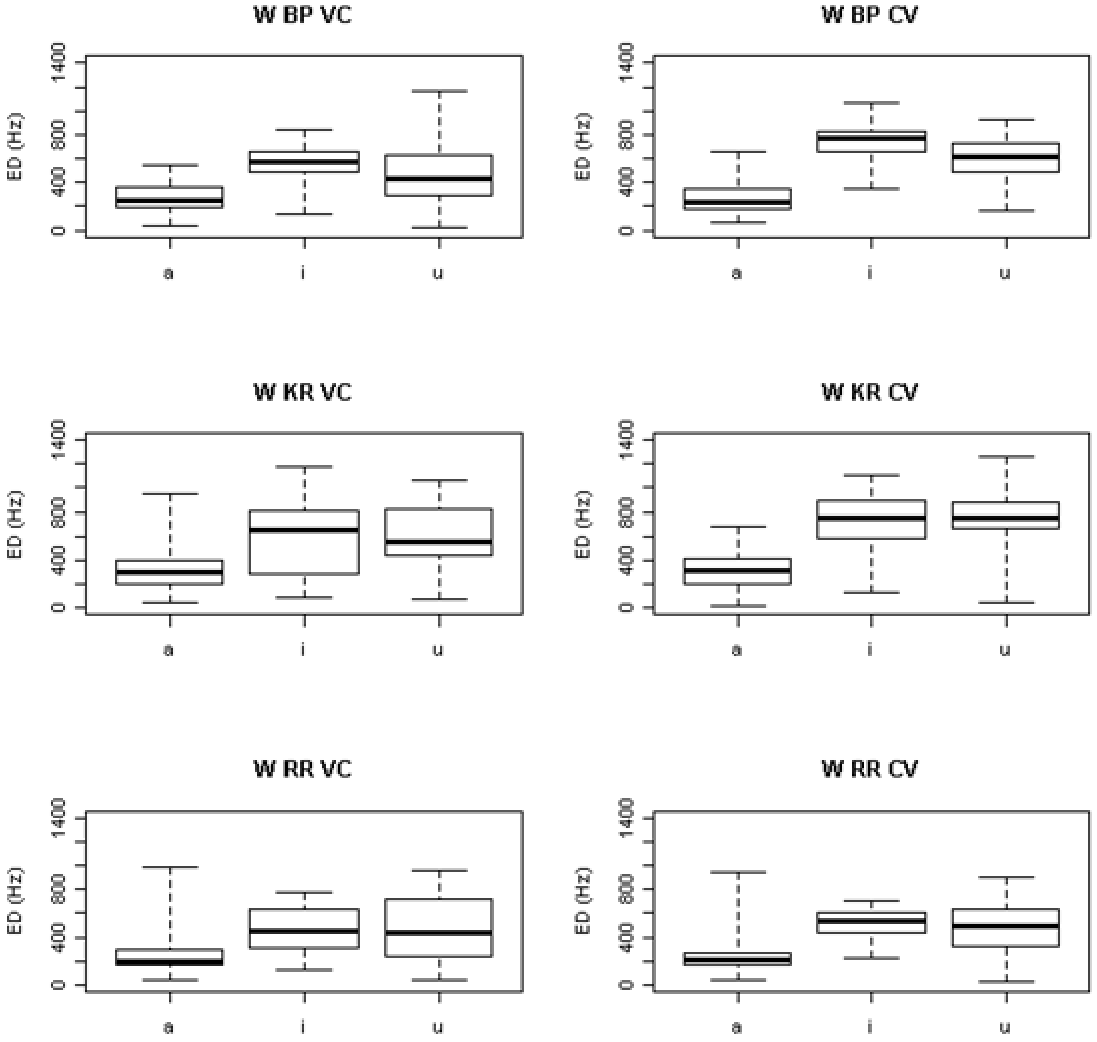


Figure 35. Boxplots of Euclidean distances to the centroid (Hz) for Warlpiri speakers for vowels in V1 (VC, left) and V2 (CV, right) conditions in CV1CV2 words. Distances are given in Hz.

In /u/, word/prosodic conditions do not differ significantly in F1 (BP, t(59.8)=-2.3, p=0.02; KR, t(86)=1.32, p=0.19; RR, t(88)=-1.19, p=0.24). In F2, for BP, frequencies are higher in V1, indicating a more front vowel (t(43)=2.84, p<0.01), whereas for KR and RR, conditions do not differ (KR, t(83)=1.71, p=0.09; RR, t(73)=0.68, p=0.5).

In summary, vowels tend not to differ across V1 and V2 conditions in F1 (with the exception of /i/ for KR). In F2, vowels /a/ and /u/ tend not to differ across conditions (with the exception of /a/ for KR and /u/ for BP), but in /i/, the speakers tend to produce a less front vowel in V1, as is illustrated by Figure 34. With regard to speaker KR, /i/ is produced with lower F1 frequencies in V2, indicating a closer vowel, while /a/ is produced with lower F2 frequencies in V1, indicating a more back vowel. In /u/, BP appears to produce a slightly raised and fronted vowel in V1 (see Figure 34).

With regard to variability, acording to modified t-tests, when vowel categories are collapsed, standard deviations do not differ according to word position and prosodic prominence. In V1, in which the vowel is prosodically prominent, for BP, KR and RR, there is more F1 variability in /a/ (non-high) than in /i u/ (high), as is also evident in Figure 34. SD values in /a/ are, for BP, SD=125Hz, for KR, SD=100Hz and for RR, SD=116Hz. In F2, there tends to be more variability in /u/ than in /i a/, as shown in Figure 34. In /u/, for speakers KR and RR, there is unusually high variability in F2 at SD=304Hz and SD=339Hz, respectively (BP, SD=263Hz). For speaker KR, unusually high F2 variability is seen in /i/ at SD=324Hz. According to Figure 34, /u/ for all speakers and /i/ for KR in particular, undergo centralisation in some tokens.

In V2, in which the vowel is prosodically weak and word-final, there is again, for all speakers, more F1 variability in /a/ (non-high) than in /i u/ (high), presumably because of increased coarticulatory sensitivity. In /a/, SD values are as follows: for BP, SD=149Hz, for KR, SD=128Hz and for RR, SD=117Hz. For BP, KR and RR, there is more F2 variability again in /u/ (back) at SD=193Hz, SD=358Hz and SD=238Hz, respectively, than in /i a/ (non-back). For KR, unusually high F2 variability is observed in /u/ in the CV context at SD=358Hz. According to Figure 34, this high variability is associated with strong centralisation in some /u/ tokens.

Across Warlpiri speakers, when /i/ is associated with relatively high variability in F2, this is in part due to instances of close front vowels becoming more front in the vicinity of a palatal, e.g., <yimi> /jimi/ ‘language’ and of a lowered F2 in vowels adjacent to rhotic/retroflex or labio-velar consonants, e.g., <mirdi> /miɖi/ ‘strong’ and <wita> /wita/ ‘small’. High variability is /u/ is due in part to very high F2 formant frequencies in vowels adjacent to oral and nasal palatals as in, e.g., <nyurru> /ɲuru/ ‘short time ago’, and also velar nasal C-to-V coarticulation as in, e.g., <ngula> /ŋula/ ‘that one’. High variability is also due to very low formant frequencies in vowels adjacent to bilabial, labio-velar and retroflex consonants, e.g., <kapu> /kapu/ ‘he will’ (again, indicating both anticipatory and carryover labial C-to-V effects).

With regard to Euclidean distances, there tends to be greater dispersion in V2 for these speakers (Wilcoxon test for paired samples, BP, V=2200, p<0.005; KR, V=5896, p<0.05), as is shown in Figure 35 per speaker in V1 and V2 condition; however, the difference does not achieve significance for speaker RR (V=5646, p=0.4).

As Figure 35 illustrates, in both V1 and V2, /a/ is closest to the grand centroid (V1 /a/, BP, ED=266Hz; KR, ED=291Hz; RR, ED=230Hz; V2, BP, ED=266Hz; KR, ED=320Hz; RR, ED=224Hz) and either /i/ is furthest from the centroid, as for BP (V1, ED=556Hz; V2, ED=565Hz) or /i/ and /u/ are equally distant, as for KR and RR (V1, KR, /i/ ED=584, /u/ ED=609Hz; RR, /i/ ED=473Hz, /u/ ED=483Hz; V2, KR, /i/ ED=732Hz, /u/ 708Hz; RR, /i/ ED=515Hz, /u/ 484Hz). Clearly, this is a ‘canonical’ realisation of a triangular vowel space with the low central vowel as anchor. KR’s vowels show greater dispersion than those of BP and RR, as is evident also in Figure 34.

5.3 Summary and discussion

In Chapter 4, it was demonstrated that peripheral consonants undergo a greater magnitude of vowel-dependent coarticulation than coronal consonants, that they are more context-sensitive and that they have lower and more variable consonant loci. It was also found that there is some effect of trajectory period on vowel-dependent coarticulation but typically not of prosodic prominence. The present chapter has examined vowel variability and dispersion in the F2 x F1 plane, focussing on vowel quality effects, and word position and prosodic prominence effects. Discussions follow in §5.3.1 on the effect of vowel quality on vowel variability and peripherality, §5.3.2 on vowel system distinctiveness and the effect of language on vowel space dispersion, and §5.3.3 on the effects of prosodic prominence and word position on vowel realisation.

In this chapter it was possible to examine the effects of numerous factors on vowel realisation in F1 and F2 at vowel midpoints. Languages were found to differ more in F1 (vowel height) than in F2 (vowel backness). Highly significant effects of word-medial consonant place were found at the midpoints of both preceding and following vowels, especially in F2, as would be predicted, in support of H9) and RQ1) with regard to consonant-dependent effects. These consonant-dependent effects appeared to be slightly stronger in the anticipatory direction, consistent with the finding of greater anticipatory than carryover vowel-dependent coarticulation (*i.e.*, higher slope values in the CV condition) in the preceding chapter. It can be inferred that the large magnitude of F2 variation found in vowels in these languages with small vowel systems relates in part to strong consonant-dependent coarticulatory effects. Several studies have demonstrated that in languages with small vowel systems, vocalic variation due to consonants is extensive (e.g., Tabain and Breen, 2011; see also, e.g., Butcher, 1994, on reduced variation in F1 relative to F2 in Australian vowel spaces).

5.3.1 Effect of vowel quality on variability and peripherality

In this section, vowel quality and its relation to variability and peripherality in the F2 x F1 space will be discussed with regard to H10) on close vowels being less variable and more peripheral than central vowels. As illustrated by vowel space plots in Figure 30, Figure 32 and Figure 34 and confirmed by the Euclidean distance results, in Burarra, Gupapuyngu and Warlpiri, the low central vowel, /a/ is the pivot or anchor of the vowel space. In Arrernte (Figure 28), the mid central vowel is the pivot in V1. Across the four languages, /a/ is realised as a low central vowel, which may be slightly retracted towards the pharynx. It appears that /i/ and /u/ are close-mid rather than close, but /i/ tends to be produced with a narrower (and more front) constriction than /u/ and is realised as [ɪ] or [e] in many environments. /i u/ tend to be more distant from one another in the vowel space than /a u/ and /a i/, thus, F2 span is greater than F1 span in these spaces. With regard to the effect of vowel quality on variability, as observed in previous studies, /u/, like /a/, is highly variable in F2 (e.g., Recasens, 1990a) and can be somewhat lax and centralised and presumably with little rounding or protrusion (Dixon, 1980; Butcher, 1999; 2006). /u/ tends to vary greatly in F2 and less so in F1, suggesting a high degree of sensitivity to constriction location in neighbouring segments rather than to the narrowness of adjacent constrictions (Recasens, 1999). /i/ may be less variable than /a u/ in F1 and F2 for some speakers because it is associated with a higher degree of dorsal constraint (involving dorsal raising and fronting and tongue bunching) and is therefore less context-sensitive, as suggested by the velar results presented in the previous chapter in §4.2.3. Moreover, /i/ tends to occur less frequently in these languages than the other vowels. Overall, vowels are much more variable in F2 (backing) than in F1 (height), consistent with the idea that much of the variability is due to consonant place effects. As has been stated, statistical procedures confirmed the importance of word-medial consonant place in vowel realisation, specifically, in F1 and F2 frequencies at vowel midpoints. H10), regarding close vowels being associated with less variability than open vowels, can be confirmed with some limitations. Further, there is a general tendency for greater dispersion for /i u/ (*i.e.*, larger Euclidean distances) than /a/, in support of H10). When variability is very high for a given vowel, this appeared to be due to strong C-to-V coarticulation exerted by an articulatorily incompatible consonant (in support of H9)), such as a palatal or labio-velar approximant (see §4.2). Contextual effects were also exerted by bilabial, retroflex/rhotic, lateral and velar consonants in particular.[56]

Vowels appear to differ in general context-sensitivity in the order /ə/ > /a/ > /u/ > /i/ (e.g., Recasens, 1995; Recasens *et al.*, 1997) in support of RQ1) with regard to a predictable relationship between vowel quality and coarticulation resistance. Front vowels tend to be less context-sensitive than central and back vowels. It appears that /i/ is not more coarticulation resistant than /a/ because it occurs in a more crowded area of the vowel space in these languages but rather because of inherent articulatory constraints. In F1, vowels /i u/ are associated with less variability than the low central vowel regardless of the distribution of adjacent segments, consistent with the articulatory (X-ray microbeam) and acoustical findings of Perkell and colleagues (Perkell & Nelson, 1983; Perkell, 1990), presumably because /a/ involves tongue dorsum-postdorsum coupling and is more sensitive to the influence of surrounding segments.

With particular regard to each of the four languages, Arrernte speakers tend to produce the mid central vowel with a lower F1 than /a/, although for speakers MM and VD, there is considerable overlap of the two central vowels, despite these being the two non-marginal vowels (in accordance with Tabain *et al.*, 2008, and Tabain & Breen, 2011, p. 76).[57] The mid central vowel is also highly variable, as would be expected given that it is a relatively unconstrained articulation that should be highly context-sensitive (it requires no raising of the tongue dorsum or lingual activation of any kind; p. 135). While both central vowels in V1 appear to be relatively free to vary in the F2 dimension, the mid central vowel tends to vary to a greater extent than the low central vowel, which indicates more coarticulatory sensitivity in the former to adjacent consonant place (consistent with Tabain & Breen, 2011). In fact, it appears to be almost targetless (van Bergem, 1994). With regard to differences between the central vowels in V1 and the central vowel in V2,

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[56] In the case of /i/, the typically raised and fronted dorsum associated with the vowel appears to be lowered in the environment of consonants with a low pre-dorsum position and pre-dorsum retraction and with lip rounding and protrusion, such as bilabials, labio-velars, velars, rhotics and laterals, supporting the claim that when there is articulatory conflict between a consonantal and a vocalic gesture, the consonantal gesture overrules the vocalic gesture (e.g., Öhman, 1966; Recasens, 1985).

[57] Tabain and Breen (2011) report for their speaker, VD, that in connected speech, the prosodically weak mid-central vowel is produced in the word-final context with a slightly lower F1 than prosodically prominent /ə/ and /a/ (VC context).

the prosodically weak central non-contrastive vowel in V2 is higher in F2 (more front) than the prosodically prominent low and mid central vowels in V1, as was evident in Figure 28. Furthermore, the non-contrastive vowel is more similar in F1 to the low central vowel in V1, presumably because of greater tongue body and/or jaw lowering in the word-final, pre-boundary position (§5.2.1).[58] This lowering and fronting of the word-final vowel in V2 suggests that the most common realisation for these speakers is closer to [a] in CV1.CV2 citation form words. Inter-speaker vowel variability is high in Arrernte, perhaps reflecting the particularly consonant-heavy nature of the language and also large differences in the number of tokens available for particular V1 qualities. /i u/ and /ə a/ do not differ greatly in degree of dispersion.

For the Burarra speakers, /ɛ/ tends to be somewhat centralised, especially for speaker KF, as reflected in the Euclidean distance results. /a/ is open and slightly retracted relative to the centre of the vowel space, again, especially for KF, but it can be realised as [æ] in the VC and CV contexts and as [ə] in the CV context. /o/ appears to be realised in a manner approximating [o] or [ɔ] for DP and KF and approximating [o̞] or [ɔ] for MW. /o/ tends to be slightly higher in F1 than /u/, and thus, is produced with a slightly higher dorsum, but /o u/ are similar in F2, and therefore in the length of the front cavity. /o u/ are also similar in their degree of dispersion, consistent with Euclidean distance results for female speakers of Kunwinjku, another five vowel language (Fletcher *et al*., 2007b). However, /u/ is more variable than /o/ in F2 (backing), in accordance with Trefry's (1983) findings. In Gupapuyngu, vowels show an effect of phonemic length, consistent with Fletcher and Butcher's (2003) findings for a female speaker of Kayardild (§2.4.3).[59] Phonemic long vowels /i iː/ and /a aː/ differ in height, while /u uː/ differ in backing, with the long vowels being more peripheral than their short counterparts. These results are consistent with Fletcher and Butcher (2003), in which they showed for Australian languages, Mayali, Dalabon and Kayardild that vowel length can be a predictor of peripherality. Presumably, when a vowel is lengthened, the extent to which it falls short of its target will decrease, as there is more time to reach the

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[58] This finding appears to be inconsistent with Henderson's (1998) finding in central Arrernte that /a/ is lower in the vowel space when stressed than when unstressed. This inconsistency may be due to the fact that the words are in citation form and/or due to a lack of separation of word and prosodic contexts in the current study (Fletcher & Butcher, 2003).

[59] These results for Gupapuyngu and Warlpiri speakers do not appear to be consistent with Fletcher and Butcher's (2003) finding for Kayardild that unaccented low vowels are more central than accented low vowels, perhaps because the present study does not permit a separation of word position and prosodic prominence, or of lexical stress and sentence accent, and because the present study involves isolated words rather than continuous speech.

target (Lindblom, 1963; see discussion in §2.3). Warlpiri speakers show a trend towards lower F1 values than the other language groups, *i.e.*, the vowel space is shifted upwards, but recall that these data have not be normalised.

5.3.2 Vowel system distinctiveness and the effect of language on vowel space dispersion

In support of H11), given a general compactness and extensive vowel overlap, it may be concluded that vowels are not widely dispersed within the available phonetic space in these languages. This pattern conforms to that found in other Australian languages such as Warlpiri, Burarra, Dalabon, Bininj Gun-wok, Kayardild and Kunwinjku (Butcher, 1994; Fletcher & Butcher, 2003; Fletcher *et al.*, 2007a,b).[60] The results suggest systemic and relational contrasts, as is consistent with the modified Adaptive Dispersion hypothesis (§2.3), which proposes that vowels are sufficiently rather than maximally dispersed through the vowel system (as discussed in §2.3.1).

In the world's languages, the number of peripheral vowels in a language tends to vary positively with F1 span, and non-peripheral vowels, with F2 span (Becker-Kristal, 2010). In these languages, the predicted relationships between F1 and F2 span and vowel inventories are not found. The predictions of dispersion theory may not hold here because the differences between the languages are too small (Livijn, 2000). Further, no evidence is seen of a clear positive correlation between vowel space expansion and vowel inventory size in support of H11) with regard to language differences. As was illustrated by Figure 27, Gupapuyngu shows slightly greater vowel space dispersion or expansion than the other three languages (ED values are especially high in Gupapuyngu for /i/). This finding of greater dispersion in Gupapuyngu is particularly interesting given the finding in Chapter 4 of greater F2 variability in vowels at VC/CV boundaries in this language. A positive correlation between vowel system size and dispersion may not be seen unless the number of vowels is very large, *i.e.*, it is probable that these systems are too similar and too small for any observed effect of vowel inventory size on vowel variability (Becker-Kristal, 2010; see also, Mok, forthcoming; *cf.* Manuel, 1990; 1999). Additionally, there is insufficient evidence of a relationship between variability at the vowel midpoint and vowel inventory size, consistent with, e.g., the findings of Recasens and Espinosa (2009c; see also, Recasens & Espinosa, 2006a,b). In these comparisons, it is apparent that vowels categorised as being of

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[60] As indicated by Butcher (1994), there is greater separation of vowels in Warlpiri than in Burarra when the vowel is short and prosodically prominent. The same could be said of Burarra and Gupapuyngu (see Figure 30 and Figure 32).

the same quality may differ somewhat both articulatorily and acoustically between systems. Recasens and Espinosa (2009c) point out that adaptive dispersion theory is not able to account for 'specific dialect-dependent production requirements which may affect [individual vowels'] degree of phonetic variability independently of vowel system size.' (p. 244) Interestingly, an effect of language on F1 and F2 formant frequencies at vowel midpoints was found on F1 but not on F2. In other words, these languages differ more in vowel height than in vowel backness.

5.3.3 Effects of prosodic prominence and word position on vowel realisation

This section addresses possible effects of prosodic prominence and word position on vowel realisation, variability (H12)) and dispersion (H13)). At the beginning of §5.2 it was observed that in CV1CV2 words vowels tend to be more open in the word-final pre-boundary position in these languages. Such a finding cannot be attributed to prosodically-driven hyper-articulation but rather suggests tongue body and jaw lowering in the word-final vowel associated with pre-boundary lengthening (see §2.4). The effect was more observable in /a/ than /u/, and more observable in /u/ than in /i/, presumably due to an interaction between pre-boundary lengthening and general context-sensitivity.

A summary of the V1/V2 comparisons per language group appears in Table 55. As seen in the table, in Burarra and Warlpiri, there is little evidence of vowel quality or variability differences between $V1_{MID}$ and $V2_{MID}$, while for Arrernte and Gupapuyngu, there is some evidence of F1 and F2 raising in V2, indicating vowel lowering and fronting in word-final pre-boundary position. There were no consistent effects of word-position and prosodic prominence on vowel space dispersion.

There are some inter-speaker differences, but for the most part, in the four languages, there is little evidence of prosodically driven vocalic hyper-articulation in accordance with H12) and H13) and with the results reported in the preceding chapter in §4.2.1 (with the possible exception of the Burarra speakers with regard to dispersion[61]). The results are consistent with Fletcher and Butcher (2003), who show that in Kayardild, Dalabon, and Mayali (Bininj Gun-wok), acoustic vowel spaces are not significantly more dispersed when vowels are prosodically prominent, but run counter to findings reported for English, Dutch and German, amongst others (§2.4; see, e.g., Fletcher *et al.*, 2007b). Further, as there is no effect of prosodic prominence on variability, it cannot be said that prosodically weak

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[61] Note that Figure 27, collapsed across Burarra speakers, does not appear to show greater dispersion in the VC condition perhaps because of a very limited distribution of /u/ in the VC condition. However, the pattern is evident in Figure 30.

vowels are more sensitive to the coarticulatory effects of surrounding segments than strong vowels in these data, counter to the claim implicit in RQ3) (*cf.* e.g., Magen, 1984; Fowler, 1981a; de Jong *et al*., 1993). Butcher and Harrington's (2003) claim that it is the word-medial consonant rather than the vowel than undergoes prosodically-driven hyper-articulation may account for these findings.

There is no evidence of positional reduction or undershoot in the word-final, pre-boundary vowel (*cf.* e.g., Vayra & Fowler, 1992, for English; see §2.3) in these languages; there is a weak tendency towards less overlap, less variability and greater peripherality in close vowels in word-final, pre-boundary position for Burarra, Gupapuyngu and Warlpiri speakers, as is consistent with the LMM results, and with the findings of Harrington *et al.* (2000a) for Warlpiri, Fletcher and Butcher (2003) for Dalabon and Mayali, and Fletcher *et al.* (2007b) for Kunwinjku (see also, Tiffany, 1959; Koopmans-van Beinum, 1980). It is suggested that when word-final vowels are more peripheral and less overlapped, rather than more reduced, this may be due to pre-boundary duration-related supralaryngeal expansion.

5.4 Conclusions

In the present study, it has been demonstrated that vowels show an effect of word-medial consonant place of articulation in both F1 and F2 formant frequencies at vowel midpoints, *i.e.*, vowels are affected by the place of articulation of neighbouring word-medial consonants. Vowels tend not to be hyper-articulated under conditions of domain-initial prosodic prominence, with the exception of an apparent effect of prosodic prominence on vowel space dispersion in the predicted direction in Burarra. This exception is consistent with the fact that unstressed vowels may be reduced or elided completely in certain environments in Burarra (Butcher, 1996; 2006; see §1.2.2.2). It has been argued (de Jong, 1995) that localised hyper-articulation, specifically, greater peripherality, in accented syllables enhances vocalic perceptual distinctions. Therefore, these findings may provide further evidence that the maintenance of perceptual distinctions between the large number of place of articulation contrasts is prioritised over the maintenance of perceptual distinctions between vowels in these 'consonant-heavy' languages (Butcher, 2006). In the following chapter, V-to-V coarticulation is studied in the four languages with the intention of measuring the effect of the place of the word-medial consonant on the magnitude of trans-consonantal coarticulation.

Table 55. Summary of the effects of word position and prosodic prominence on F1 and F2 frequencies, SD values and ED values for Arrernte, Burarra, Gupapuyngu and Warlpiri speakers. When a pattern is identified, at least two of the three speakers are associated with significant results.

Comparison	**V**	**Arrernte**	**Burarra**	**Gupapuyngu**	**Warlpiri**
Effect of word/prosodic condition on F1	**a**	*n.s.*	*n.s.*	F1 is lower in /a/ in V1 (less open).	*n.s.*
	ə	F1 is lower in /ə/ in V1 than in V2 (less open).	N/A	N/A	N/A
	i	N/A	*n.s*	Inter-speaker variation.	Tendency towards no effect.
	u	N/A	*n.s*	F1 is lower in /u/ in V1 (less open).	*n.s*
Effect of word/prosodic condition on F2	**a**	F2 is lower in /a/ in V1 than in V2 (backer).	*n.s.*	Inter-speaker variation.	Tendency towards no effect.
	ə	*n.s*	N/A	N/A	N/A
	i	N/A.	*n.s.*	*n.s.*	F2 is lower in /i/ in V1 (backer).
	u	N/A	F2 is higher in /u/ in V1 (fronter).	Inter-speaker variation.	Tendency towards no effect.
Effect of word/prosodic condition on SD		N/A	N/A	Tendency towards no effect.	*n.s.*
Effect of word/prosodic condition on ED		N/A	More dispersion in V1.	*n.s.*	More dispersion in V2.

6 Vowel-to-vowel coarticulation

6.1 Introduction

In this chapter, trans-consonantal vowel-to-vowel coarticulation is investigated in order to observe differences in the magnitude of spatial V-to-V coarticulation across various consonant places of articulation and associated flanking vowel qualities and target (fixed, constant or encroached) vowel qualities (terms after, e.g., Magen, 1997). In the following sections, results will be presented by language and word-medial consonant place of articulation. In §6.2, the results are reported in the following order: Burarra (§6.2.1), Gupapuyngu (§6.2.2), Warlpiri (§6.2.3) and Arrernte (§6.2.4), as few results are available for Arrernte. In §6.3, the discussion of the results addresses flanking vowel effects (§6.3.1) and word-medial consonant effects on V-to-V coarticulation (§6.3.2), the effect of word position and prosodic prominence (§6.3.3), and the effects of inventory size and vowel space crowding (§6.3.4). §6.4 concludes. In the chapter to follow, Chapter 7, the final conclusions are drawn.

6.1.1 Hypotheses

Several research questions have been posited with respect to V-to-V coarticulation (§2.5). The more relevant research questions comprise the following:

1. does the place of articulation of a consonant or the quality of a vowel [*i.e.*, vowel closeness] determine the extent to which it is coarticulated by an adjacent segment in Australian languages, and by extension, does it determine the extent to which it exerts coarticulation in other segments (RQ1))?
2. does the place of articulation of the intervening consonant modulate trans-consonantal V-to-V coarticulation and more specifically, does a high coarticulation resistant consonant block or delay V-to-V coarticulation (RQ5))?
3. are prosodically prominent vowels more likely to exert coarticulation and less likely to undergo coarticulation, all else being equal (RQ3));
4. is there an effect of measurement point on V-to-V coarticulation, such that there are stronger V-to-V coarticulatory effects closer to the vowel-consonant boundary and weaker effects further away (RQ4)).

In addition to these four research questions, two hypotheses can also be proposed. As introduced in §2.1.2 and §2.2, /i/ is described in the literature as the most coarticulation resistant and aggressive of the point vowels because it is highly articulatorily constrained while /a/ is least resistant and aggressive and least articulatorily constrained, and /u/ is intermediate. The results reported in the preceding two chapters, Chapter 4 and Chapter 5 have been consistent with this view. The first of the V-to-V coarticulation hypotheses is therefore:

H14) Close vowels exert stronger and/or more frequent trans-consonantal V-to-V coarticulatory effects than /a/ in F1, F2 and F3.

The next hypothesis, H15), concerns the relative importance of the flanking vowel and the medial consonant place of articulation on the target vowel. This hypothesis predicts that there is an association between (i) the magnitude of V-to-V coarticulation and the identity of the vowels involved *i.e.*, their closeness, and (ii) the magnitude of V-to-V coarticulation and the place of the intervening consonant (that is, predicted place effects following from the results given in §4.2 and §5.2):

H15) The effect of word-medial consonant place of articulation (/p t ʈ c k/) outweighs the effect of flanking vowel quality (/i a u/) on the target vowel (/a u/) according to analyses of variance (where the dependent variable is F1, F2 and F3 frequencies in vowel-consonant trajectories).

Once again, an investigation of language-specific behaviour in this context is interesting given the small size of the vowel inventories in Australian languages and the rich set of place of articulation contrasts (§1.2 and §2.1.2).

6.1.2 Methodology

The corpus for this set of experiments is discussed in Chapter 3 in addition to the measurement points and statistical methods. All words in this experiment were included in the word lists given in Appendices A and B. Throughout this chapter, only plots illustrating significant effects at the 0.05 level of significance in the predicted direction were chosen for inclusion and further interpretation. All other plots cannot be included here or in the Appendices due to lack of space.

In this preliminary study of V-to-V coarticulation, all consonants are oral stops, flanking vowel contexts are /i a u/, those being the vowels common to the four languages, and target vowel contexts are /a u/ (there are insufficient /i/ tokens). The first three formants are considered as each provides important information about the effect of the flanking vowel and the medial consonant place. All vowels are short. Furthermore, as in the experiment presented in Chapter 5, all vowels in V1 position are prosodically prominent, while all vowels in V2 position are prosodically weak.

To recapitulate, the measurement points are as follows: $V1_{MID}$ (0.5), $V1_{EQ}$ (the *equidistant* point between the preceding and following points, or 0.7) and $V1_{OFF}$

(0.9) if the target vowel is V1, and $V2_{ON}$ (0.1), $V2_{EQ}$ (0.3) and $V2_{MID}$ (0.5) in V2 if the target vowel is V2. An example plot has been given in Chapter 3. As observed in Chapter 5, in these languages, typically, the vowel /i/ has a low mean F1 and a high F2, while /a/ has a high F1 and a low F2 and /u/ has a low F1 and F2. In interpreting the formant values in the target vowels, therefore, it is assumed that the effect of /i/ on /a/ is manifested as a lower F1 and a higher F2. Similarly, the effect of /u/ on /a/ should be manifested as a lower F1 and F2 and the effect of /a/ on /u/ should be manifested as a higher F1 and F2. F3 will also be considered in this chapter given the known effects of the palatal and in particular the retroflex stop on F3 frequencies (see §3.4.3 and §4.2.2). As stated in §3.4.3.1, two procedures are utilised in this chapter. Both involve comparisons of overall 'trajectory shapes' between sequences differing solely in the quality of the flanking vowel, e.g., /apa/ ~ /ipa/. The first procedure is designed to focus on the effects of the flanking vowel on the target vowel (by means of t-tests and a visual inspection of plots). This procedure allows for a thorough and careful analysis of V-to-V coarticulation in a given place of articulation environment with a given target vowel quality. The second procedure is designed to determine both the effects of the quality of the flanking vowel on the target vowel and the effects of the word-medial consonant place of articulation (by means of analyses of variance and Tukey's post-hoc comparisons). A result in which the large majority of significant comparisons involve the consonant place factor rather than the vowel quality factor is taken to mean that the former factor is contributing more to the realisation of the fixed vowel. A result in which the majority of significant comparisons involve the vowel quality factor is taken to mean that this factor is contributing more to the realisation of the fixed vowel. It is important to reiterate that not all comparisons across the medial consonant are present in the corpus for these languages and speakers.

6.2 Results

6.2.1 Vowel-to-vowel coarticulation – Burarra

This section reports on the effects of the flanking vowel and the intervocalic consonant on V-to-V coarticulation in Burarra bisyllabic words in F1, F2 and F3. For Burarra and Gupapuyngu in this chapter, /p/ indicates /p|b/, /t/, /t|d/, and so on. Averaged, linearly time-normalised V-to-V coarticulation plots are given in Figure 36 to Figure 41. Normalised time is on the x-axis. Recall that in each figure, the left plot represents the entire V1, from onset to $V1_{OFF}$, and the right plot, the entire V2, from $V2_{ON}$ to offset, in C1V1C2V2 words. Burarra Welch-corrected t-test results are given in Table 56. Results are reported first by word-medial consonant place, then by the target vowel quality.

6.2.1.1 Bilabial stop

For Burarra speaker, DP, /apa/ and /ipa/ are examined between $V2_{ON}$ and $V2_{MID}$ in the prosodically weak, target vowel, /a/, to determine whether there are differences between the sequences that suggest that /i/ is exerting carryover V-to-V coarticulation in /ipa/. The two sequences are compared statistically and results are given in full in Table 56. The plots are given in Figure 36. In F1, between $V2_{ON}$ and $V2_{MID}$, in /apa/ there is a 34Hz increase and in /ipa/, a 94Hz increase. As /ipa/ is also lower in F1 frequency throughout V1, this lower $V2_{ON}$ indicates some degree of carryover V-to-V coarticulation in /ipa/ in F1 (t(24)=2.13, $p<0.05$), suggesting a slightly less open vowel. However, only relatively small visual differences can be observed in F1, and there is no evidence of carryover-coarticulation in F2 or F3.

For Burarra speakers, KF and MW, in /apa/ and /ipa/, between $V2_{ON}$ and $V2_{MID}$ in /a/, shown in Figure 37 and Figure 38, comparisons are significant or approach significance in F3 (KF, t(23)=2.12, $p<0.05$; MW, t(7)=2.01, $p=0.08$; see Table 56), but the flanking vowel /i/ is associated with a lowering rather than a raising of F3 frequencies in the target vowel. It is not clear whether the source of this F3 lowering is /i/ or the particular interaction between the bilabial stop and the front vowel (perhaps relating to labial specifications, but not jaw height).

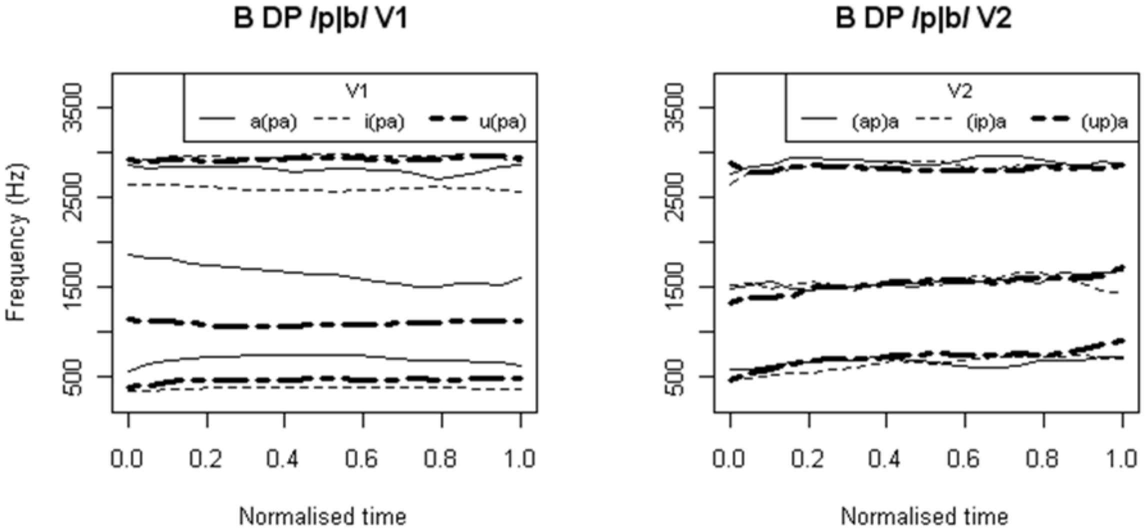

Figure 36. Plots for Burarra speaker, DP, of the sequence /VpV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Three plots are superimposed: a) /apa/, b) /ipa/, and c) /upa/. Note that the y-axis upper limit is 0.025.

Table 56. Burarra, results of t-tests with Welch correction. Measurement points are $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$. ^ Means differ in the opposite direction to that expected. p=* 0.05, ** 0.01, *** 0.001.

			t		
Sp	**V**	**C**	**F1**	**F2**	**F3**
DP	**aa-ia**	**p**	2.13*	0.41	0.52
	aa-ua		-0.21	0.51	1.25
	aa-ua	ʈ	-0.63	3.25*	1.34
	aa-ia	**c**	-2.63*^	1.98	0.92
	aa-ua		-1.1	0.97	1.12
KF	**aa-ia**	**p**	0.15	-0.26	2.12*
	aa-ua		-1.25	-1.33	5.1***
	aa-ua	ʈ	-1.05	2.32*	1.77
	aa-ia	**c**	-1.06	-1.27	-0.13
MW	**aa-ia**	**p**	1.17	0.5	2.01
	aa-ua		2.95**	0.43	6.49***
	aa-ua	ʈ	2.03	2.27*	0.7
	aa-ia	**c**	0.23	-1.9	-0.71

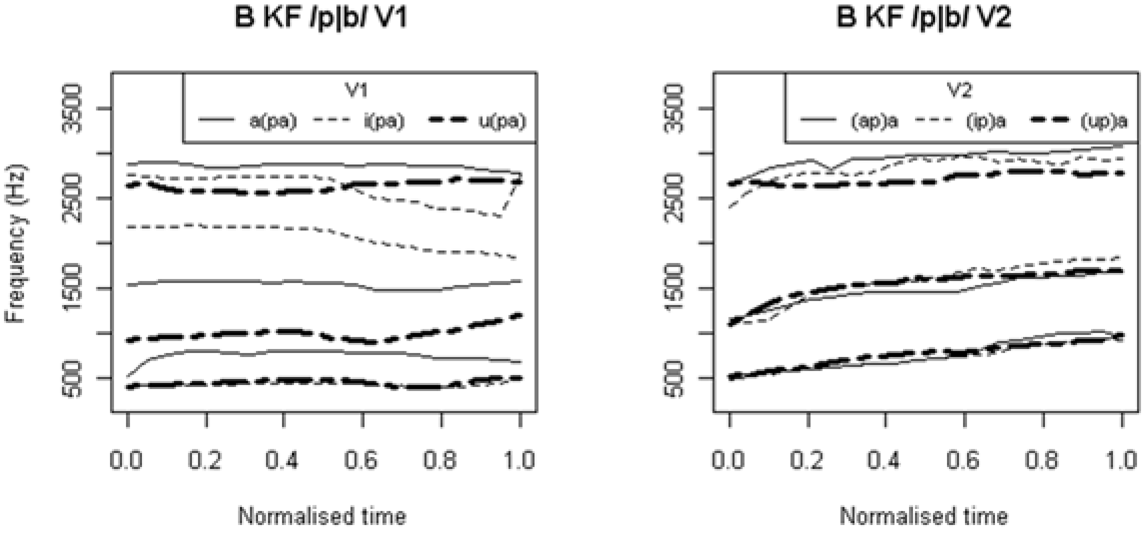

Figure 37. Plots for Burarra speaker, KF, of the sequence /VpV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Three plots are superimposed: a) /apa/, b) /ipa/, and c) /upa/. Note that the y-axis upper limit is 0.025.

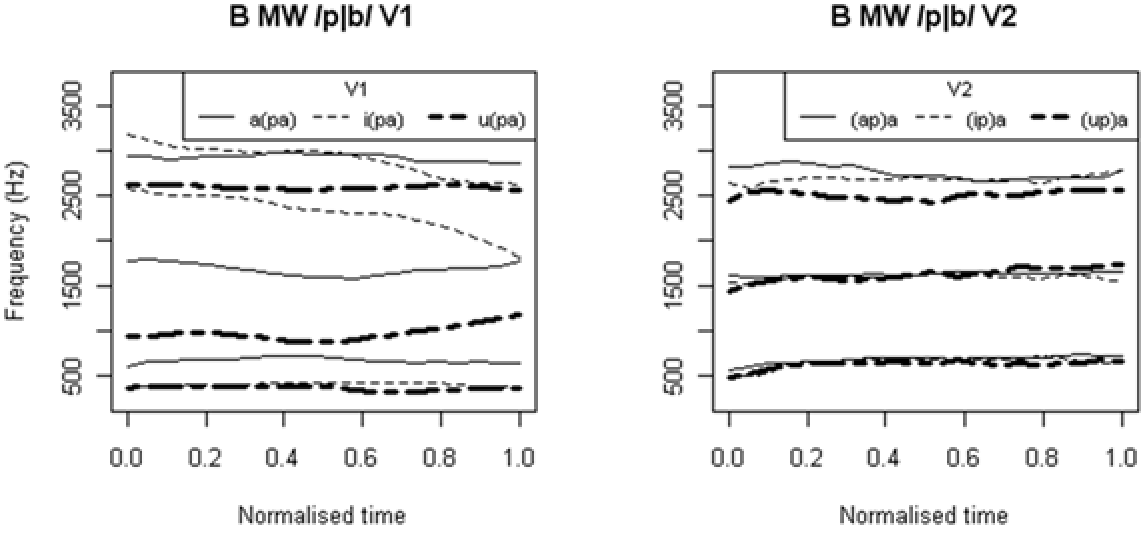

Figure 38. Plots for Burarra speaker, MW, for the sequence /VpV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Three plots are superimposed: a) /apa/, b) /ipa/, and c) /upa/.

Certainly, the plots suggest bilabial C-to-V coarticulation at consonant edges. Therefore, there is insufficient evidence of carryover V-to-V coarticulation (*cf.* Table 56). All other comparisons are non-significant.

For DP, in /apa/ and /upa/ between $V2_{ON}$ and $V2_{MID}$, no comparisons are significant (see Table 56). For KF and MW, comparing the same sequences (plotted in Figure 37 and Figure 38), there is evidence of carryover V-to-V coarticulation in /upa/ in F3 (KF, $t(19)=5.10$, $p<0.0001$; MW, $t(17)=2.95$, $p<0.01$), suggesting a backing of the contriction; /upa/ is associated with lower F3 formant frequencies throughout V1 and V2. Additionally, for MW, the comparison is significant in F1 ($t(17)=2.95$, $p<0.01$). F1 lowering here indicates a relatively narrow and close constriction at $V2_{ON}$. All other comparisons are non-significant.

6.2.1.2 Retroflex stop

In the sequences /aʈa/ and /uʈa/ between $V2_{ON}$ and $V2_{MID}$, it is shown in Figure 39, Figure 40 and Figure 41, that comparisons are significant in F2 (Table 56; DP, $t(28)=3.54$, $p<0.01$; KF, $t(28)=2.32$, $p<0.05$; MW, $t(28)=2.27$, $p<0.05$); F2 lowering between $V2_{ON}$ and $V2_{MID}$ indicates backing. The plots show strong C-to-V coarticulation; a large decrease in F3 formant frequencies from approximately $V1_{MID}$ to $V1_{OFF}$ suggest strong anticipatory word-initial retroflex C-to-V coarticulation, while strong similarities at $V2_{ON}$ between the sequences in F1 and F2 indicate strong word-medial consonantal constraints at consonant release (consistent with results reported in Chapter 4).

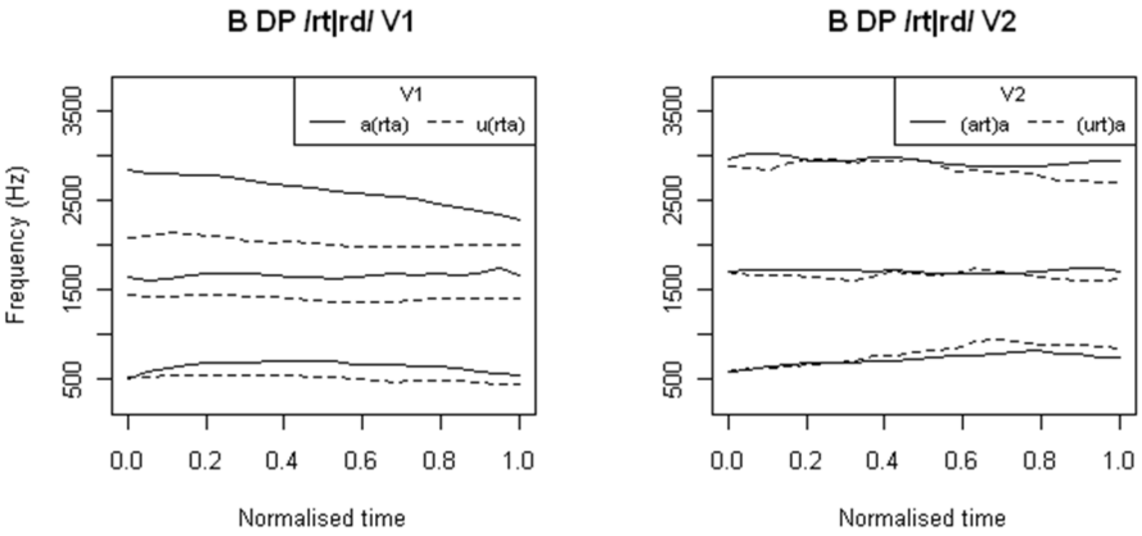

Figure 39. Plots for Burarra speaker, DP, of the sequence /VʈV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency of in Hz. Two plots are superimposed: a) /aʈa/, b) /uʈa/. ‘rt’ represents /ʈ/ and ‘rd’, /ɖ/.

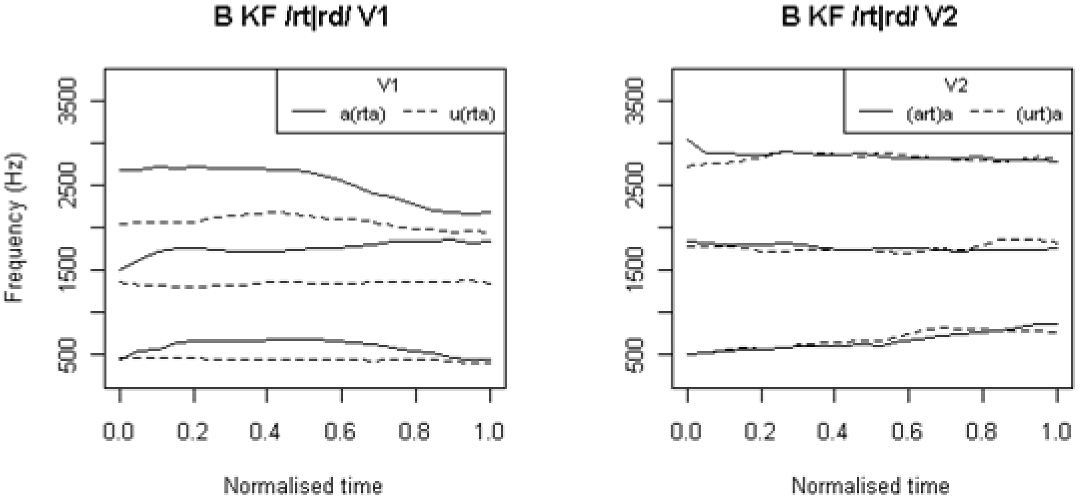

Figure 40. Plots for Burarra speaker, KF, of the sequence /VʈV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency of in Hz. Two plots are superimposed: a) /aʈa/, b) /uʈa/. ‘rt’ represents /ʈ/ and ‘rd’, /ɖ/.

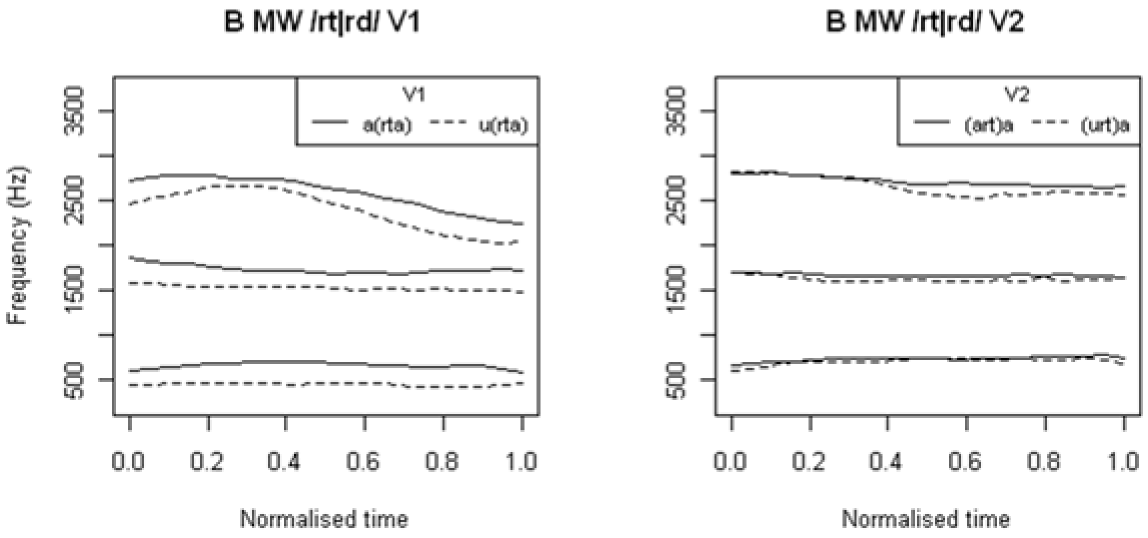

Figure 41. Plots for Burarra speaker, MW, for the sequence /VʈV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Two plots are superimposed: a) /aʈa/, b) /uʈa/. 'rt' represents /ʈ/ and 'rd', /ɖ/.

6.2.1.3 Palatal stop

For speakers DP, KF and MW, all palatal stop comparisons are non-significant (see Table 56). Close similarities across the two sequences for each speaker at $V1_{OFF}$ and especially at $V2_{ON}$ suggests strong constraints on the articulatory and acoustical realization of the stop exerted by the palatal (consistent with findings presented in §4.2.1.2). The results are consistent with the claim that the word-medial palatal consonant is blocking V-to-V coarticulation.

6.2.1.4 Comparisons across word-medial consonant places of articulation

In this section, comparisons are made across word-medial consonant place environments per speaker. For these speakers, analyses are conducted for the target vowel /a/ in V2 position (where it is prosodically weak) only and for medial consonant place, /p|b ʈ|ɖ c|ɟ/. Statistical results are tabulated in Table 57 and Table 58 rather than within the text for reasons of readability.

Table 57. Summary of main effects for Burarra speakers in two-way ANOVAs for carryover V-to-V coarticulation and medial consonant /p ʈ c/ effects, per speaker and formant. The target vowel is V2, /a/. Measurement points are $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$. p=* 0.05, ** 0.01, *** 0.001.

Sp	Formant	df	F
DP	**F1**	4,112	5.67**
	F2	4,112	31.89***
	F3	4,112	3.718*
KF	**F1**	4,82	2.02
	F2	4,82	77.68***
	F3	4,82	14.12***
MW	**F1**	4,106	5.484**
	F2	4,106	32.19***
	F3	4,106	4.65*

Table 58. Tukey's post-hoc comparisons for Burarra speakers with reported significance level (p). Measurement points are $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$. The /i/-/u/ comparison is not given. The comparisons are of formant frequencies at the three equidistant measurement points across different /VCV/ environments per speaker and target vowel quality. p=* 0.05, ** 0.01, *** 0.001.

Sp	Target V	F	C			Flanking V	
	V2		**p~c**	**ʈ~c**	**ʈ~p**	**a~i**	**a~u**
DP	**a**	**F1**	0.001***	0.0001***	0.51	0.93	0.56
		F2	0.0001***	0.0001***	0.0001***	0.14	0.46
		F3	0.06	0.77	0.01**	0.74	0.13
KF	**a**	**F2**	0.0001***	0.0001***	0.0001***	0.73	0.8
		F3	0.0001***	0.0001***	0.27	0.23	0.005**
MW	**a**	**F1**	0.97	0.005**	0.005**	0.45	0.086
		F2	0.0001***	0.0001***	0.05*	0.26	0.8
		F3	0.057	0.38	0.55	0.83	0.005**

According to Table 57, in comparisons conducted per speaker with the target vowel /a/ in V2 position, formant frequencies in the target vowel (at $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$) differ significantly as a function of flanking (V1) quality (three levels: /i a u/) and medial consonant place (three levels: /p ʈ|ɖ c|ɟ/) in all formants for DP and MW and in F2 and F3 for KR (F1 approaches significance).

Tukey's post-hoc comparisons, reported in full in Table 58, indicate that the palatal stop differs from the bilabial and retroflex stops in F1 and F2 for DP, in F2 and F3 for KF and in F2 for MW. The retroflex and bilabial stops differ in F2 and F3 for DP, in F2 for KF and in F1 and F2 for MW. In every case, consonantal effects on formant frequencies are as expected on the basis of results presented in §4.2, e.g., the palatal is associated with lower F1 and higher F2 and F3 formant frequencies than the bilabial stop, the retroflex is associated with lower F3 frequencies than the bilabial and palatal. With regard to flanking vowel effects, for KF and MW, /u/ is associated with lower F3 formant frequencies in the target vowel compared to /a/, indicating backing. No other comparisons for the three speakers are significant. No claims can be made concerning whether prosodic prominence in the flanking vowel has any effect on V-to-V coarticulation as all Burarra sequences involve a V1, prosodically prominent, flanking vowel.

6.2.2 Vowel-to-vowel coarticulation – Gupapuyngu

For the Gupapuyngu speakers, V-to-V coarticulation plots are given in Figure 42 to Figure 49. All Gupapuyngu Welch-corrected t-test results are given in Table 59. As for the Burarra speakers, results are reported first by place of articulation of the word-medial consonant, then by the quality of the target vowel.

6.2.2.1 Bilabial stop

For Gupapuyngu speakers AM and BT, with regard to /apa/ and /apu/ between $V1_{MID}$ and $V1_{OFF}$ (in the prosodically prominent vowel), as shown in Figure 42 (upper) and Figure 43 (upper), respectively, comparisons are significant in F1 (AM, $t(16)=7.81$, $p<0.0001$; BT, $t(20)=2.23$, $p<0.05$). A relatively low F1 in /apu/ suggests a narrowing or raising of the constriction. Comparisons are also significant in F2 (AM, $t(10)=5.81$, $p<0.0005$; BT, $t(21)=4.56$, $p<0.0005$); F2 formant frequencies are relatively low in /apu/, suggesting a retraction of the constriction location. However, for both speakers and both formants, the situation is complicated by strong carryover word-initial palatal C-to-V coarticulation in /apa/ in V1 in the <yapa> /japa/ 'sister' tokens. All other comparisons are non-significant. For EG, comparing /apa/ and /apu/, all comparisons are non-significant (see Table 59).

For AM, with regard to /upu/ and /apu/, the comparison is significant in F3 ($t(9)=-2.64$, $p<0.05$). Between $V2_{ON}$ and $V2_{MID}$, /a/, Figure 42 (lower) shows a larger decrease in the /upu/ condition than in the /apu/ condition, although there is also evidence of strong carryover word-initial retroflex C-to-V coarticulation involving F3 lowering in V1 of the /upu/ sequence; the word is <rupu> /ɹupu/ 'possum' (*cf.* Table 59). Note also that in the same /apu/ sequence, there was evidence of anticipatory coarticulation in the lower formants. Hence, there is insufficient evidence of carryover V-to-V coarticulation in /apu/ in F3. All other comparisons are non-significant. With regard to the same (/upu/ and /apu/) sequences for BT, all comparisons are non-significant.

Table 59. Gupapuyngu, results of t-tests with Welch correction. When the target vowel is V1, measurement points are $V1_{MID}$, $V1_{EQ}$ and $V1_{OFF}$. When the target vowel is V2, measurement points are $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$. ^ Means differ in the opposite direction to that expected. p=* 0.05, ** 0.01, *** 0.001.

Sp	**V**	**C**	**F1**	**F2**	**F3**
AM	**aa-au**	**p**	7.8***	5.81***	-3.98**^
	uu-au		0.00	-0.2	-2.64*
	aa-ua	**t**	1.55	-6.58***^	0.77
	uu-ua		2.81*^	-4.22***	1.99*^
	aa-ia	**k**	1.95	1.23	1.58
	aa-ua		-0.15	0.74	-5.11***^
	aa-au		-1.39	2.12*	-4.43***^
	uu-ua		0.97	5.73***^	-1.78
	uu-au		-0.14	5.00***^	0.86
BT	**aa-au**	**p**	2.23*	4.56***	0.82
	uu-au		0.44	-0.07	-0.35
	aa-ua	**t**	-0.55	-1.67	-5.78***^
	uu-ua		-1.02	-0.85	-1.87
	aa-ia	**k**	-2.68**	4.48***	3.59**^
	aa-ua		-4.27***^	8.13***	4.62***^
	aa-au		0.88	5.48***	0.95
	uu-ua		-6.43***	-6.96***^	0.46
	uu-au		2.7*^	5.13***^	2.0
EG	**aa-au**	**p**	1.44	1.59	-1.04
	aa-ua	**t**	0.41	1.75	-2.19*
	uu-ua		0.34	0.18	-1.41
	aa-ua	**k**	-1.44	0.38	4.84***
	uu-ua		-3.49**	-3.93***	13.95***^

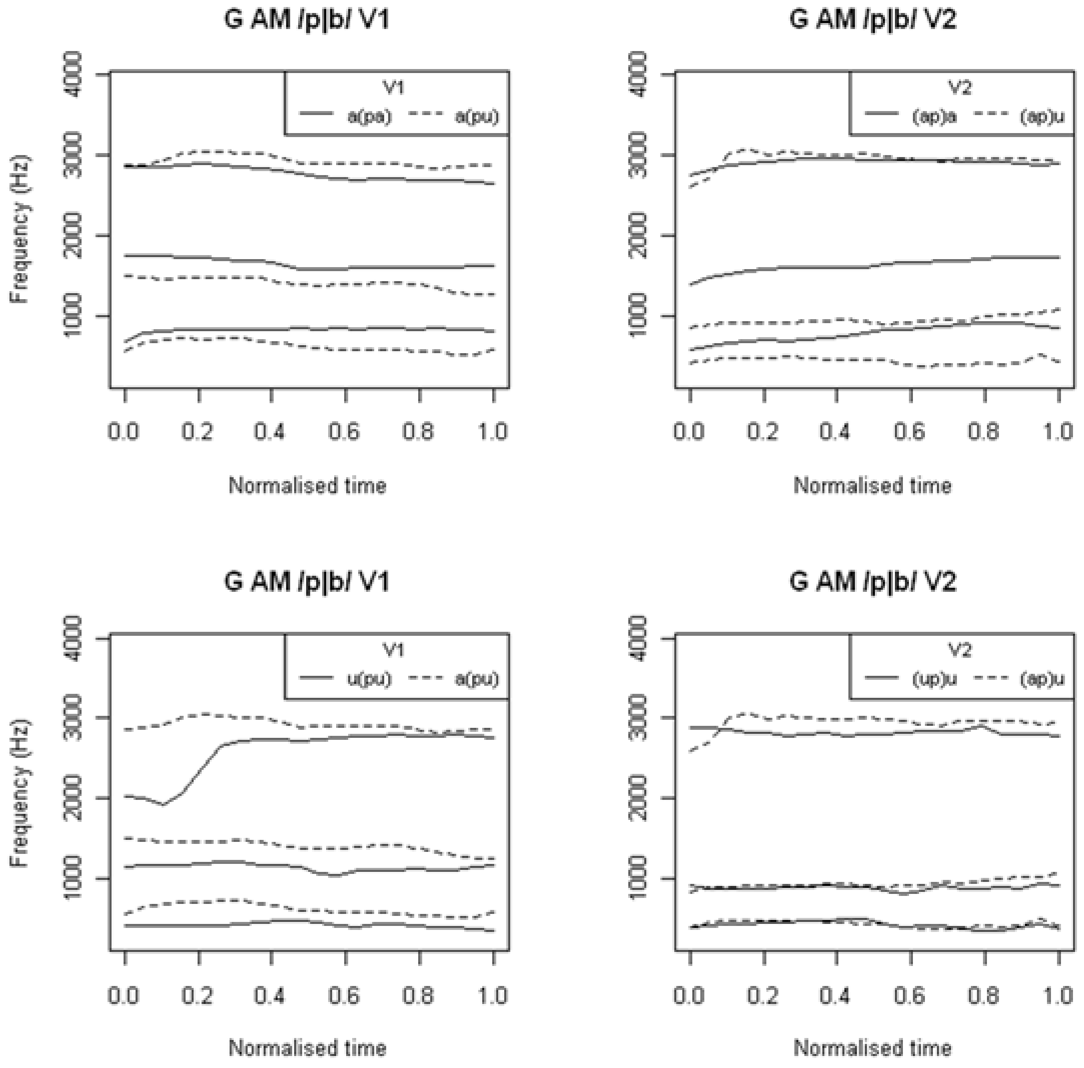

Figure 42. Plots for Gupapuyngu speaker, AM, for the sequence /VpV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Two plots are superimposed: upper plots, a) /apa/ and b) /apu/, lower plots, a) /upu/ and b) /apu/.

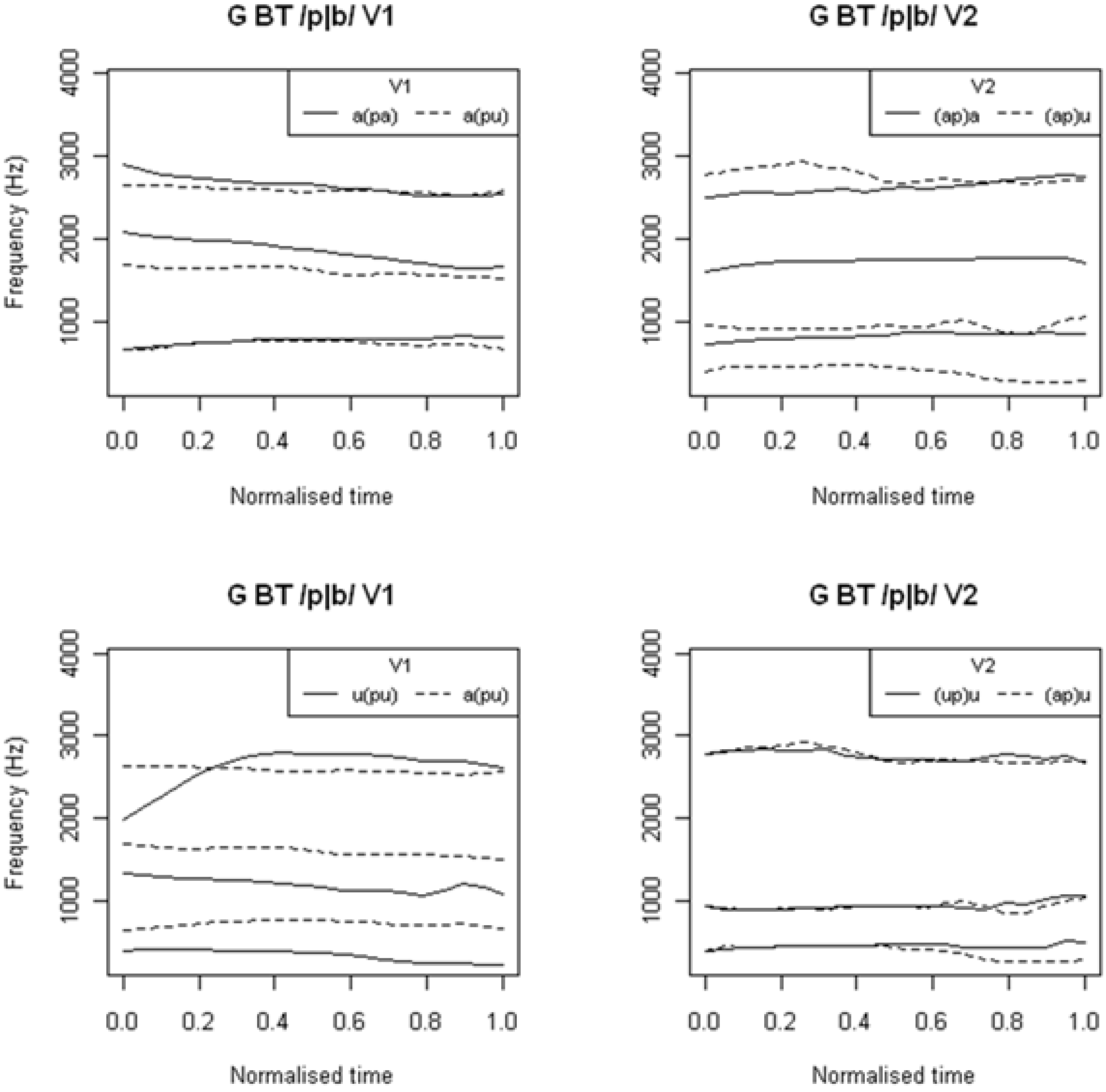

Figure 43. Plots for Gupapuyngu speaker, BT, for the sequence /VpV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Two plots are superimposed: upper plots, a) /apa/ and b) /upa/, lower plots, a) /upu/ and b) /apu/.

6.2.2.2 Alveolar stop

Comparing /ata/ and /uta/ for speakers AM and BT, between $V2_{ON}$ and $V2_{MID}$ (in the prosodically weak vowel), all comparisons are non-significant in F2 (see Table 59). For EG, comparing the same sequences, between $V2_{ON}$ and $V2_{MID}$, /a/, in F3, as shown in Figure 44, the comparison is significant ($t(15)=-2.19$, $p<0.05$), but this is not a clear carryover V-to-V effect as flanking vowel /u/ is associated with *higher* F3 frequencies after 0.2 (20%) in the target vowel. Further, the lowering of F3 word-finally in /ata/ appears to be a word-final/pre-boundary effect (as suggested by the findings reported for F1/F2 in §5.2). Across the /ata/ and /uta/ sequences, formant frequencies are very similar at $V2_{ON}$, indicating that relatively strong constraints are exerted by the word-medial consonant at release (consistent with findings reported in §4.2.1.3). All other comparisons are non-significant.

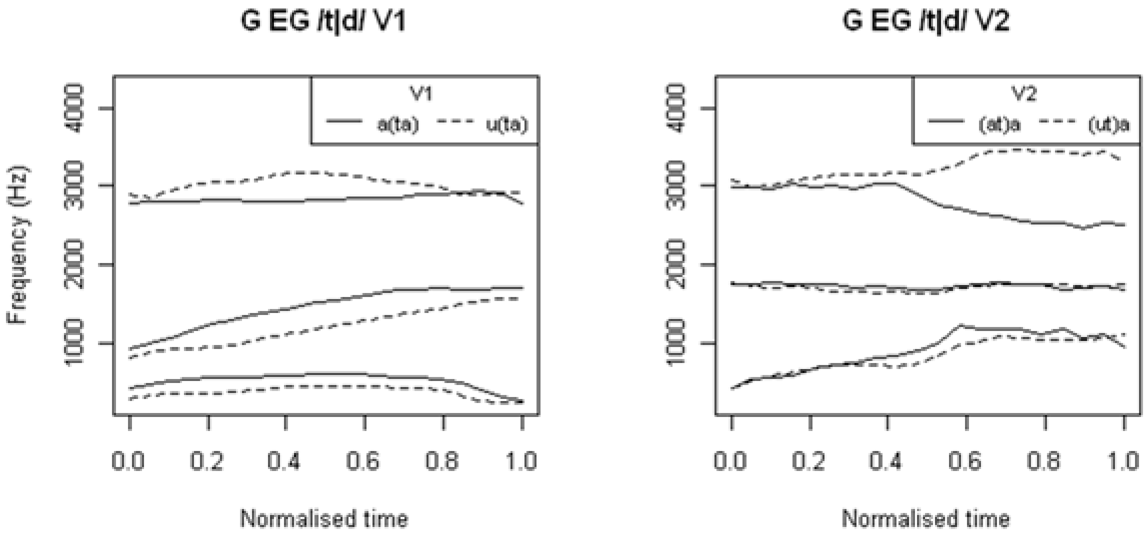

Figure 44. Plots for Gupapuyngu speaker EG for the sequence /VtV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency of in Hz. Two plots are superimposed: a) /ata/, b) /uta/. Note that the y-axis upper limit is 4250Hz.

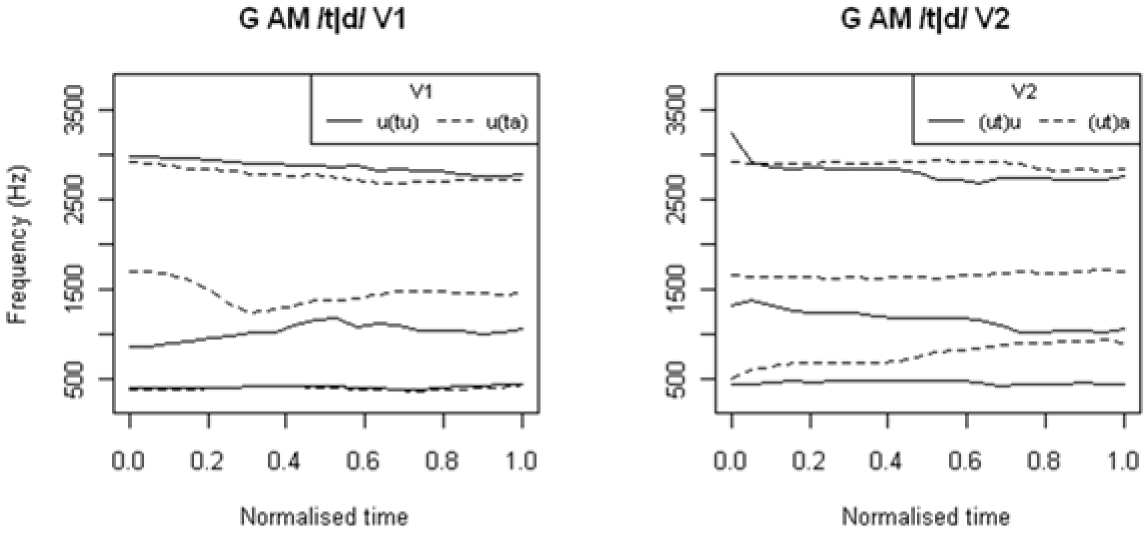

Figure 45. Plots for Gupapuyngu speaker AM for the sequence /VtV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency of in Hz. Two plots are superimposed: a) /utu/, b) /uta/.

For AM, with regard to /utu and /uta/, shown in Figure 45, between $V1_{MID}$ and $V1_{OFF}$ in /u/, the comparison is significant in F2 (t(22)=-4.22, p<0.0005). The plot shows a 105Hz increase in V1 of /utu/ and a 227Hz increase in /uta/. As this larger increase involves a movement towards a higher F2 at $V2_{MID}$, there is anticipatory V-to-V coarticulation in /uta/, suggesting a fronting of the constriction. These results are particularly interesting as they provide evidence of a non-close vowel exerting coarticulatory effects and, conversely, the strength of the symmetrical /u/ environment. Again, strong constraints appear to be exerted by the word-medial consonant release in F1 and F3. For BT and EG, comparing /utu/ and /uta/, all comparisons are non-significant.

6.2.2.3 Velar stop

For speakers AM and BT, with regard to /aka/ and /ika/, between $V2_{ON}$ and $V2_{MID}$, it is shown in Figure 46 (upper) and Figure 47 (upper), respectively, that comparisons are significant or approach significance in F1 (AM, t(15)=1.95, p=0.07; BT, t(28)=-2.68, p<0.01); the relatively low F1 in /ika/ suggests tongue and/or jaw raising and a more forward constriction. For BT, in F2, between $V2_{ON}$ and $V2_{MID}$, there is a negligable increase in /aka/ and a 79Hz decrease in /ika/. The larger decrease is due to a high $V2_{ON}$ in /ika/. Given a high $V1_{MID}$ and $V1_{OFF}$ in the same sequence, it appears that carryover V-to-V coarticulation is occurring in /ika/ (t(22)=4.48, p<0.0005). The raising of F2 at $V2_{ON}$ suggests fronting, consistent with the results reported in §4.2.3. All other comparisons for AM and BT are non-significant. In the /aka/ context, for all Gupapuyngu speakers, the situation is complicated by the fact that all words are palatal-initial, and there is strong carryover word-initial palatal C-to-V coarticulation.

For speakers AM and EG, with regard to /aka/ and /uka/, between $V2_{ON}$ and $V2_{MID}$, as shown in Figure 46 (upper) and Figure 49 (upper), comparisons are significant in F3 (AM, t(21)=-6.58, p<0.0005; t(11)=4.83, p<0.0005). For AM, Figure 46 (upper) shows that /u/ is again associated with higher rather than lower F3 frequencies in the target vowel, which does not clearly suggest V-to-V coarticulation. For EG, Figure 49 (upper) shows a minimal increase in /aka/ and a 51Hz increase in /uka/. F3 of /uka/ is lower throughout both V1 and V2, suggesting a backed constriction, which may be associated with V-to-V coarticulation and a backing of the velar constriction, as reported in the /u/ context for Gupapuyngu speakers in §4.2.3. For BT, the comparison is significant in F2 (t(20)=8.13p<0.0001). Figure 47 (upper) shows that F2 formant frequencies are lower in /uka/ both at $V1_{ON}$ and at $V1_{MID}$, indicating V-to-V coarticulation, again suggesting a more retracted vowel and velar constriction consistent with the results reported in §4.2.3. All other comparisons are non-significant.

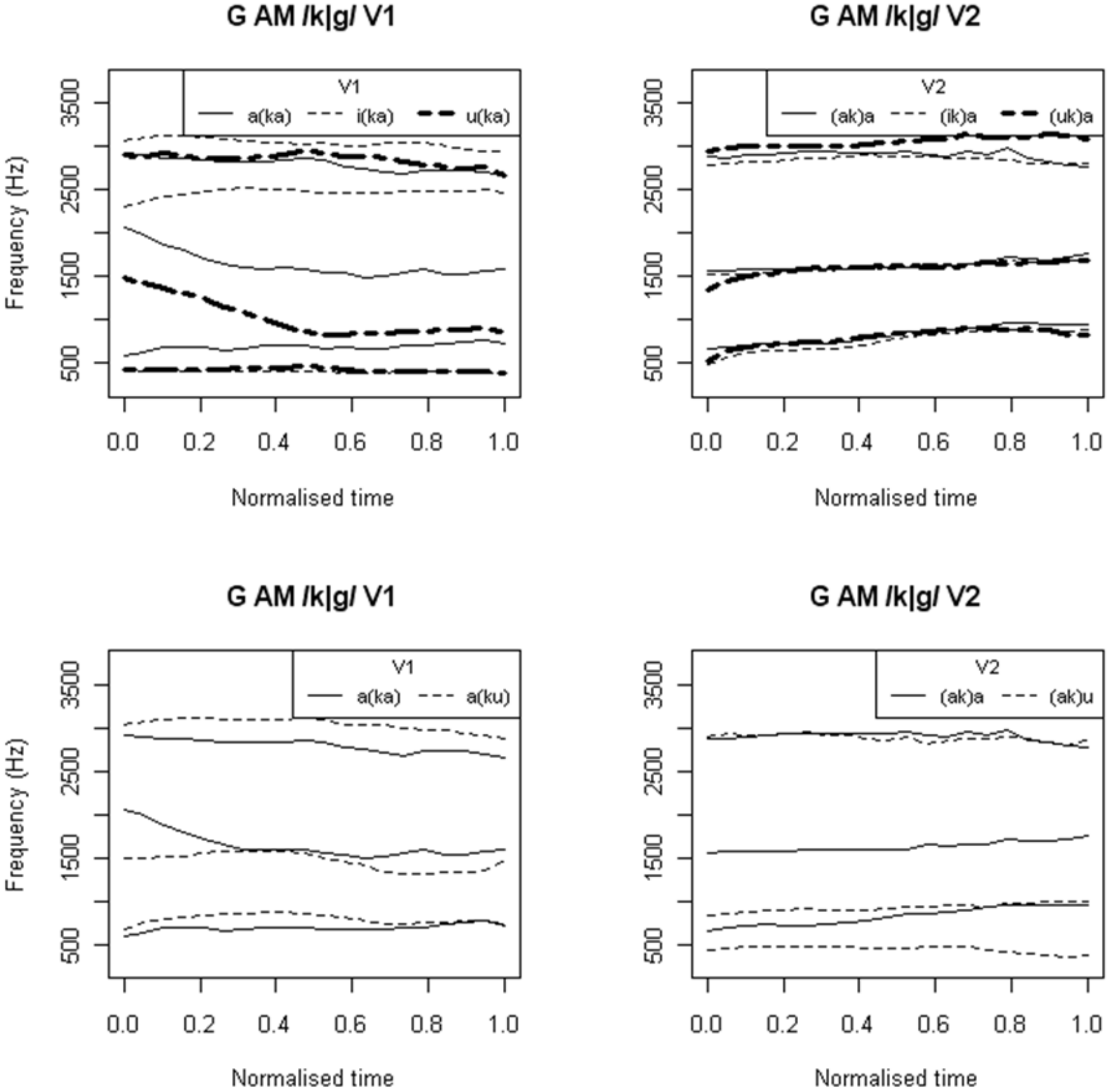

Figure 46. Plots for Gupapuyngu speaker, AM, for the sequence /VkV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Three and two plots are superimposed: upper: a) /aka/, b) /ika/ and c) /uka/, lower: a) /aka/, b) /aku/.

For AM, with regard to /aka/ and /aku/ between $V1_{MID}$ and $V1_{OFF}$ in /a/ in Figure 46 (lower), the comparison is significant in F2 ($t(25)=2.12$, $p<0.05$). The plot shows a minimal decrease in /aka/ and a large, 223Hz, decrease in /aku/. Here there is evidence of strong anticipatory F2 V-to-V coarticulation in /aku/, similar to that found previously in /aka/ ~ /uka/ comparisons for the Gupapuyngu speakers. For BT, with regard to the same sequences and formant, Figure 47 (lower) shows a 197Hz decrease in F2 in /aka/ and a negligable increase in /aku/. The lower F2 values at $V1_{MID}$ and especially $V1_{OFF}$ in /aku/ are consistent with anticipation of lower F2 values at $V2_{ON}$ and $V2_{MID}$ in the same sequence. However, the gradual rise from the $V1_{ON}$ to $V1_{MID}$, most likely due to some labio-velar word-initial tokens, and the plateau from $V1_{MID}$ to $V1_{OFF}$ complicate the situation. Therefore, there is insufficient evidence of anticipatory V-to-V coarticulation (*cf.* Table 59). All other comparisons for these speakers are non-significant.

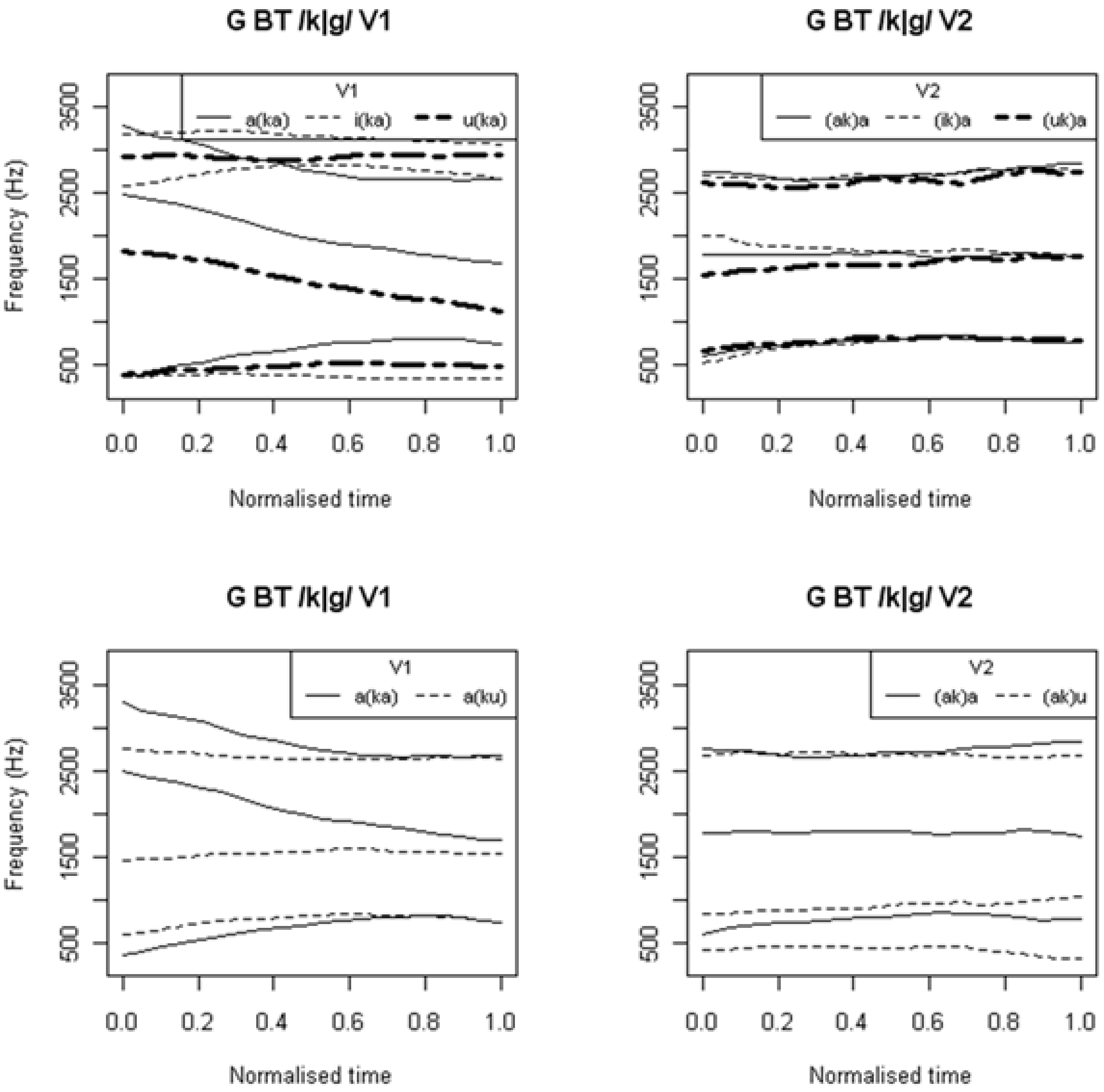

Figure 47. Plots for Gupapuyngu speaker, BT, for the sequence /VkV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Three and two plots are superimposed: upper: a) /aka/, b) /ika/ and c) /uka/, lower: a) /aka/, b) /aku/.

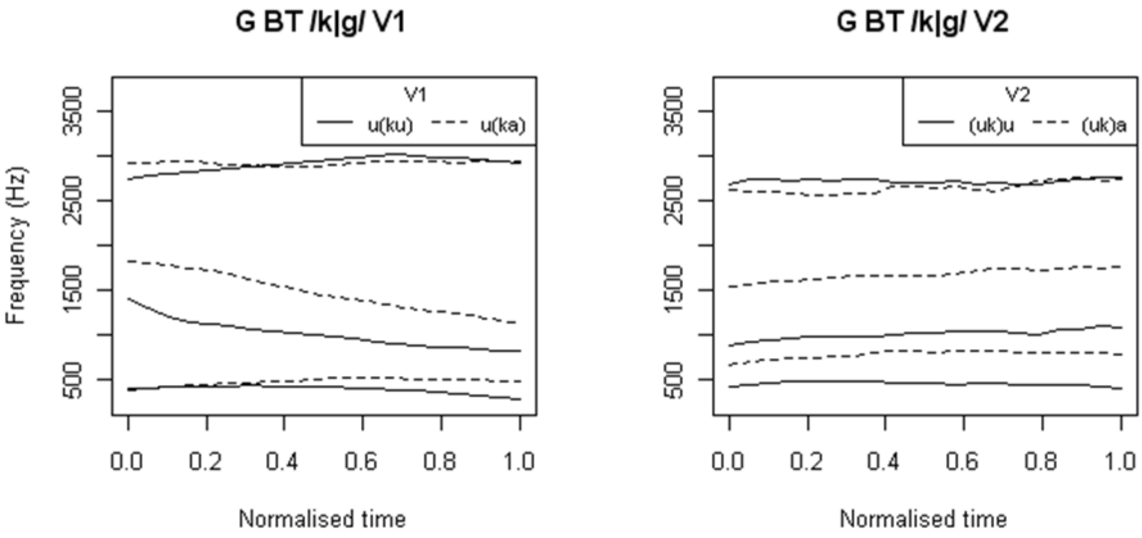

Figure 48. Plots for Gupapuyngu speaker, BT, for the sequence /VkV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Two plots are superimposed: a) /uku/ and b) /uka/.

For AM, comparing /uku/ and /uka/, all comparisons are non-significant (Table 59). For BT and EG, in the same sequences, between $V1_{MID}$ and $V1_{OFF}$, shown in Figure 48 and Figure 49 (lower), comparisons are significant in F1 (BT, $t(22)=-6.43$, $p<0.0001$; EG, $t(11)=-3.49$, $p<0.01$), although there are clearly also some C-to-V effects at $V1_{OFF}$ and $V2_{ON}$ in the two sequences associated with EG. The relatively high F1 in /uka/ suggests slight dorsum/jaw lowering. All other comparisons are non-significant.

For EG, in F2, between $V1_{MID}$ and $V1_{OFF}$, there is a 24Hz decrease in /uku/ and a 52Hz decrease in /uka/. The larger decrease in /uka/ is due to a higher $V1_{MID}$, and both $V1_{MID}$ and $V1_{ON}$ appear to be raised by the word-initial palatal in some tokens. It is difficult to determine whether this C-to-V coarticulation is causing the slightly higher F2 frequency at $V1_{OFF}$ in /uka/ than in /uku/. In F3, a more likely interpretation is that there is carryover V-to-V coarticulation induced by /u/ in /a/, given that it involves a lowering rather than a raising of formant frequencies (Table 63). For AM and BT, comparing /uku/ and /aku/, all comparisons are non-significant (Table 59).

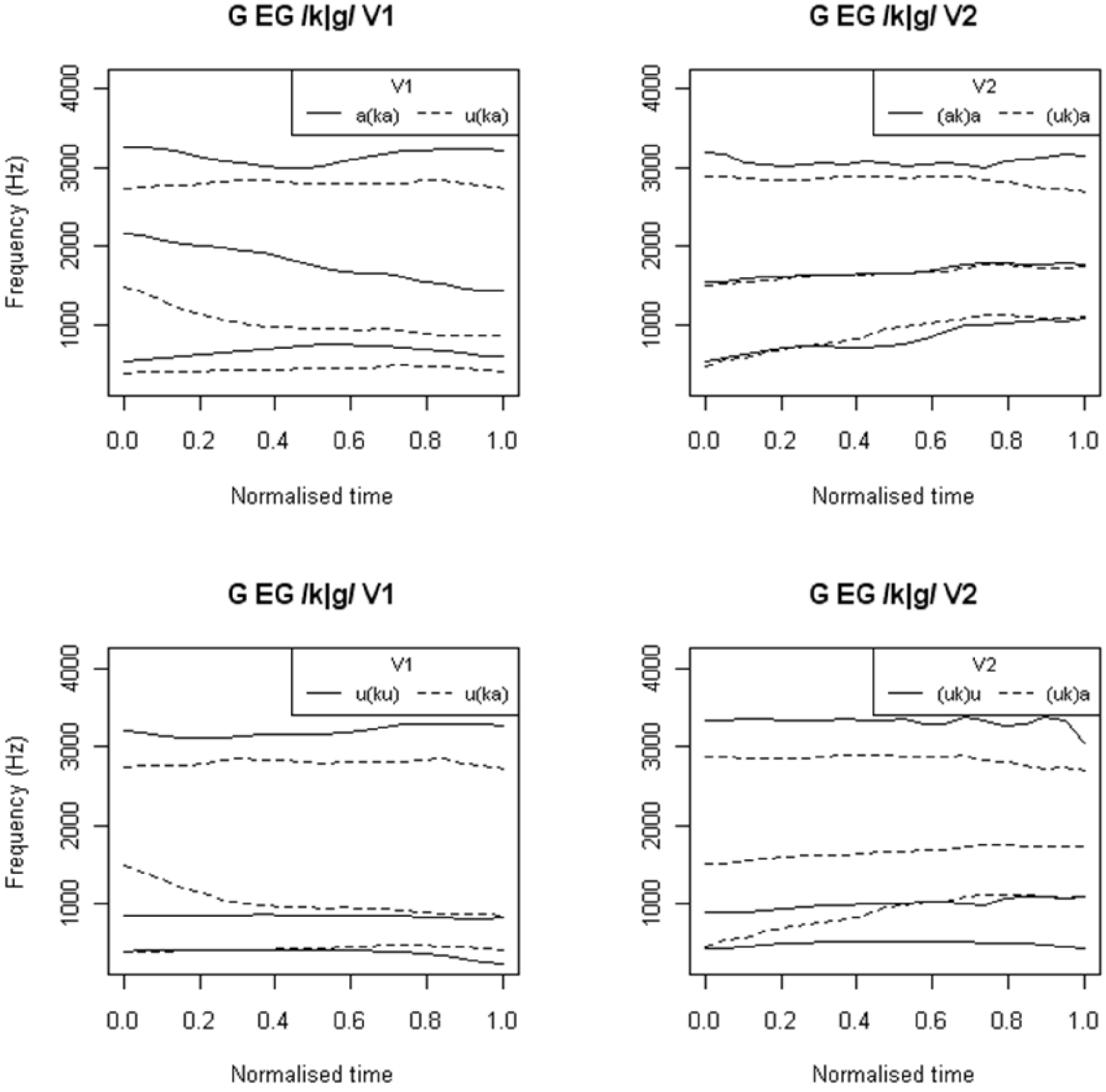

Figure 49. Plots for Gupapuyngu speaker, EG, for the sequence /VkV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Two plots are superimposed: upper, a) /aka/ and b) /uka/, lower, a) /uku/ and b) /uka/. Note the y-axis upper limit of 4100Hz.

6.2.2.4 Comparisons across word-medial consonant places of articulation

For the Gupapuyngu speakers, analyses are conducted for the target vowels /a u/ in both V1 (a prosodically prominent vowel; at $V1_{MID}$, $V1_{EQ}$ and $V1_{OFF}$) and V2 (a prosodically weak vowel; at $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$) positions and for medial consonant place of articulation, /p|b t|d k|g/. Statistical results are given in Table 60 to Table 62 (for all target vowel qualities and positions).

Target vowel /a/ in V1

According to Table 60, in comparisons conducted per speaker with the target vowel /a/ in V1 position, formant frequencies in the target vowel differ significantly as a function of flanking (V2) quality (AM and EG, two levels: /a u/; BT, three levels: /i a u/) and medial consonant place (three levels: /p t k/) in F2 and F3 for AM and in all formants for BT and EG. The results of Tukey’s post-hoc comparisons are given in detail in Table 61 for AM and in Table 62 for BT and EG. With regard to flanking vowel effects, for all speakers, /u/ is associated with lower F2 formant frequencies in the target vowel than /a/, indicating backing (approaching significance for EG). With regard to consonantal effects, for AM, BT and EG, again in F3, the velar stop is associated with higher formant frequencies than the bilabial stop (and the alveolar stop for EG). For BT, the bilabial stop is also associated with lower F3 frequencies than the alveolar stop. Furthermore, in F2, the alveolar stop is associated with higher formant frequencies than the peripheral stops for this speaker, as would be anticipated. All other comparisons are non-significant.

Target vowel /a/ in V2

According to Table 60, in comparisons conducted per speaker with the target vowel /a/ in V2 position, formant frequencies in the target vowel differ significantly as a function of flanking (V1) quality (three levels: /i a u/) and medial consonant place (three levels: /p t k/) in F2 for AM, in all formants for BT and in F2 and F3 for EG.

In Tukey’s post-hoc comparisons, for BT, /u/ is associated with lower F2 formant frequencies than /a/, while for BT and also AM, /i/ is associated with higher F2 formant frequencies than /a/ (approaching significance for AM). With regard to consonantal effects, for BT and EG, in F2, the bilabial is associated with low, the velar with intermediate, and the alveolar with high formant frequencies. For BT, the bilabial stop is associated with higher F1 and lower F3 formant frequencies than the alveolar and the velar stops. For EG, the alveolar is associated with higher F2 and F3 frequencies than the peripheral stops (consistent with results reported in Chapter 4). All other comparisons are either non-significant or means do not differ in the expected direction.

Table 60. Summary of main effects in two-way ANOVAs for Gupapuyngu speakers for anticipatory and carryover V-to-V coarticulation and medial consonant place /p t k/ effects per speaker and formant. The comparisons are of formant frequencies at the three equidistant measurement points in the target vowel /a u/ across different /VCV/ environments per speaker and target vowel quality. p=* 0.05, ** 0.01, *** 0.001.

		V1 a		**V2 a**		**V1 u**		**V2 u**	
Sp	**Formant**	**df**	**F**	**df**	**F**	**df**	**F**	**df**	**F**
AM	**F1**	4,61	2.16	5,96	2.275	3,53	6.56***	3,50	0.35
	F2	4,61	4.44**	5,96	16.06***	3,53	15.2***	3,50	14.65***
	F3	4,61	9.01***	5,96	1.976	3,53	0.14	3,50	2.78*
BT	**F1**	3,65	2.4	4,76	5.116**	3,47	13.39***	3,53	1.758
	F2	3,65	17.73***	4,76	16.38***	3,47	27.77***	3,53	63.62***
	F3	3,65	6.06**	4,76	3.86**	3,47	5.97**	3,53	5.28**
EG	**F1**	3,41	3.15*	3,59	0.45	2,42	1.6	N/A	N/A
	F2	3,41	3.87*	3,59	8.2***	2,42	126.7***	N/A	N/A
	F3	3,41	11.01***	3,59	5.7**	2,42	3.79*	N/A	N/A

Table 61. Tukey's post-hoc comparisons for Gupapuyngu speaker AM, with reported significance level (p). The /i/-/u/ comparison is not given. The comparisons are of formant frequencies at the three equidistant measurement points in the target vowel /a u/ across different /VCV/ environments per speaker and target vowel quality. ^ Means differ in the opposite direction to that expected. p=* 0.05, ** 0.01, *** 0.001.

Sp	**Target V**		**F**	**C**			**Flanking V**	
	V1	**V2**		**p~k**	**t~k**	**t~p**	**a~i**	**a~u**
AM	**a**		**F2**	0.77	0.86	0.46	N/A	0.005**
			F3	0.0005***	0.1	0.86	N/A	0.005**^
		a	**F2**	0.99	0.82	0.97	0.079	0.087^
	u		**F1**	0.98	0.005**	0.05*	N/A	0.059^
			F2	0.2	0.0001***	0.063	N/A	0.2
		u	**F2**	0.19	0.0001***	0.0001***	N/A	0.095^
			F3	0.98	0.05*	0.05*	N/A	0.975

Table 62. Tukey’s post-hoc comparisons for Gupapuyngu speakers, BT and EG, with reported significance level (p). The /i/-/u/ comparison is not given. The comparisons are of formant frequencies at the three equidistant measurement points in the target vowel /a u/ across different /VCV/ environments per speaker and target vowel quality. ^ Means differ in the opposite direction to that expected. p=* 0.05, ** 0.01, *** 0.001.

Sp	**Target V**		F	**C**			**Flanking V**	
	V1	**V2**		**p~k**	**t~k**	**t~p**	**a~i**	**a~u**
BT	**a**		**F2**	0.78	0.01**	0.05*	N/A	0.0001***
			F3	0.01**	0.29	0.005**	N/A	0.3
		a	**F1**	0.005**	0.38	0.001***	0.61	0.5
			F2	0.005**	0.05*	0.0001***	0.0005***	0.05*
			F3	0.05*	0.3	0.005**	0.76	0.53
	u		**F1**	0.0001***	0.01**	0.64	N/A	0.0001***
			F2	0.14	0.0001***	0.05*	N/A	0.0001***
			F3	0.01**	0.005**	0.76	N/A	0.5
		u	**F2**	0.96	0.0001***	0.0001***	N/A	0.05*^
			F3	0.005**	0.1	0.58	N/A	0.29
EG	**a**		**F1**	0.83	0.073	0.085	0.1	N/A
			F2	0.13	0.94	0.059	0.07	N/A
			F3	0.0001***	0.005**	0.33	0.36	N/A
		a	**F2**	0.05*	0.05*	0.0001***	0.478	N/A
			F3	0.98	0.005**	0.01**	0.13	N/A
	u		**F2**	N/A	0.0001***	N/A	0.19	N/A
			F3	N/A	0.82	N/A	0.01**^	N/A

Target vowel /u/ in V1

According to Table 60, in comparisons conducted per speaker with the target vowel /u/ in V1 position, formant frequencies in the target vowel differ significantly as a function of flanking (V2) quality (two levels: /a u/) and medial consonant place (three levels: /p|b t|d k|g/) in F1 and F2 for AM, in F2 and F3 for EG and in all formants for BT. In Tukey's post-hoc comparisons (given in Table 61 and Table 62), with regard to flanking vowel effects, for BT, /a/ is associated with higher F1 and F2 formant frequencies than /u/. With regard to medial consonant effects, for AM, the alveolar is associated with lower F1 and higher F2 frequencies than the peripheral stops (approaching significance in F2). For BT, the velar is associated with higher F1 and F3 formant frequencies than lower F2 frequencies than the other stops. For BT and EG, the alveolar is associated with high F2 formant frequencies than the peripheral stop(s), consistent with previous findings (§4.2). All other comparisons are either non-significant or means do not differ in the expected direction.

Target vowel /u/ in V2

According to Table 60, in comparisons conducted per speaker with the target vowel /u/ in V2 position, formant frequencies in the target vowel differ significantly as a function of flanking (V1) quality (AM, two levels: /a u/; BT, three levels: /i a u/) and medial consonant place (three levels: /p t k/) in formants F2 and F3 for AM and BT. For both speakers, post-hoc comparisons show that the alveolar stop is associated with higher F2 formant frequencies than the peripheral stops. For AM, the alveolar is also associated with lower F3 formant frequencies than the peripheral stops, while for BT in F3, the bilabial is associated with higher formant frequencies than the velar stop. No other comparisons are significant. Across the four target vowel contexts, there is no clear tendency for a prosodically prominent flanking vowel to exert stronger coarticulatory effects than a weak flanking vowel.

6.2.3 Vowel-to-vowel coarticulation – Warlpiri

For the Warlpiri speakers, V-to-V coarticulation plots are given in Figure 50 to Figure 54. All Warlpiri Welch-corrected t-test results are given in Table 63. As for other languages, results are reported first by place of articulation of the word-medial consonant, then by the quality of the target vowel.

Table 63. Warlpiri, results of t-tests with Welch correction. When the target vowel is V1, measurement points are $V1_{MID}$, $V1_{EQ}$ and $V1_{OFF}$. When the target vowel is V2, measurement points are $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$. ^ Means differ in the opposite direction to that expected. p=* 0.05, ** 0.01, *** 0.001.

Sp	**V**	**C**	**F1**	**F2**	**F3**
BP	**aa-ai**	**t**	-0.35	-2.06	0.58
	aa-ua	**k**	0.63	0.98	-1.05
	uu-ua		1.47	9.42***^	-2.34*^
KR	**aa-au**	**p**	-0.95	3.09**	-1.10
	aa-ua		-1.10	1.08	-0.91
	aa-ai	**t**	-0.73	-1.59	6.37***^
	aa-ia		-0.82	0.05	-0.39
	aa-ua	**k**	-1.36	2.68*	-6.55***^
	uu-ua		-0.44	3.99***^	-1.53
RR	**aa-au**	**p**	-2.67*^	2.60*	0.47
	aa-ua		1.90	1.87	0.93
	aa-ai	**t**	-2.28*^	-0.12	-0.98
	aa-ia		0.42	0.64	1.51
	aa-ai	**k**	-1.29	-6.50***	0.17
	aa-au		-3.32**^	7.24***	1.71
	aa-ua		-0.70	1.71	-0.53
	uu-au		1.47	4.49**^	0.48
	uu-ua		4.00**^	7.02***^	-3.34**

6.2.3.1 Bilabial stop

With regard to /apa/ and /apu/, between $V1_{MID}$ and $V1_{OFF}$ in prosodically prominent V1, /a/, shown in Figure 50 and Figure 51, comparisons for speakers KR and RR are significant in F2 (KR, t(22)=3.09, p<0.01; RR, t(20)=2.60, p<0.05). The relatively low F2 formant frequencies in /apu/ suggest backing. For both speakers, there is evidence of C1-to-V1 coarticulation in F1 and F2 associated with those tokens involving a word-initial palatal (<japa> /ɟapa/ 'elder bro.'). All other comparisons are non-significant. Comparing /apa/ and /upa/ for KR and RR, between $V1_{ON}$ and $V1_{MID}$, all comparisons are non-significant (Table 63).

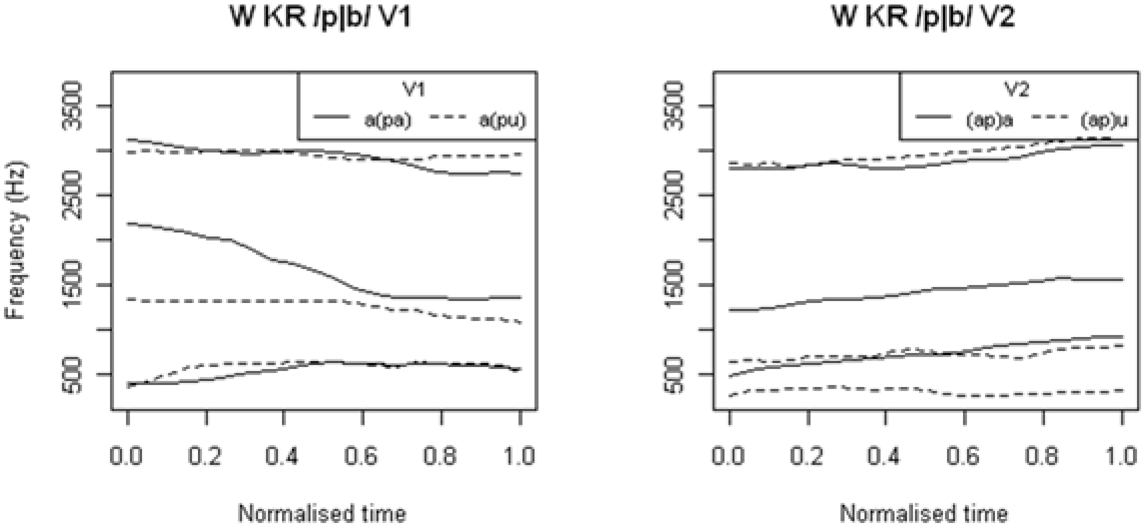

Figure 50. Plots for Warlpiri speaker, KR, for the sequence /VpV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Two plots are superimposed: a) /apa/ and b) /apu/.

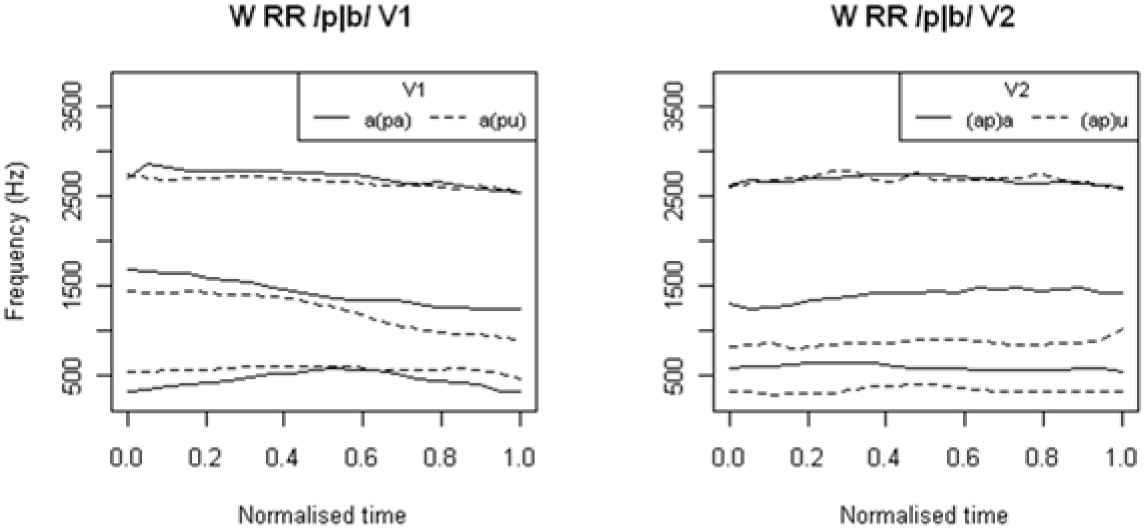

Figure 51. Plots for Warlpiri speaker, RR, for the sequence /VpV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Two plots are superimposed: a) /apa/ and b) /apu/.

6.2.3.2 Alveolar stop

For all Warlpiri speakers, all comparisons are non-significant (or means do not differ in the expected direction; see all Warlpiri Welch-corrected t-test results in Table 63. For the three speakers, there is evidence of strong C-to-V coarticulation. For BP and RR, comparing /ata/ and /ati/, in the latter, there is a very strong C-to-V effect induced by the word-initial labio-velar. At $V1_{OFF}$ there is also some visual evidence of an anticipatory alveolar C-to-V effect. For KR and RR, comparing /ata/ and /ita/, there is a great similarity between the sequences at $V2_{ON}$, suggesting strong alveolar C-to-V coarticulation.

6.2.3.3 Velar stop

For BP, comparing /aka/ and /uka/ and /uku/ and /uka/, all comparisons are non-significant (or means do not differ in the expected direction; Table 63). For RR, comparisons are non-significant in /aka/ and /uka/. For this speaker, similar F1 and F3 formant frequencies across sequences up to and beyond $V2_{MID}$ indicate strong vowel-dependent coarticulation of the word-medial consonant, consistent with results given in §4.2.3, *i.e.*, the whole sequence appears to be backed.

For KR, comparing /aka/ and /uka/, between $V2_{ON}$ and $V2_{MID}$ in prosodically weak /a/ (shown in Figure 52), the comparison is significant in F2 ($t(16)=2.70$, $p<0.05$). There is a 20Hz decrease in /aka/ and a 44Hz decrease in /uka/. /uka/ is lower in F2 frequency both at $V2_{ON}$ and $V2_{MID}$. As /uka/ is lower in F2 frequency throughout V1, this slightly lower frequency in V2 indicates carryover V-to-V coarticulation (thus, backing).

For RR, with regard to /aka/ and /aki/ and to /aka/ and /aku/ (shown in Figure 53) between $V1_{MID}$ to $V1_{OFF}$, comparisons are significant in F2 ($t(9)=-6.50$, $p<0.0001$; $t(11)=7.23$, $p<0.0001$, respectively; see Table 63). In /aka/ and /aki/, between $V1_{MID}$ and $V1_{OFF}$, /a/, in F2, there is a minimal increase in /aka/ and a 113Hz increase in /aki/. Apparent F2 raising in /a/ before /i/ suggests fronting. In /aka/ and /aku, between $V1_{MID}$ and $V1_{OFF}$, /a/, in F2, a minimal increase is observed in /aka/ and a 75Hz decrease in /aku/. This decrease appears to occur in anticipation of a low F2 frequency throughout V2 and thus indicates anticipatory V-to-V coarticulation. This lower F2 between $V1_{MID}$ and $V1_{OFF}$ might suggest backing (although recall that the velar stop may be causing some F2 lowering; see §4.2.3). All other comparisons are non-significant.

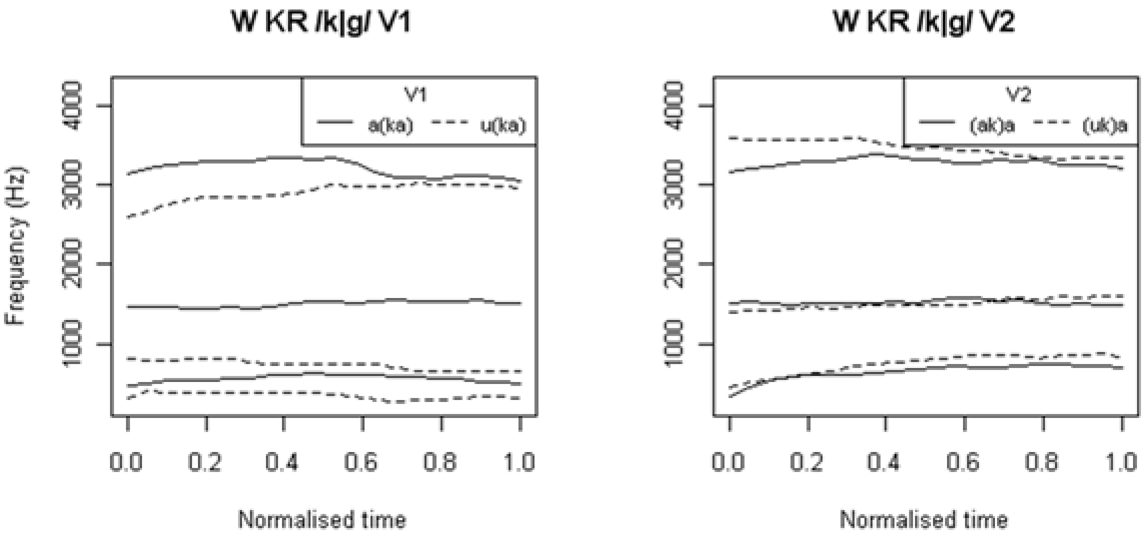

Figure 52. Plots for Warlpiri speaker, KR, /k/ across V1 and V2 in superimposed /Vka/ sequences. Two plots are superimposed: a) /aka/, b) /uka/. Note the y-axis upper limit of 4200Hz.

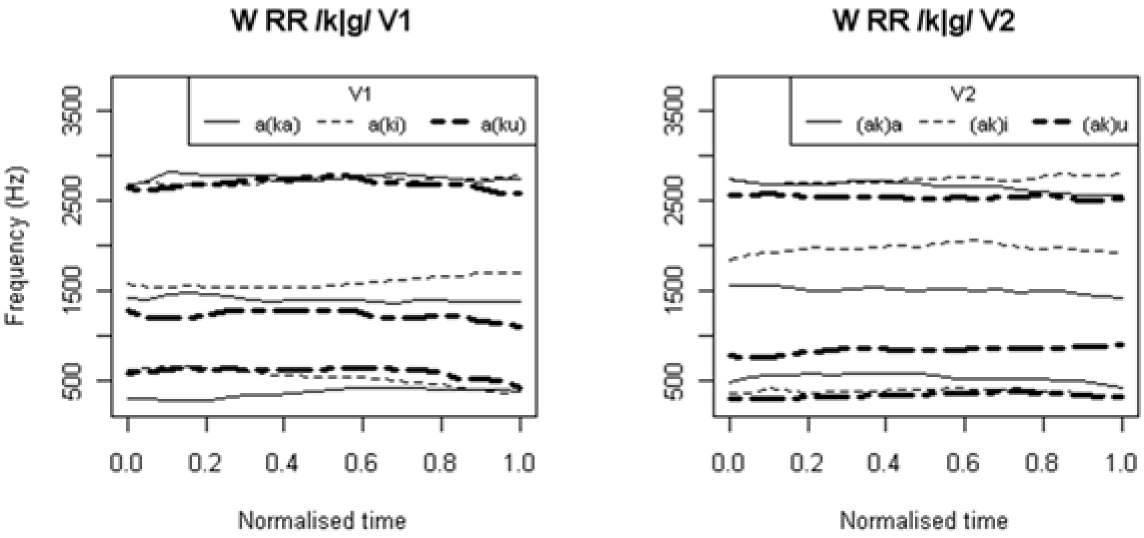

Figure 53. Plots for Warlpiri speaker, RR, /k/ across V1 and V2 in superimposed /VkV/ sequences. Three plots are superimposed: a) /aka/, b) /aki/ and /aku/.

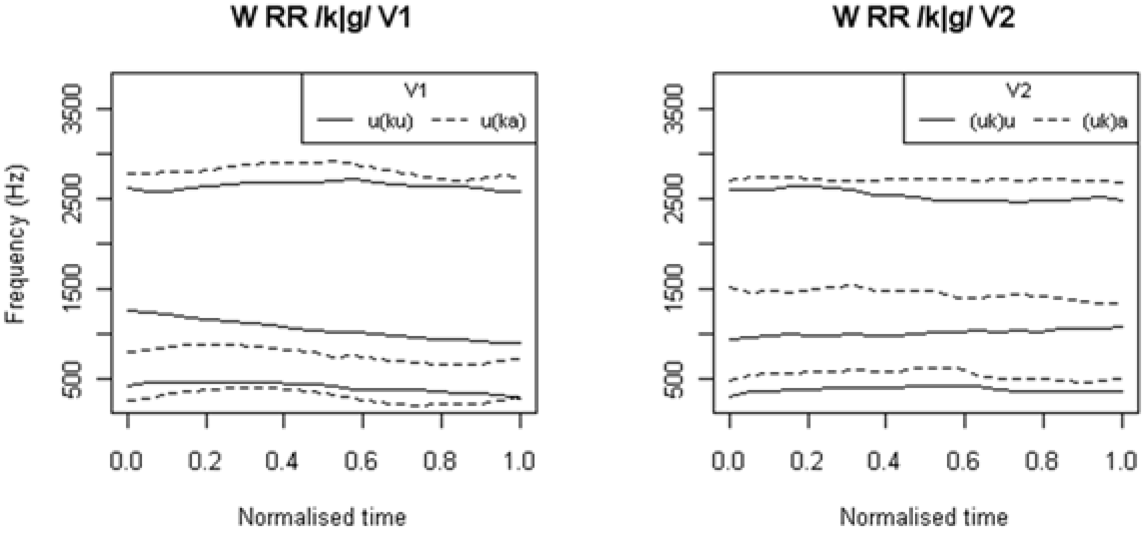

Figure 54. Plots for Warlpiri speaker, RR, /k/ across V1 and V2 in superimposed /VkV/ sequences. Two plots are superimposed: a) /uku/ and b) /uka/.

For RR, comparing /uku/ and /uka/, shown in Figure 54, between $V1_{MID}$ and $V1_{OFF}$ in /a/, the comparison is significant in F3 ($t(23)=7.02$, $p<0.005$). A 47Hz increase is observed in the /uku/ condition and a 230Hz increase in the /uka/ condition. F3 is higher throughout both vowels, which may indicate anticipatory V-to-V coarticulation (suggesting fronting). All other comparisons are non-significant.

In general, these F2 results for KR and RR for the velar stop are consistent with the finding in §4.2.3 that the velar varies greatly in F2 according to vowel context (as shown by high variability in vowels at vowel-velar stop boundaries) and therefore would permit some V-to-V coarticulation in F2.

6.2.3.4 Comparisons across word-medial consonant places of articulation

For the Warlpiri speakers, analyses are conducted for the target vowels /a u/ and the medial consonants /p t k/ in both V1 (a prosodically prominent vowel; at $V1_{MID}$, $V1_{EQ}$ and $V1_{OFF}$) and V2 (a prosodically weak vowel; at $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$) positions. Statistical results are tabulated in Table 64 and Table 65.

Target vowel /a/ in V1

According to Table 64, in comparisons conducted per speaker with the target vowel /a/ in V1 position, formant frequencies in the target vowel differ significantly as a function of flanking (V2) quality (BP, two levels: /a u/; KR and RR, three levels: /i a u/) and medial consonant place (three levels: /p t k/) in all formants for BP and KR and in F1 and F2 for RR. The results of post-hoc comparisons are tabulated in Table 65. With regard to vowel effects, for KR and RR, /u/ is associated with lower F2 formant frequencies than /a/. With regard to consonantal effects, for all speakers, the bilabial is associated with lower F2 formant frequencies than other stops, consistent with results reported in §4.2.1.5. In fact, for RR, all stops differ in F2 (the alveolar is associated with intermediate and the velar with high frequencies). For BP, the bilabial differs from other stops also in F1 and F3 (it is associated with intermediate F1 and low F3 frequencies), while for KR, the alveolar is associated with lower F1 frequencies than the bilabial stop and the velar is associated with higher F3 formant frequencies than the other stops. All other comparisons are non-significant.

Post-hoc comparisons in these word-medial /p t k/ environments indicate that for RR, the flanking vowel /u/ is associated with lower F2 formant frequencies in the target vowel than /a/. With regard to consonantal effects, in F1, for RR, the alveolar stop is associated with lower formant frequencies than the peripheral stops, while for BP, all stops differ (the alveolar is associated with low, the velar with intermediate and the bilabial with high frequencies). In F2, for all speakers, the bilabial is associated with low, the velar with intermediate and the alveolar with high frequencies (with the exception of /t k/ for BP), consistent with results reported in §4.2.1.5. For KR, all consonants also differ in F3 (the bilabial is associated with low, the alveolar with intermediate and the velar with high frequencies), while for BP, the velar is associated with frequencies intermediate between the bilabial and the alveolar stops. These consonant-dependent effects are generally consistent with the results reported in Chapter 4. All other comparisons are non-significant (or means do not differ in the expected direction).

Table 64. Warlpiri, summary of main effects in two-way ANOVAs for anticipatory and carryover V-to-V coarticulation and medial consonant place /p t k/ effects per speaker and formant. The comparisons are of formant frequencies at the three equidistant measurement points in the target vowel /a u/ across different /VCV/ environments per speaker and target vowel quality. p=*0.05, ** 0.01, *** 0.001.

		V1 a		**V2 a**		**V1 u**		**V2 u**	
Sp	**Formant**	**df**	**F**	**df**	**F**	**df**	**F**	**df**	**F**
BP	**F1**	**3,38**	6.7***	3,41	8.7***	N/A	N/A	N/A	N/A
	F2	**3,38**	24.04***	3,41	11.89***	N/A	N/A	N/A	N/A
	F3	**3,38**	36.36***	3,41	15.5***	N/A	N/A	N/A	N/A
KR	**F1**	**4,46**	5.347**	4,55	1.57	2,33	0.11	N/A	N/A
	F2	**4,46**	12.23***	4,55	27.21***	2,33	6.967**	N/A	N/A
	F3	**4,46**	13.68***	4,55	49.33***	2,33	1.28	N/A	N/A
RR	**F1**	**4,67**	5.2**	4,58	5.522***	N/A	N/A	2,33	2.116
	F2	**4,67**	28.86***	4,58	38.71***	N/A	N/A	2,33	3.7*
	F3	**4,67**	2.01	4,58	1.08	N/A	N/A	2,33	3.49*

Table 65. Tukey's post-hoc comparisons for Warlpiri speakers with reported significance level (p). The /i/-/u/ comparison is not given. The comparisons are of formant frequencies at the three equidistant measurement points across different /VCV/ environments per speaker and target vowel quality. ^ Means differ in the opposite direction to that expected. p=*0.05, ** 0.01, *** 0.001.

Sp	**Target V**		**F**	**C**			**Flanking V**	
	V1	**V2**		**p~k**	**t~k**	**t~p**	**a~i**	**a~u**
BP	**a**		**F1**	0.01**	0.45	0.001***	0.68	N/A
			F2	0.0001***	0.86	0.0001***	0.68	N/A
			F3	0.0001***	0.58	0.0001***	0.22	N/A
		a	**F1**	0.05*	0.0001***	0.05*	N/A	0.86
			F2	0.0005***	0.99	0.0001***	N/A	0.41
			F3	0.0001***	0.0001***	0.63	N/A	0.59
KR	**a**		**F1**	0.23	0.16	0.0005***	0.63	0.73
			F2	0.05*	0.1	0.0001***	0.99	0.05*
			F3	0.0001***	0.0001***	0.75	0.005**^	0.97
		a	**F2**	0.0001***	0.0005***	0.0001***	0.81	0.093
			F3	0.0001***	0.0001***	0.0001***	0.5	0.01**^
	u		**F2**	0.05*	N/A	N/A	N/A	0.05*^
RR	**a**		**F1**	0.69	0.47	0.89	0.067	0.0005***^
			F2	0.0005***	0.0001***	0.0001***	0.156	0.0005
		a	**F1**	0.15	0.05*	0.0001***	0.76	0.53
			F2	0.0001***	0.0001***	0.0001***	0.58	0.05*
		u	**F2**	0.2	N/A	N/A	N/A	0.05*^
			F3	0.05*	N/A	N/A	N/A	0.91

Target vowel /u/ in V1

According to Table 64, for KR, in comparisons conducted per speaker with the target vowel /u/ in V1 position, formant frequencies in the target vowel differ significantly as a function of flanking (V2) quality (three levels: /i a u/) and medial consonant place (three levels: /p t k/) in F2 only. Post-hoc comparisons show only that the bilabial stop is associated with higher F2 formant frequencies than the velar stop (with a difference in means of approximately 130Hz), consistent with results reported in §4.2. All other comparisons are non-significant.

Target vowel /u/ in V2

According to Table 64, for RR, in comparisons conducted per speaker with the target vowel /u/ in V2 position, formant frequencies in the target vowel differ significantly as a function of flanking vowel (V1) quality (three levels: /i a u/) and medial consonant place (three levels: /p t k/) in F2 and F3. Post-hoc comparisons indicate that the bilabial stop is associated with higher F3 formant frequencies than the velar stop (with a difference in means of approximately 140Hz). All other comparisons are non-significant. As in Gupapuyngu, there is no clear effect of prosodically prominence in the flanking vowel on the presence or absence of V-to-V coarticulation.

6.2.4 Vowel-to-vowel coarticulation – Arrernte

For the Arrernte speakers, only for speaker MM is more than one comparison of sequences with a shared target vowel possible (/apa/ ~ /ipa/ and /aka/ ~ /uka/). For speaker VD, one comparison is possible (/apa/ ~ /ipa/). Where available, results are reported first by place of articulation of the word-medial consonant, then by the quality of the target vowel. All Arrernte Welch-corrected t-test results are given in Table 66.

For Arrernte speaker, MM, /apa/ and /ipa/ are examined between $V2_{ON}$ and $V2_{MID}$ (CV) in prosodically weak /a/, as shown in Figure 55. In this case, the comparison is significant in F3 ($t(19)=7.18$, $p<0.0001$). The relatively low F3 frequencies in /i/ of /ipa/ are maintained into V2, indicating carryover F3 V-to-V coarticulation, although it is unclear whether this effect is exerted by the flanking vowel or the bilabial consonant (as seen in Burarra comparisons in §6.2.1.1). All other comparisons are non-significant.

For VD, for whom only this comparison is possible, with regard to /apa/ and /ipa/ between $V2_{ON}$ and $V2_{MID}$ (Figure 56), the comparison is significant in F2 ($t(21)=-2.79=p<0.05$). There is a 106Hz increase in the /apa/ sequence and only a 35Hz increase in the /ipa/ sequence. The /ipa/ sequence is associated with a higher F2 than the /apa/ sequence both in V1 and at $V2_{ON}$ and $V2_{MID}$, indicating carryover V-to-V coarticulation (fronting). All other comparisons are non-significant.

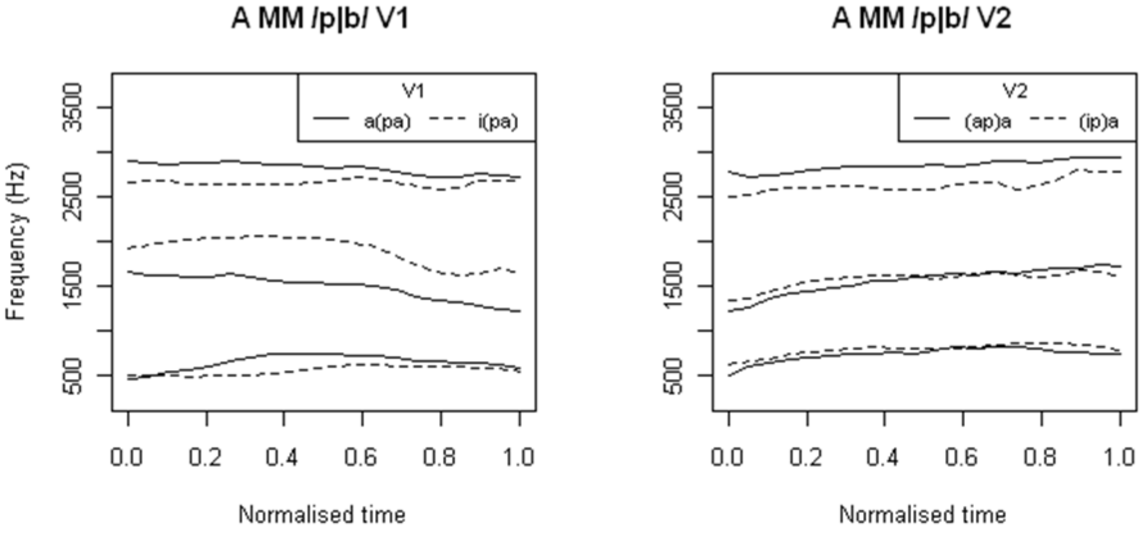

Figure 55. Plot for Arrernte speaker, MM, of the sequence /VpV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Two plots are superimposed: a) /apa/ and b) /ipa/.

Table 66. Arrernte, results of t-tests with Welch correction. Measurement points are $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$. p=* 0.05, ** 0.01, *** 0.001.

			t		
Sp	**V**	**C**	**F1**	**F2**	**F3**
MM	**aa-ia**	**p**	-1.31	0.6615	7.18***
	aa-ua	**k**	0.24	3.4732**	-0.18
VD	**aa-ia**	**p**	-2.13	-2.79*	-0.01

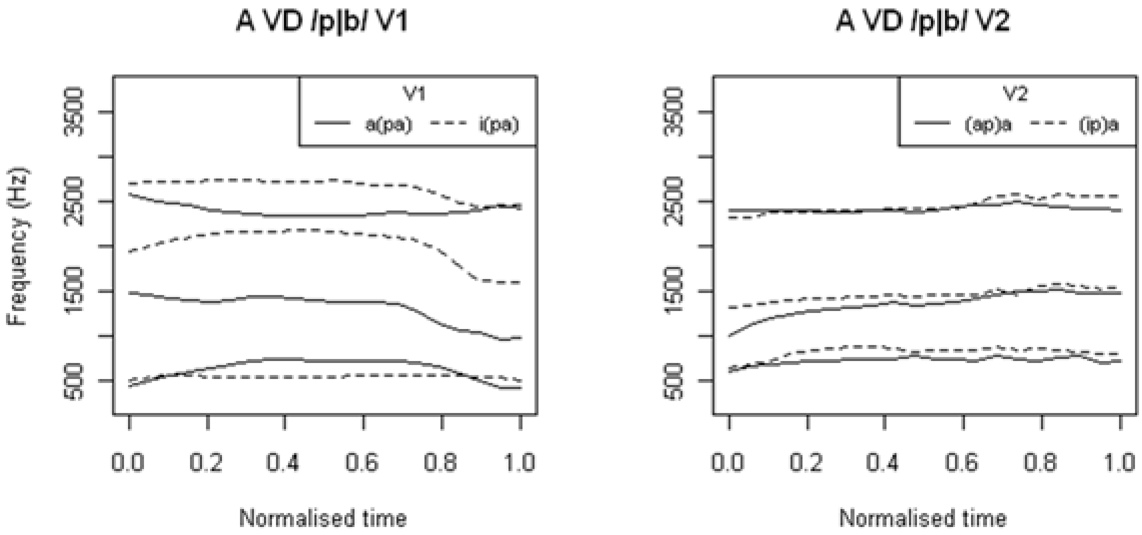

Figure 56. Plot for Arrernte speaker, VD, of the sequence /VkV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Two plots are superimposed: a) /apa/, b) /ipa/.

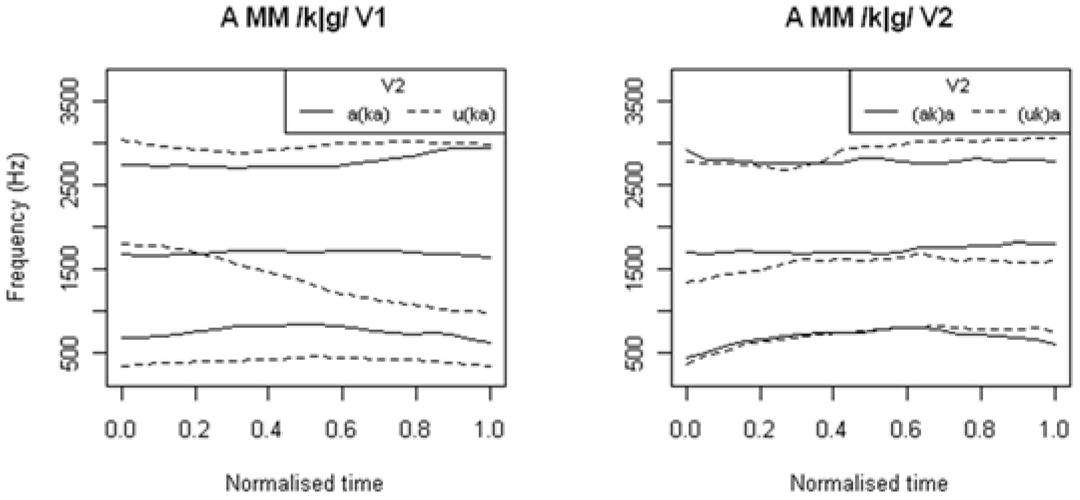

Figure 57. Plot for Arrernte speaker, MM, for the sequence /VkV/ and formants 1 to 3; (L) V1 or VC, (R) V2 or CV. On the x-axis, normalised time, and on the y-axis, frequency in Hz. Two plots are superimposed: a) /aka/, b) /uka/.

6.2.4.1 Velar stop

For MM, comparing /aka/ and /uka/, between $V2_{ON}$ and $V2_{MID}$ in prosodically weak /a/, shown in Figure 57, the comparison is significant in F2 (136Hz, $t(22)=3.47$, $p<0.005$). Within the first half of V2, there is a minimal decrease in /aka/ and a

128Hz increase in /uka/. Just as /uka/ is lower in F2 frequency during V1, it is lower in frequency in V2, although approaching /aka/ at $V2_{MID}$. This relatively low F2 frequency in V2 indicates carryover V-to-V coarticulation (suggesting backing). All other comparisons are non-significant.

6.2.4.2 Comparisons across word-medial consonant places of articulation

For MM, in the four sequences in which prosodically weak V2 is /a/ and V1 (prosodically prominent) varies, the measurement points being $V2_{ON}$, $V2_{EQ}$ and $V2_{MID}$ in /a/, formant frequencies in the target vowel (V2) differ significantly as a function of flanking vowel (V1) quality (three levels: /i/ /a/ /u/) and medial consonant place (two levels: /p k/) in F2 and F3 (F2, $F(3,44)=3.591$, $p<0.05$; $F(3,44)=9.495$, $p<0.0001$) but not in F1 ($F(3,44)=1.479$, $p<0.233$). Tukey's post-hoc comparisons indicate that in F2, the difference between medial consonants approaches significance at $p<0.07$. In F3, the flanking vowel, /a/, is associated with lower formant frequencies in the target vowel than /i/ ($p<0.001$) and the bilabial is associated with lower F2 and F3 frequencies than the velar ($p<0.01$). It is unclear whether this result for the consonants relates to the labialisation of the bilabial consonant in /p^{w}ap(a)/ [p^{w}ap^{w}a]. No other comparisons are significant.

6.2.5 Summary of results

6.2.5.1 Procedure 1: Results per word-medial consonant place of articulation

In this section, V-to-V coarticulation results conducted on pairs of sequences (generated by t-tests) are summarised with regard to the identity of the flanking and target vowels and to the place of articulation of the intervening consonant. Typically, V-to-V coarticulation was exerted by a close vowel rather than the low central vowel and V-to-V coarticulatory effects were only present in one formant, if any. Prosodically prominent flanking vowels did not appear to be more likely than weak vowels to exert V-to-V coarticulation.

In Burarra, when the intervening stop is bilabial, close vowels tend to induce carryover V-to-V coarticulation in the low central vowel sporadically in F1 (DP, MW) or F3 (KF, MW) (suggesting dorsum/jaw raising in the case of flanking vowel, /i/ and backing rather than lip rounding in the case of flanking vowel /u/). When the stop is retroflex, /u/ exerts carryover coarticulation in /a/ in F2 (all speakers) but not in F1 or F3 (suggesting a backing of the constriction). Carryover coarticulation tends not to be exerted across an intervening palatal stop by close vowels (with one exception pertaining to F1, suggesting dorsum/jaw raising).

In Gupapuyngu, when the intervening stop is bilabial, anticipatory coarticulation is possibly exerted by /u/ in /a/ F1 and F2 for AM and BT (suggesting raising and backing) but not for EG. Carryover coarticulation tends not to be exerted by a prosodically prominent /a/ on weak /u/ in any formant and there is strong inter-speaker variability in the context of /a/ exerting coarticulation on /u/; only for speaker AM is there significant evidence of such coarticulation, in F2 (fronting). When the intervening stop is alveolar, /u/ tends not to exert carryover coarticulation. When the intervening stop is velar, there is again evidence of inter-speaker variability; across the velar, when close vowels are the flanking vowel, for AM, coarticulation tends to occur sporadically only for /u/ on /a/ in F2 or F3 (suggesting constriction backing rather than lip rounding, given findings in §4.2.3 and §5.2). For BT, coarticulation is occasionally exerted by /u/ on /a/ in F2 (backing) and possibly on one occasion by /a/ on /u/, and by /i/ on /a/ in F1 and F2. For EG, coarticulation is possibly exerted by /u/ on /a/ in F3 only (suggesting backing rather than lip rounding), while /a/ may be exerting coarticulatory effects in F1, and possibly, F2 (suggesting gestural blending).

In Warlpiri, for KR and RR, when the intervening consonant is bilabial, coarticulation occurs only in the anticipatory direction and only in F2 (relating to anteriority). Coarticulation is not exerted by /i/ on /a/ across the alveolar stop. With regard to the velar stop, no significant coarticulation is seen for BP, while for KR and RR, coarticulation exerted by close vowels on /a/ occurs sporadically in F2 (suggesting a change in anteriority). Coarticulation tends not to be exerted by /a/ on /u/ across the velar stop (with the possible exception of /uka/ for RR, in F3).

In Arrernte, for MM and VD, coarticulation tends to occur in the higher formants in the context of close flanking vowels and intervocalic peripheral consonants. Furthermore, these peripheral consonants tend to differ in their coarticulatory effects on the target vowel in F3 (for MM; the bilabial exerts F3 lowering).

6.2.5.2 Procedure 2: Results across word-medial consonant places of articulation

Overall, in these results, word-medial consonant effects on the target vowel were both more frequent and more systematic than flanking vowel effects. With regard to flanking vowel effects across word-medial consonant places of articulation, for Burarra speakers, KF and MW, /u/ is associated with lower F3 formant frequencies than /a/ (carryover). For the Gupapuyngu speakers, /u/ is associated with lower F2 formant frequencies than /a/ (anticipatory and carryover) and, specifically, when V2 is the target vowel, /a/, /i/ tends to be associated with higher F2 formant frequencies than /a/ (carryover). When V1 is the target vowel, /u/, /a/ is associated with higher F1 formant frequencies than /u/ (anticipatory). For the Warlpiri speakers, /u/ is frequently associated with lower F2 formant frequencies than /a/ when /a/ is the target vowel (anticipatory and carryover). For Arrernte speaker MM, /i/ tends to exert V-to-V coarticulation in F3. In general, when V-to-V effects occur, they tend to be associated with the flanking vowel /u/ rather than /i/. However, this may reflect a difference in vowel distribution; there were very few /a i/ comparisons in the corpus.

With regard to the effects of the place of articulation of the intervocalic consonant on the target vowel (in that half of the vowel close to the vowel-consonant boundary), generalising across the four languages, the bilabial is associated with (relatively) intermediate F1, low F2 and low to intermediate F3 frequencies in the target vowel, while the velar is associated with intermediate or high F1 frequencies and relatively low F2 frequencies (there is no clear pattern in F3). The relationship between the peripherals varies and there may be some differences according to target vowel quality. The alveolar is associated with low to intermediate F1 frequencies and with intermediate F2 and F3 frequencies in the target vowel. The retroflex is associated with low F1 frequencies (but not as low as those associated with the palatal), with intermediate F2 frequencies and with the lowest F3 frequencies. The palatal is associated with low F1 frequencies and high F2 and F3 frequencies. For the most part, these findings are cconsistent with those reported in §4.2.

6.3 Discussion

In this chapter, it was examined whether V-to-V coarticulation occurs in these languages and whether there is an effect of intervocalic consonant place of articulation or flanking or target vowel quality. This section constitutes a discussion of the results of the present chapter with regard to the relevant research questions and hypotheses introduced at the beginning of the chapter.

The most clearly evident of the findings reported in this chapter is that formant transitions in target vowels are more likely to be dependent on the place of articulation of the intervocalic consonant than on the quality of the flanking vowel. Nevertheless, some evidence was presented of carryover trans-consonantal V-to-V coarticulation in Arrernte and Burarra and of both carryover and anticipatory coarticulation in Gupapuyngu and Warlpiri, confirming RQ4). Vowel-dependent coarticulatory effects were found in the full target vowels, /a/ and /u/ (the latter for Gupapuyngu speakers). In Gupapuyngu and Warlpiri, there is a tendency towards coarticulation in F2 rather than F1 or F3. This preference for F2 coarticulation is consistent with findings in a number of languages (e.g., Swedish: Öhman, 1966; Catalan: Recasens, 1984b; English: Fowler, 1981a,b; Fowler & Brancazio, 2000) and with the finding in Chapter 4 of greater vowel variability in the F2 plane. There are no clear trends for Burarra and Arrernte speakers. Further, there are no clear trends in terms of the direction of coarticulation.

The realisation of V-to-V coarticulation in this corpus is acoustically variable, as in studies of languages such as English (Brancazio & Fowler, 1998; Fowler and Brancazio, 2000). There is also evidence of inter-language and inter-speaker variability, for example, in the apparent relative timing of the onset of the V2 gesture, as far as can be ascertained on the basis of proportional, or linearly normalised, timing. However, a number of patterns can be observed in the four languages and these will be discussed in the following sections.

6.3.1 Effect of flanking vowel quality and measurement point on vowel-to-vowel coarticulation

This study has shown that close vowels can exert V-to-V coarticulation, and do so more often than non-close vowels, in accordance with RQ1) and H14). This asymmetry relating to segmental identity can be accounted for by Recasens' DAC model (see §2.2.1), according to which close vowels are more resistant to coarticulation (and therefore more coarticulation aggressive) because they involve more dorsum raising. Yet /a/, whether in V1 or V2, appears to induce coarticulatory effects in /u/ for some Gupapuyngu speakers, typically across the velar.[62] That the velar would allow such V-to-V coarticulation is not surprising given that velar stops exhibit strong vowel-dependent F2 effects (§4.2.3). It was not found that /a/ is more likely to be coarticulated by /i/ than /u/, although /i/ appears to be more resistant to coarticulation (as demonstrated in preceding chapters; in agreement with, e.g., Butcher, 1989, in English). This is likely due at least in part to the low frequency of /i/. It appears that /i/ can exert fronting and raising effects in /a u/, and /u/ can exert raising and backing effects in /a/. For the Gupapuyngu speakers (and possibly Warlpiri speaker, RR), /a/ appeared to be capable of exerting fronting and lowering effects on /u/.[63]

With regard to the question of whether V-to-V coarticulation is more evident closer to the word-medial consonant boundary than further away, while some

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[62] It is not unknown for close vowels to undergo coarticulation exerted by /a/ (see, e.g., Butcher, 1989, on English). When /a/ exerts V-to-V coarticulation in at least one formant, it is occasional (occurring no more often than in 50% of possible cases), it is on /u/ and the speakers are Gupapuyngu speakers (with one exception, the sequence /uka/ for Warlpiri speaker, KR).

[63] It is presumed that /u/ is not necessarily a rounded vowel given the findings reported in §5.2 and the literature discussed in §1.2 and elsewhere.

perturbation is seen at the VC and CV boundaries, the proposition in RQ4) can be confirmed; the normalised trajectories between adjacent vowels indicate that the VCV sequence cannot be regarded as a linear sequence of three successive gestures but rather as a number of coproduced gestures, where consonantal gestures are superimposed onto continous, overlapping, vowel articulations (Öhman, 1966, p. 165; Fowler, 1983; Browman & Goldstein, 1987; amongst others). Consequently, the experimental findings of this study are interpreted as supporting the predictions of a coproduction model. Moreover, the DAC model appears to account well for variability in coarticulatory overlap in this study (as in Fowler & Brancazio, 2000). Further claims as to the relative timing relations of gestures cannot be made on the basis of these acoustical analyses. The results are consistent with the findings of Recasens (1999) and Fowler and Brancazio (2000) amongst others that vowel-dependent coarticulatory effects may be present both in the transition and also extending back into the steady state portion of the vowel. The movement within a flanking vowel towards a following target vowel in some cases commences at the onset of V1 rather than at the midpoint (e.g., in F2 in /apu/ for Gupapuyngu speakers, AM and BT).

6.3.2 Effect of consonant place of articulation on vowel-to-vowel coarticulation

With respect to RQ5) concerning word-medial consonantal modulation of V-to-V coarticulation and to H15) regarding the effects of consonant place on such coarticulation outweighing any flanking vowel effects, in the present study, the target vowel was more frequently and systematically affected by the place of articulation of the word-medial consonant than by the quality of the trans-consonantal vowel.[64] The majority of target vowels, whether prosodically prominent or otherwise, were seen to reflect the acoustic properties of the adjacent consonant and not the flanking vowel. Clear and consistent effects of word-medial consonant place of articulation were shown on the target vowel not only close to the consonant boundary but also further into the vowel (as for, e.g., Swedish: Öhman, 1966; American English: Fowler & Brancazio, 2000). This is highly consistent with the finding in the preceding chapter that word-medial consonant place has a

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[64] Incidentally, with regard to the coarticulatory effects of consonants other than those in word-medial position on vowel-to-vowel coarticulation, in this chapter, it was observed in <yapa> /japa/ 'sister', produced by Gupapuyngu speaker, BT, that C1 can affect both V1 and V2 in C1V1C2V2 words. The palatal place of articulation is particularly coarticulation resistant and aggressive for the speakers in this study. For Tilsen (2007), this long distance effect suggests that the extent of carryover coarticulation is restricted by the speech planning mechanism (*i.e.*, a cognitive mechanism) and not merely by biomechanics (*cf.* Recasens, 1984b; 1987). (See Magen, 1997, on long distance coarticulation between vowels.)

significant effect on vowel realisation in F1 and F2 *at vowel midpoints*. Thus, the claims made in H15) and that underlie RQ5) and additionally RQ1) regarding the effect of consonant place (and vowel quality) on coarticulation, are supported. These consonantal effects are consistent with the results reported in the preceding chapters.[65] They are also consistent with the literature on the relative importance of perceptual cues to consonant place and cues to vowel quality in these languages (*i.e.*, consonant cues are more protected; see §2.1.2.3).[66] Additionally, they are consistent with the literature on consonantal effects on V-to-V coarticulation (Fowler, 2005; Fowler & Brancazio, 2000; Cole *et al*., 2010, amongst others). The finding of more prominent consonant-dependent than vowel-dependent effects is consistent with Recasens' claim that in VCV sequences, a highly constrained medial consonant will exert strong C-to-V coarticulatory effects so as to ensure that the consonantal gesture is successfully realised, and will interfere with any (V-to-C and) V-to-V effects, and more generally, a consonantal gesture will override or dominate an adjacent vocalic gesture if the two are antagonistic (e.g., Recasens, 1984a,b).[67] Given that this pattern was found for the majority of the places of articulation, it appears that the DAC values of these consonants are relatively high *i.e.*, consonants are relatively coarticulation resistant, despite findings of a high degree of vowel-to-consonant coarticulation in §4.2.1. The particular interaction between consonant places of articulation and vowel qualities (hence, constraints on variability) that obtains in these Australian languages would necessitate a modification of the basic DAC values (see, in particular, Recasens *et al*., 1995).

The acoustical effects of the word-medial consonant on the target vowel tend to be strongest in F2 - as indicated by the consonant-dependent coarticulation results reported in §4.2 (see discussion in §4.3.1) and in §5.2, and as found by, e.g., Fant (1960), Purcell (1979), Recasens (e.g., 1984a) and Cole *et al.* (2010), F2

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[65] In Chapter 4 it was clearly shown that some consonant places of articulation, such as the palatal, are associated with a smaller degree of coarticulatory sensitivity than others, *i.e.*, greater coarticulation resistance, and that some, such as the palatal and the retroflex, tend to exert strong C-to-V coarticulation. Further, the particular formant changes associated with the coarticulatory influence of the consonant place are in accord with those seen in Chapter 4 (and are consistent within language groups), for example, the palatal was associated with lower F1 and higher F2 formant frequencies in the target vowel than the bilabial stop and the bilabial was associated with relatively low F2 and F3 frequencies in the target vowel, relative to, say, the alveolar stop.

[66] It should be pointed out that in many cases there may be anticipatory or carryover V-dependent coarticulation but it commences or ends during the consonant interval rather than during the target vowel and so cannot be measured acoustically.

[67] Given the nature of the corpus, the question of whether the magnitude of V-to-V coarticulation is dependent on the magnitude of C-to-V and V-to-C coarticulation cannot be answered at this stage in this research. The corpus does not permit control over the identity of the word-initial consonant (which it has been shown in this chapter can affect not only V1 but also V2), and does not include tokens for many consonant and vowel combinations within CVCV words.

being inversely related to tongue dorsum backing and the degree of tongue dorsum (or linguo-palatal) contact - followed by F3 and finally F1. It is in the point of constriction along the vocal tract and therefore in F2 and F3 transitions that the phonetic basis of place of articulation contrasts is known to reside (Delattre *et al.*, 1955).

Further, there is some weak preliminary evidence in favour of RQ5) regarding the blocking of V-to-V coarticulation by intervening relatively high resistant consonants, such as palatal stops, as predicted by the DAC model (see §2.2.1; e.g., Recasens, 1984b; 1986; Recasens *et al.*, 1997; Fowler, 2005), but the effect of coarticulation resistance was not consistent. Recall that Fowler and Brancazio (2000) also found only weak evidence that there is a higher magnitude of V-to-V coarticulation across low resistant consonants than high resistant ones in American English. In accordance with Fowler and Saltzman (1993) and coproduction theory as a whole, it appears that lingual consonants can function as an articulatory barrier to other simultaneous gestures, such that the V-to-V gesture may reemerge further into the vowel when this gesture becomes predominant. As in Recasens (1984b), this barrier effect was observed to some extent in both the anticipatory and carryover directions. As such, in combination with the results reported in the previous chapters, there is some evidence in this study that coarticulation resistance and coarticulatory aggressiveness vary positively (as seen in studies of non-Australian languages, e.g., English: Bladon & Nolan, 1977; Fowler, 1981a,b; Catalan: Recasens & Espinosa, 2009a,b,c). In these results, any barrier effect was more observable at the onset of V2 as strong output constraints for the alveolar, retroflex and palatal stops appeared to delay the reemergence of V-to-V coarticulation.

When V-to-V coarticulation does occur, it is most likely to occur across the peripherals. However, in German, Butcher and Weiher (1976) found that dorsal consonants allow less trans-consonantal coarticulaton than non-dorsal ones, such as bilabials. The bilabial consonant typically, cross-linguistically, has no lingual specification, and so the tongue is free to conform to an underlying V-to-V gesture but, of course, the labial gesture associated with the consonant may affect all three formants in neighbouring vowels. In the present study, the velar was shown in §4.2.1 and in §4.2.3 to be highly susceptible to vowel–dependent effects and was highly context-sensitive in the F2 dimension. The relative lack of coarticulation across the coronals is consistent with the findings presented in Chapter 4. It may be due to several factors: mutual gestural incompatibility, and relatedly, relatively high coarticulation resistance (e.g., Recasens, 1984a,b). Coronals appear to be articulatorily dominant consonants that have relatively strong lingual specifications.

The lingual gestures of the retroflex and the palatal in particular appear to place great constraints on the tongue dorsum so that this particular set of muscles cannot be utilised by the ‘vowel articulatory system’ (in a broad sense; see §2.1.2).

A comment should be made on the implications of the large number of comparisons in which the direction of the difference was the opposite of that indicating V-to-V coarticulation, which were particularly evident in Gupapuyngu (Table 59) but also in Warlpiri (Table 63). It appears likely that these patterns are due to consonant-dependent coarticulation (specifically, medial consonant-flanking vowel interaction, and perhaps word-initial consonant effects), which was shown to be widespread in the analysis of variance results (as supported by the findings presented in Chapter 5 on the effect of word-medial consonant place on neighbouring vowels). Additionally, they may be due to word-final or pre-boundary vowel lowering effects (Chapter 5). It is not possible to make any further comments at this stage.

6.3.3 Effects of word position and prosodic prominence on vowel-to-vowel coarticulation

No consistent effect of prosodic prominence and word position on trans-consonantal V-to-V coarticulation was observed in the results presented in this chapter, counter to the claim impicit in RQ3) and consistent with findings presented in Chapters 4 and 5. These results are also consistent with those reported by Fletcher (2004) and by Mok and Hawkins (2004), who did not find that vowels in English, Cantonese and Mandarin were typically more likely to undergo vowel-dependent coarticulation by a stressed than an unstressed vowel (but *cf.* Fowler, 1981a; Cho, 1999; 2004; Mok, forthcoming). In this and preceding chapters, there is little evidence that the phonetic correlates of stress in these Australian languages include vocalic (spatial) hyper-articulation, at least in the context of citation form words.[68]

6.3.4 Effects of inventory size and vowel space crowding on vowel-to-vowel coarticulation

With respect to RQ2), which states that language-specific inventory differences explain some differences in coarticulation patterns, in these results, there is no predictable effect of vowel inventory size or vowel space crowding on V-to-V coarticulation (consistent with Mok & Hawkins, 2004; Mok, forthcoming; but *cf.*

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[68] It may be speculated that word-medial consonants carry prosodic prominence in these languages (Butcher & Harrington, 2003; see §2.4). Additionally, it may be that prosodic prominence in vowels is reflected more in duration or amplitude than in formant frequencies, at least in languages other than Burarra (see, e.g., Beddor *et al.*, 2002). Hence, it appears that any coarticulatory resistance displayed by vowels such as /i/ should be attributed to inherent articulatory (dorsal) constraint rather than prosodically induced articulatory strengthening.

Manuel, 1990; 1999; see §2.3.2). It is likely that the four languages in this study are too similar in their vowel inventories to show such effects (see also §5.3.2). Furthermore, there is insufficient evidence of an effect of the number of coronal categories on the magnitude of V-to-V coarticulation across a coronal stop (RQ2)), consistent with the findings in Chapter 4.

6.4 Conclusions

In this chapter, it has been demonstrated that while trans-consonantal vowel-to-vowel coarticulation occurs in these languages, vowel coproduction is strongly modulated by the intervocalic consonantal gesture; consonant place of articulation is reflected in the target vowel both near the consonant boundary and at the vowel midpoint. This pattern is consistent with previous findings that there is a strong imperative to protect place of articulation distinctions in Australian languages, especially in word-medial consonants (see, e.g., §2.1.2.3). There is no clear trend with regard to the direction of trans-consonantal V-to-V coarticulation. In the next chapter, general conclusions will be drawn.

7 Conclusions

The primary goal of this dissertation was to investigate the acoustics of spatial coarticulation between consonants and vowels and between vowels across an intervening consonant in Australian languages. Accordingly, spectral data was analysed in various consonant place of articulation and vowel quality environments in the speech of three speakers of each of four languages: Arrernte, Burarra, Gupapuyngu and Warlpiri. The results of the study will be summarised in the following sections and the principal implications will be discussed.

7.1 Consonant-vowel coarticulation

A major aim of this dissertation was to identify the effect of consonant place of articulation on consonant-vowel coarticulation, while taking into account factors such as language, prosodic prominence and trajectory period (the relative position of the consonant and vowel). The primary research question, RQ1), concerned whether consonant place of articulation or vowel quality determines the extent to which a segment is coarticulated (*i.e.*, the extent of coarticulation resistance), and by extension, whether consonant place or vowel quality determines the extent to which a segment exerts coarticulation (*i.e.*, the extent of coarticulatory aggressiveness) in Australian languages. In the experiments presented in Chapter 4, it was shown that the magnitude of vowel-to-stop coarticulation is indeed dependent on the consonant place of articulation. Peripheral (*i.e.*, velar and bilabial) stops underwent more coarticulation than non-peripheral (alveolar, retroflex and palatal) stops, and palatal stops tended to undergo least coarticulation. V-to-C coarticulatory effects appeared to decrease inversely with the degree of tongue-dorsum constraint for /k/ > /p/ > /t/ > /ʈ/ > /c/, consistent with the DAC model (Recasens *et al.*, 1997; Recasens & Pallarès, 2001). Moreover, variability for the consonant in the vowel at the vowel-consonant boundary (as reported in Chapter 4) appeared to reflect coarticulatory sensitivity and tended to decrease in the same order; the peripheral stops were associated with more variability in neighbouring vowels at vowel-consonant boundaries and were thus more context-sensitive than non-peripheral stops. In general, the results were consistent with the claim of a positive correlation between coarticulation resistance and aggressiveness as proposed by the DAC model, e.g., /c/ is both relatively resistant to coarticulation and tends to exert a high degree of coarticulation in these languages. These results indicate a strong imperative to preserve place of articulation contrasts, particularly in word-medial consonants, as demonstrated and discussed in many studies by Butcher and colleagues (e.g., Butcher, 2006; Fletcher *et al*., 2007b; 2010).

In the particular case of the retroflex place of articulation, it was demonstrated that the stop is associated with an intermediate to high resistance to vowel-dependent coarticulation, presumably because a typical retroflex stop in these languages involves dorsum raising and a complex and precise tip/blade articulation. Anticipatory consonant-to-vowel effects in /a/ exceeded carryover effects. As predicted, the pre-palatalisation of apicals was evident in low central vowels in word-initial contexts for some Arrernte speakers (two of three), and there was an absence of such pre-palatalisation in Burarra, Gupapuyngu and Warlpiri. For the speakers of non-Arandic languages, the retroflex stop was associated with F3 lowering (retroflexion) in the preceding vowel. As for the palatal stop, this consonant tended to be relatively coarticulation resistant, typically undergoing little vowel-dependent coarticulation, allowing little variation in adjacent vowels, exerting strong C-to-V coarticulation, particularly in F2, and modulating V-to-V coarticulation. As in the case of the retroflex consonant, anticipatory consonant-to-vowel effects exceeded carryover effects, but there was also a strong carryover component, presumably associated with the strong biomechanical constraints for the consonantal gesture. It is widely accepted that palatals impose a high degree of articulatory constraint on the tongue body (e.g., Recasens, 1984a,b).

With regard to peripheral (velar and bilabial) stops, it was suggested that these consonants are weakly coarticulation resistant because the velar stop varies markedly in constriction location according to adjacent vowel quality and the bilabial stop is known to allow more tongue body coarticulation than lingual consonants. Experimental support was provided for the claim that velar stops vary in the anteriority of the constriction according to the target of the following vowel in Australian languages (e.g., Butcher & Tabain, 2004) as in languages such as Swedish and American English (Öhman, 1966; Kent & Moll, 1972). In other words, velars are minimally resistant to coarticulation by vowels. It was demonstrated in Chapter 4 that F2 frequency at the onsets and midpoints of vowels following velar stops increases almost monotonically for the vowels /u/ < /a/ < /i/ and thus that the location of the velar constriction differs in the backing/fronting dimension according to the following vowel target, indicating that gestural blending is involved. The velar stop is post-velar or even uvular when it precedes back vowels, fronted when it precedes front vowels, and approximately intermediate preceding central vowels. Hence, there appear to be three distinct vowel allophones in each of the four languages. In the context of front and low central vowels, consonant-vowel coarticulation was maximal, but in the context of back vowels, for the Burarra, Gupapuyngu and Warlpiri speakers, the location of the velar constriction was posterior to that of the vowel target. This indicated a very retracted constriction location with sub-maximal coarticulation (e.g., Recasens, 2006; Recasens & Espinosa, 2006b). As to the coarticulatory behaviour of peripheral stops more generally, in the experiments presented in Chapter 4 and secondarily in Chapter 6, consonant places of articulation were seen to be divisible into two main categories with respect to coarticulation: peripheral and non-peripheral, consistent with the results reported for the F2 dimension by Fowler and Brancazio (2000). The primarily phonological peripheral/non-peripheral distinction in the Australian literature is thus supported by strong phonetic evidence, which demonstrates that acoustic phonetic techniques can be used to confirm phonological categories. This distinction is in line with the [+/-coronal] and [+/-grave] features in Jakobson, Fant and Halle's (1952) Feature Theory and Ohala's ideas on the misperception of velars/bilabials (e.g., Ohala, 1981, pp. 192-193).

With regard to a general trend in the direction of vowel-to-consonant coarticulation, it was demonstrated that anticipatory vowel-to-consonant coarticulation exceeds carryover coarticulation, at least for the non-Arandic languages. (The broad claim of a general avoidance of anticipatory coarticulation, discussed in §1.4, was not supported by the results.) Thus, in the present study, some support was provided for the word-medial consonant strengthening hypothesis (see §1.4 and §4.3.2) and for the claim of tighter control in the VC trajectory period than in the CV period, and therefore, according to Tabain *et al.* (2004), for an underlying VC or VC(C) structure in all four Australian languages and not merely in Arrernte. However, on the F2 variability (or variance) measure of context-sensitivity there was insufficient evidence of a *cross-linguistic* bias in trajectory period, as was found by Tabain *et al*. (2004) for Arrernte, Yanyuwa and Yindjibarndi. The findings, when considered as a whole, certainly do not demonstrate a CV bias, at least in bi- or tri-syllabic words, and thus, on the view of Breen, Butcher, Tabain and colleagues (e.g., Breen, 1991; Breen & Pensalfini, 1999; Tabain *et al*., 2004), this dissertation provides evidence against the claim that underlying CV syllables are universally unmarked.

A minor question concerned whether it is appropriate to draw a link between coarticulation resistance and the LE with regard to Australian languages. In the set of experiments presented in Chapter 4, it was possible to draw a link between coarticulation resistance and the LE, and between (i) consonant place of articulation and (ii) relative magnitudes of coarticulation and coarticulation resistance, more specifically. The results support the claim that this link holds universally and not merely with regard to commonly studied European languages, consistent with the arguments made by Fowler and colleagues (Fowler, 1994; Brancazio & Fowler, 1998; Fowler & Brancazio, 2000; Iskarous *et al*., 2010) on the basis of both acoustic and articulatory data (see §2.1.2).

With regard to the effect of language on consonant-vowel coarticulation, while the coronal consonant inventories of Burarra and Warlpiri are similar, and the overall consonant inventories of Arrernte and Gupapuyngu are similar, it is Gupapuyngu and Warlpiri that behave more similarly with regard to coarticulation, which is inconsistent with RQ2) on the matter of whether the number of coronal categories in the inventory appears to affect the magnitude of consonant-vowel coarticulation. Further examinination is needed using some kind of direct articulatory investigation.

To conclude, these results constitute important additions to the literature particularly with respect to the role of consonant place of articulation in coarticulation, to the effect of trajectory period (the relative position of the consonant and vowel) on the magnitude of consonant-vowel coarticulation, and to the relationship between consonant place of articulation, context-sensitivity and F2 consonant loci.

7.2 Vowel variability and dispersion and vowel-to-vowel coarticulation

The more vowel-focused experiments in this dissertation pertained to (i) vowel variability and dispersion, and (ii) vowel-to-vowel coarticulation. The experiment concerning vowel variability and dispersion was performed with the aim of quantifying spectral patterns and spectral variability in vowels in order to inform the subsequent experiment on vowel-to-vowel coarticulation. The results also inform a more general question concerning the factors of word-medial consonant place and prosodic prominence or word position in vowel production in the four languages. In support of RQ1) with regard to whether the quality of a vowel determines the extent to which it is coarticulated by an adjacent segment, in the experiment presented in Chapter 5, /i/ was seen to be the most peripheral and least variable and thus context-sensitive of the three point vowels (see §2.2), as was also suggested by the /ki/ ~ /ci/ comparison results reported in Chapter 4. Across the three experimental chapters, the degree of coarticulatory sensitivity in vowels appeared to decrease inversely with the degree of tongue dorsum constraint for /a/ > /u/ > /i/ as predicted by the DAC model. /i/ is known to be more resistant than most other vowels to consonant-dependent coarticulatory effects in many languages, such as Catalan (Recasens, 1985) and American English (Stevens & House, 1963). With regard to the acoustic vowel spaces as a whole, the languages displayed sufficient distinctiveness with some overlap, in accordance with the claims made by Butcher and colleagues (Butcher, 1994; Fletcher & Butcher, 2003; Fletcher *et al.*, 2007a,b). Further support for the claim implicit in RQ1) with regard to consonant-dependent coarticulatory effects was provided by the finding in Chapter 5 that word-medial consonant place of articulation has a significant effect on F1 and F2 formant frequencies at vowel midpoints.

The second major aim of this dissertation was to identify and describe patterns in vowel-to-vowel coarticulation in order to analyse whether, as has been found for English, Catalan and Swedish, there is V-to-V coarticulation that is modulated by the place of articulation of the intervening consonant and by the quality of the flanking vowel. In the final experiment (Chapter 6), trans-consonantal V-to-V coarticulation was investigated with special attention to the effects of the place of articulation of the intervening consonant. The primary research question concerned whether or not V-to-V coarticulation occurs in Australian languages, suggesting an underlying vocalic diphthongal gesture (RQ4)). The secondary research question concerned whether (i) this coarticulation is modulated by the place of articulation of the intervening consonant and (ii) whether a high coarticulation resistant consonant can be seen to block such coarticulation (RQ5)). The results of the experiment provided some evidence of V-to-V coarticulation, which was typically induced by close vowels, in support of RQ4) and of RQ1) with regard to the relationship between vowel quality and coarticulatory aggressiveness. In accordance with a coproduction model (Bell-Berti & Harris, 1979; 1981; 1982), it appeared that the strength of this V-to-V coarticulation increased in a gradual manner closer to the consonant boundary (as far as could be ascertained on the basis of proportional timing).[69] Confirming RQ5) with respect to modulation, word-medial consonant place of articulation was seen to systematically modulate V-to-V coarticulation, especially in F2 (associated with anteriority and dorsal constraint),[70] as found by, e.g., Öhman (1966), and as is consistent with the finding in Chapter 5 of an effect of word-medial consonant place on neighbouring vowels that is

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[69] Given constraints on the scope of this dissertation, temporal coarticulation could be considered only in a very preliminary manner.

[70] It should be pointed out that any claims about the relationship between C-to-V and V-to-V coarticulation are preliminary, and a more systematic analysis will be carried out in future research. Such an analysis would also clarify the issue of the relationship between coarticulatory sensitivity and the size of the coronal stop inventory.

stronger in F2 than in F1. The effects of the word-medial consonant in the vowel-to-vowel coarticulation analysis included both short and long distance effects. In other words, the analyses were successful in relating the majority of the variation in F1, F2 and F3 frequencies in the target vowel to variation in consonant place of articulation (consistent with findings presented in Chapter 5). Moreover, there was some preliminary evidence of (predominantly coronal) consonants blocking V-to-V coarticulation. Overall, V-to-V coarticulation appeared to be limited because of the need to preserve word-medial consonant place information, in accordance with the 'place of articulation imperative' (e.g., Butcher, 1995; 2006). Drawing together these and previous results, it appears that when there is articulatory conflict between an adjacent consonant and vowel, the consonantal gesture overrides the vocalic one, thus supporting the claim that in trans-consonantal vowel-to-vowel coarticulation, consonantal gestures are superimposed onto continuous, overlapping, vocalic gestures.

With regard to the question of whether prosodically prominent vowels are more likely to exert coarticulation and less likely to undergo coarticulation in Australian languages, all else being equal (RQ3)), the experimental findings reported in Chapters 4, 5 and 6 support the notion that the spatial effects of prosodic prominence on the nucleus are not strong in these languages, unlike the effects shown in English. This finding is in accordance with the literature on post-tonic strengthening and lengthening in Australian languages such as Warlpiri. As Butcher and Harrington (2003) suggest, the articulatory strengthening or hyper-articulation of the word-medial consonant (and not of the vowel, as in English) would have the effect of 'enhancing the greatest number of contrasts in [the] phonemic system' (p. 324). However, an interaction between consonant place and prosodic prominence was reported, which indicated that for /t c k/, less vowel-dependent coarticulation occurred when the vowel was weak, as might be predicted. Further, as was shown in §5.2.2, an effect of prosodic prominence on Burarra vowel space dispersion indicated some prosodically-driven hyperarticulation, consistent with the fact that unstressed vowels may be reduced or elided completely in certain environments in this language (Butcher, 1996; 2006; as discussed in §1.2.2.2).

7.3 Closing remarks

With regard to the wider implications of the dissertation, the findings provide support for Recasens' (e.g., Recasens *et al.*, 1997) DAC model within the framework of coproduction models of coarticulation. Considerable support is provided for a claim of systematicity in the relationship between place of articulation, coarticulation and coarticulation resistance, as in the DAC model. It has been shown that this model can account for the relative magnitudes of coarticulation resistance and aggressiveness displayed by alveolar, retroflex, palatal, bilabial and velar stops in these languages. Further, the findings are consistent with the claim that the model is able to account for a large number of articulatory types and patterns, and for other types of variation that lead to cross-linguistic differences in coarticulation, such as variation in the realisation of prosodic prominence (Recasens, 1985; 1986; Recasens *et al*., 1997). Recall that DAC values are modifiable, in the manner that Recasens *et al.* (1995; 1997) propose, on the basis of language-specific articulatory patterns and constraints on variability. Support is also provided for a claim concerning the coproductive nature of speech production as formalised in a coproduction model; the findings are consistent with the view that articulatory gestures are coordinated and thus the vocal tract responds at any one time to commands for more than one segment (Manuel, 1999, p. 182). Moreover, in providing evidence for the 'place of articulation imperative' (e.g., Butcher, 1995; 2006) and for the claim that prosodically-driven hyperarticulation occurs in Burarra, evidence has been provided for the theory of 'adaptive variability' (Lindblom, 1983; 1989; 1990), in which the speaker adapts his or her speech production to the perceptual demands of the hearer.

This dissertation raises a number of questions that should be addressed in future research. It is clear that there is a need for a planned consonant-vowel and V-to-V coarticulation study in Australian languages in order to confirm the role of word-medial consonant place of articulation in modulating coarticulation. Such a study would also provide further evidence for the claim that 'V-to-V coarticulation proceeds according to contrasting degrees of constraint associated with gestures for adjacent phonemes', which as Recasens argues, needs to be tested with data from a good sample of languages (Recasens, 1986, p. 85). Additionally, it is important that articulation and perception studies be carried out to inform some of the discussions in this work, particularly to elucidate the relationships between coarticulation, kinematics, articulatory timing, and syllable structure, e.g., to demonstrate a true VC syllable bias, and to provide more information as to the articulatory characteristics of retroflexes and palatals in these languages.

It has been suggested that prosodic context (beyond prosodic prominence as considered thus far) in addition to the fortis/lenis distinction and duration in the word-medial consonant are likely to affect coarticulatory patterns in these languages. These factors should be investigated thoroughly in order to confirm and extend the results of previous experiments in showing that the majority of the durational and spectral contrasts may be found in the word-medial consonant in Australian languages. Temporal and prosodic factors that should be considered are vowel duration or lengthening (particularly domain-finally, to confirm the suggestion made in Chapter 5 that /a u/ may be more open word-finally because of pre-boundary lengthening) and higher level prosodic boundary effects. Ideally, the factors of prosodic prominence and word position or position-in-utterance should be separated. A temporal analysis will allow more to be said concerning coarticulation theories and the predictions of various coarticulation models. Future studies should also investigate the differences in consonant-vowel coarticulation that occur when consonantal manner is varied in these languages. As the work of Recasens (e.g., 1991; 1997; Recasens & Pallarès, 2001; Recasens & Espinosa, 2006; 2009) and others has shown, even within the same place of articulation, articulation strategies and sensitivity to coarticulatory effects can differ markedly according to manner requirements.

In sum, on the basis of the results reported in this dissertation, it can be argued that coarticulatory processes in Australian languages are largely governed by the need to maintain perceptual distinctions between consonant places of articulation, consistent with the 'place of articulation imperative' (e.g., Butcher, 1995; 2006). As such, this dissertation has addressed the role of language-particular phonological structure in coarticulation. More broadly, it has contributed to the literature concerning distinguishing language-specific speech behaviour from universals of speech behaviour. The findings reported in this dissertation support the view that in order to better understand the relationship between the biomechanics and the acoustics of speech, it is necessary to study coarticulation in both more commonly and less well studied languages. It is hoped that this dissertation will be seen to contribute a relatively comprehensive account of the acoustics of spatial coarticulation between stop consonants and vowels in Australian languages.

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Appendices

This appendices includes materials relating to Chapters 4, 5 and 6 in that order. These materials primarily comprise word lists and detailed results of statistical analyses. The core word lists (pertaining to consonant-vowel coarticulation) are included in Appendix A. All words in the experiments concerning the comparison of retroflexes and palatals, and the analysis of vowel-dependent velar coarticulation are included in these lists. Supplementary word lists (that is, lists of words not included in the core lists, which pertain to the analysis of vowel variability and dispersion and to V-to-V coarticulation) are included in Appendix B.

Appendix A – Consonant-vowel coarticulation

Locus Equations, F2 variability and F2 consonant loci – Arrernte word list

ahentye /aɰəɲca/ “throat”

akakweme /akakʷəma/ “bite”

akangkeme /akaŋkəma/ “smiling, be pleased”

(a)kaperte /(a)kapəʈa/ “head”

akeke /akəka/ “cut (past)”

(a)kngeke /(a)ᵏŋəka/ “carried”

akunye /akuɲa/ “poor fellow, poor thing”

akurrknge /akurᵏŋa/ “brain”

(a)kutne /(a)kuᵗna/ “ignorant”

akwalyenge /akʷaʎəŋa/ “left-handed”

akwarratye /akʷaraca/ “right-handed”

akweke /akʷəka/ “small”

alarte /alaʈa/ “point”

alepe /aləpa/ “firestick”

alkngarnte /alᵏŋaɳʈa/ “sideways”

alkngirnte /alᵏŋiɳʈa/ “eyebrow”

alkwerte /alkʷəʈa/ “shield”

alpeke /alpəka/ “went back”

alte /alta/ “hair”

alturle /altuɭa/ “west”

akurne /akuɳa/ “bad”

alwelileke /alʷəliləka/ “took off (clothes)” [irlwlhe-ileke ?]

amake /amaka/ “elbow”

ampatye /ampaca/ “my sis.’s child”

ampe /ampa/ “child”

(a)mpenye /(a)mpəɲa/ “leftovers”

ampere /ampəra/ “knee”

amulte /amulta/ “arm”

aneke /anəka/ “stayed, was”

anetyene /anəcəna/ “will stay” [tyenhe ?]

angepe /aŋəpa/ “crow”

angente /aŋənʈa/ “mirage, heat haze”

angkentye /aŋkəɲca/ “speech”

angkertangkerte /aŋkəʈaŋkəʈa/ “lizard (sp.)” [angkete-angkete ?]

angkulye /aŋkuʎa/ “cloud”

antere /antəra/ “fat”

antulye /antuʎa/ “shade”

antyeme /aɲcəma/ “rides”

antyipere /aɲcipəɹa/ “bat”

antyityerre /aɲcicəra/ “frog sp.”

anwakerre /anʷakəra/ “we (plural, e.g., fa. & sons)”

anyente /aɲənta/ “one”

aparre /apara/ “butt of spear”

(a)peke /(a)pəka/ “maybe”

apere /apəɹa/ “river red gum”

apethe /apət̪a/ “pouch”

apure /apuɹa/ “ashamed”

(a)purrke /(a)purke/ “tired”

apurte /apuʈa/ “clump”

apwerte /apʷəʈa/ “stone”

apwerteke /apʷəʈəka/ “hailstone”

areke /aɹəka/ “saw”

arerte /aɹəʈa/ “mad”

arethape /aɹət̪apa/ “baby”

arletye /aɭəca/ “raw”

arlewatyerre /aɭəwacəra/ “goanna”

arlkweke /aɭkʷəka/ “ate”

arlpe /aɭpa/ “ear” [irlpe ?]

arlpatye /aɭpaca/ “ringneck parrot”

arlpmernte /aɭᵖməɳʈa/ “rigid”

arlte /aɭʈa/ “day”

arlwekere /aɭʷəkəɹa/ “sg. women’s camp”

arnartne /aɳaᶵɳa/ “scrub”

(a)rneke /(a)ɳəka/ “for a stick”

arnkentye /aɳkəɲca/ “single men’s camp”

arnkwertarnkwerte /aɳkʷəʈaɳkʷəʈa/ “crooked”

arnperrke /aɳpərka/ “centipede”

arntengatye /aɳʈəŋaca/ “(my) sis.-in-law”

arrakerte /arakəʈa/ “mouth”
arrentye /arəɲca/ “devil”
arrirlpe /ariɭpa/ “sharp”
arrkernke /arkəɳka/ “bloodwood”
arteke /aʈəka/ “built”
artekerre /aʈəkəra/ “root”
artepe /aʈəpa/ “back”
artewe /aʈəwa/ “bush turkey”
artitye /aʈica/ “teeth”
artule /aʈula/ “plain”
artwaye /aʈ^{w}aja/ “hey man!”
artwe /aʈ^{w}ə/ “man”
artweke /aʈ^{w}əka/ “for the man”
atantheke /atan̪t̪əka/ “speared”
aternnge /atəɳŋa/ “dirty”
atheke /at̪əka/ “ground up”
(a)thetheke /at̪ət̪əka/ “red”
atnakerte /a^{t}nakəʈa/ “buttocks”
atnerte /a^{t}nəʈa/ “stomach”
atnwaltye /a^{t}n^{w}aʎca/ “intestine”
atnyatye /a^{c}ɲaca/ “mo.’s bro.”
(a)tnyeke /(a)^{c}ɲəka/ “fell, dug”
atnyetyenhe /a^{c}ɲəcən̪a/ “will fall”

atwakeye /at^{w}akəja/ “wild orange”
atwatye /at^{w}aca/ “gap”
atweke /at^{w}əka/ “hit”
atwetyeke /at^{w}əcəka/ “to hit”
atyanke /acanka/ “bull ant”
atyemeye /acəməja/ “mother’s father”
atyenge /acəŋa/ “for me”
atyepe-atyepe /(a)cəpacəpa/ “happy, lively”
atyete /acəta/ “soft”
atyewe /acəwa/ “friend”
atyeye /acəja/ “younger bro.”
awenhatye /awən̪aca/ “fa.’s sis. (aunt)”
(a)wenke /(a)wənka/ “young woman”
aywerte /aj^{w}əʈa/ “spinnifex”
iltyarnme /iʎcaɳma/ “yabby”
iltye /iʎca/ “hand”
iltywiltye /iʎc^{w}iʎca/ “grasshopper”
ilweke /il^{w}əka/ “died”
inngerre /inŋəra/ “face”
ingke /iŋka/ “foot”
inteltye /intəʎca/ “grasshopper”
intelyapelyape /intəʎapəʎapa/ “butterfly”
intepinteme /intəpintəma/ “is lying”
iparrpe /iparpa/ “quick”
iperte /ipəʈa/ “hole”
irretye /irəca/ “eagle hawk”
irrpeme /irpəma/ “go in, enter”
irrkwentye /irk^{w}əɲca/ “policeman”
irrtyarte /ircaʈa/ “spear”
itelareme /itəlarəma/ “know”
itethe /itət̪a/ “alive”
iweke /iwəka/ “threw”
kake /kaka/ “elder bro.”
karnemarre /kaɳəmara/ “leech”
kele /kəla/ “all right”
kereke /kəɹəka/ “for meat”
kertne /kə^{ʈ}ɳa/ “top”
kngakeke /^{k}ŋakəka/ “cut out”
kwarte /k^{w}aʈa/ “egg”
kwatye /k^{w}aca/ “water”
kwepalepale /k^{w}əpaləpala/ “bell-bird”
kwerte /k^{w}əʈa/ “smoke”
kwetere /k^{w}ətəɹa/ “nulla-nulla”
lhenpe /l̪ənpa/ “armpit”
lyeke /ʎəka/ “prickle”
lyete /ʎəta/ “today”
merneke /məɳəka/ “for tucker”
metye /məca/ “blunt”

mparntarenye or mparntwe-arenye /mpaɳʈaɹəɲa/ “ASp person”
mpenge /mpəŋa/ “cooked”
mpetyane /mpəcana/ “(skin name)”
mpwaltye /mp^{w}aʎca/ “frog”
mpwepe or mpepe /mp^{w}əpa/ or /mpəpa/ “middle”
mpwernatye /mp^{w}əɳaca/ “my bro.-in-law”
mwantye /m^{w}aɲca/ “carefully”
mwantyele /m^{w}aɲcəla/ “carefully” [*sic*.]
mweratye /m^{w}əɹaca/ “wife’s mo., mo.-in-law, son-in-law”
mweremwenke /m^{w}əɹəm^{w}ənka/ “blow fly”
ngkarte /ŋkaʈa/ “God, priest”
ntarne /ntaɳa/ “shallow”
nthakentye /n̪t̪akəɲca/ “how many?”
nthenhenge /n̪t̪ən̪əŋa/ “where from?”
ntuye /ntuja/ “wife’s father”
ntyange /ɲcaŋa/ “permanent (water)”
ntyerneke /ɲcəɳəka/ “smelt”
parlkene /paɭkəna/ “kingfisher”
pekathe /pəkat̪a/ “half-caste”
pelhe /pəl̪a/ “spit”
penangke /pənaŋka/ “(skin name)”
pengarte /pəŋaʈa/ “(skin name)”
petyeke /pəcəka/ “came”
pmwerrke /^{p}m^{w}ərka/ “yesterday”
pwape /p^{w}apa/ “whirlwind”
pwarrtyeme /p^{w}arcəma/ “shine”
ranterante /ɹantəɹanta/ “same”
rterneke /ʈəɳəka/ “straightened”
rternele /ʈəɳəla/ “in a dish”
rterte /ʈəʈa/ “wet ground”
takwe /tak^{w}a/ “windbreak”
tangentyele /taŋəɲcəla/ “together”
thipe /t̪ipa/ “bird”
tneke /^{t}nəka/ “stood”
tyape /capa/ “grub”
ulampulampe /ulampulampa/ “heron”
ulkerte /ulkəʈa/ “blue tongue lizard”
urnteme /uɳʈəma/ “dancing”
ulpmernte /ul^{p}məɳʈa/ “dust”
ulthentye /ul̪t̪əɲca/ “heavy”
ulyepere /uʎəpəɹa/ “thigh”
uterne /utəɳa/ “summer, sun”
utnheke /u$^{\text{t̪}}$n̪əka/ “bit (pst.)”
utnanthe /u^{t}nan̪t̪a/ “scrub”
utyipme /uci^{p}ma/ “rib”
utyuwe/utyewe /ucuwa/ “thin”
weke /wəka/ “hit (throwing)”
yalke /jalka/ “wild onion”
yenpe /jənpa/ “skin”
yweke /j^{w}əka/ “don’t know”

Locus Equations, F2 variability and F2 consonant loci – Burarra word list

an-gulol /angulol/ “snot”
an-jarral /anɟaral/ “old man”
an-maka /anmaka/ “stingray”
bacha /baca/ “to fight”
bakala /bakala/ “hair, leaves”
bala /bala/ “house”
balacha /balaca/ “corn sack”
balaja /balaɟa/ “veg. food”
balarra /balara/ “wattle”
balay /balaj/ “long way, far”
balka /balka/ “stick to”
balma /balma/ “completed”
balngga /balŋga/ “afternoon”
bama /bama/ “head, top”
baman /baman/ “long time ago”
bamana /bamana/ “guard, look after”
bamba /bamba/ “to walk along”
banda /banda/ “lower leg”
barlanggu /baɭaŋgu/ “anchor”
barlmarrk /baɭmark/ “wind, electricity”
barnda /baɳɖa/ “l/neck turtle”
barnimbirr /baɳimbir/ “morning star”
barnja /baɳɟa/ “to lay down”
barpa /baɹpa/ “be sore, in pain”
barra /bara/ “buttocks, river mouth”
barrba /barba/ “put, let in”
barrja /barɟa/ “split, burst”
barrnguma /barŋuma/ “to enter, put on clothes”
barrwa /barwa/ “last, after, later”
bartpa /baʈpa/ “wave(s)”
bawa /bawa/ “leave, abandon”
bicha /bica/ “to tie, fasten”
bijibijiya /biɟibiɟija/ “to be tangled, mixed up”
bima /bima/ “back, spine”
birduk /biɖuk/ “water lily”
birlpa /biɭpa/ “to mend”
birrirrija /biribiriɟa/ “to stir, rotate”
bitima /bitima/ “follow, chase”
bocha /boca/ “to spit out”
bokpurra /bokpura/ “frog”
bokulcha /bokulca/ “to thunder”
bordich /boɖic/ “saliva”
borrich /boric/ “dream”
borrwa /borwa/ “think, remember”
bugula /bugula/ “water”
bukula /bukula/ “forehead”
bundultul /bundultul/ “water goanna”
bundurr /bundur/ “clan, tribe”
bungga /buŋga/ “to fall down, land”
bunyja /buɲɟa/ “to lick, suck”
burdacha /buɖaca/ “bird”
burdak /buɖak/ “yet, still, wait”
burlba /buɭba/ “tree sp.”
burluja /buɭuɟa/ “to be swollen, humped”
burraya /buraja/ “later, soon”
burrpa /burpa/ “gut”
buwarta /buwaʈa/ “plains turkey”
dalmurk /dalmuɹk/ “flea”
daltalja /daltalɟa/ “to knock, shake sthg. out”
darrngap /darŋap/ “last one, only child”
darrtarr /dartar/ “fire stick”
delipa /dɛlipa/ “baby, child”
dericha /dɛɹica/ “to stop, be still”
derrka /dɛrka/ “stringy bark”
derta /dɛʈa/ “strong, tight”
dildilja /dildilɟa/ “to draw, scribble”
dirrtirrja /dirtirɟa/ “to stretch oneself”
diwija /diwiɟa/ “be open”
dolja /dolɟa/ “come up (from u’water)”
duldulja /duldulɟa/ “to knock, tap”
dulgu /dulgu/ “yellow ochre”
dungunbarra /duŋunbara/ “witchetty grub”
durtcha /duʈca/ “be full, pregnant”
gaba /gaba/ “there (not far out of sight)”
gacha /gaca/ “to dry up”
gachangay /gacaŋaj/ “s/water turtle”
gajarrk /gaɟark/ “echidna”
gaka /gaka/ “move”
galang /galaŋ/ “hook”
galgu /galgu/ “flying fox”
galpa /galpa/ “to call to come”
gana /gana/ “have eyes open”
ganarda /ganaɖa/ “there (near you)”
ganyawa /gaɲawa/ “yellow seaweed”
gapa /gapa/ “there (far out of sight)”
gapal /gapal/ “flood plain”
gapapa /gapapa/ “fa.’s sis. (aunt)”
garda /gaɖa/ “there (near you)”
gardabal /gaɖabal/ “garfish, long tom”
gardany /gaɖaɲ/ “spider”

garla /gaɭa/ “flesh, meat”
garligarli /gaɭigaɭi/ “boomerang”
garlma /gaɭma/ “to get up”
garnday /gaɳɖaj / “f. kangaroo”
garrarla /garaɭa/ “ibis”
garrnggalk /garŋgalk/ “fish sp.”
gartcha /gaʈca/ “be stuck, bogged”
gat /gat/ “spider”
gata /gata/ “star”
gawata /gawata/ “another place there”
gaymucha /gajmuca/ “dust, litter”
gaypa /gajpa/ “to swindle, cheat”
geka /gɛka/ “today”
gengama /gɛŋama/ “to be shy”
gerrkpawa /gerkpawa/ “to dodge, duck”
gipa /gipa/ “already”
girlirla /giɭiɭa/ “box jelly fish”
giya /gija/ “egg”
goba /goba/ “magpie goose”
gochila /gocila/ “abdomen”
gojarra /goɟara/ “tired, lazy”
golja /golɟa/ “be cheeky”
golmba /golmba/ “applause”
goma /goma/ “body, trunk”
gomkaka /gomkaka/ “mid-aged person”
gonyja /goɲa/ “call, shout”
gopa /gopa/ “keep for oneself”
gornda /goɳɖa/ “cut, chop”
guburda /gubuɖa/ “road”
gu-derda /gudɛɖa/ “sickness”
gugu /gugu/ “quickly, first”
gukukuwa /gukukuwa/ “to cool (vt.)”
guli /guli/ “rudder”
gu-lotok /gulotok/ “little brown dove”
gumbach /gumbac/ “chest”
gun-jong /gunɟoŋ/ “tree, stick”
gupa /gupa/ “fish spear; to build a roof”
gurkur /guɹkuɹ/ “cough”
gurubuk /guɹubuk/ “sm. white dove”
gutkutcha /gutkutca/ “to run fast”
gutuwa /gutuwa/ “to pick up, gather”
guyba /gujba/ “to sink, drown”
jachacha /ɟacaca/ “mo.’s bro.”
jakaba /ɟakaba/ “to close, block up”
jal /ɟal/ “desire”
jalkaka /ɟalkaka/ “to water, refresh”
jamcha nggu /ɟamcaŋnu/ “mo.’s bro.’s child”
janara /ɟanaɹa/ “ceremony”
janrra /ɟanra/ “stone, rock”
japa /ɟapa/ “elder bro.”
japarna /ɟapaɳa/ “dry”
japurra /ɟapura/ “lip, cheek”
jaram /ɟaɹam/ “spider web”
jarl /ɟaɭ/ “hurry up”
jarnpa /ɟaɳpa/ “tree sp.”
jarrcha /ɟarca/ “carve, slice”
jarrka /ɟarka/ “goanna sp.”
jarrma /ɟarma/ “blame”
jawa /ɟawa/ “throat, voice”
jaywa /ɟajwa/ “to aim at”
jel /ɟɛl/ “sand, ground”
jenicha /ɟɛnica/ “to make a mess”
jerlk /ɟɛɭk/ “stringy bark bark”
jichicha /ɟicica/ “fish (gen.)”
jikara /ɟikaɹa/ “paperbark”
jilpirr /ɟilpir/ “mud”
jingga /ɟiŋga/ “pandanus nut”
jinimbu /ɟinimbu/ “salmon”
jirrngurk /ɟirŋuɹk/ “fog, dew”
joborr /ɟobor/ “rule, law”
jolnga /ɟoŋla/ “smoke”
jongok /ɟoŋok/ “mo.-in-law”
jortka /ɟoʈka/ “wake s.o. up”
junumba /ɟunumba/ “to bury”
jungka /ɟuŋk/ “hat”
jurlpa /ɟuɭpa/ “end, bottom”
jurra /ɟura/ “paper”
lakchima /lakcima/ “to open”
lamurrpa /lamurpa/ “elder sis./bro.”
lipalipa /lipalipa/ “dugout canoe”
lopcha /lopca/ “to break, come apart”
lupaka /lupaka/ “to drown (vt.)”
magaya /magaja/ “friendly”
maka /maka/ “fa.’s mo.”
malcha /malca/ “to accompany”
mampa /mampa/ “mother”
man.garba /maŋaɹba/ “river”
marda /maɖa/ “tail”
marlgaway /maɭgawaj/ “clearing, open space”
marnba /maɳba/ “dolphin”
marrga /marga/ “get s.o. to go with you”
marrka /marka/ “try”
marrpa /marpa/ “take care of, wait for”

martay /maʈay/ “flower”
mernda /mɛɳɖa/ “arm”
mingka /miŋka/ “sandfly”
miliyak /milijak/ “widowed, divorced”
mipila /mipila/ “eye”
mirdi /miɖi/ “strong”
mirrka /mirka/ “chest”
mirlcha /miɭca/ “to lightning [*sic*.]”
morduk /moɖuk/ “sm. dilly bag/mullet”
mu-dawarr /mudawar/ “S.E. wind”
mukumul /mukumul/ “bronze-winged pigeon”
mungba /muŋba/ “to complete”
murlucha /muɭuca/ “fishnet”
murndurn /muɳɖuɳ/ “string, rope”
murrba /murba/ “swarm, buzz”
nanyja /naɲɟa/ “pelican”
ngardawa /ŋaɖawa/ “because”
ngarmbuwa /ŋaɹmbuwa “to be quiet”
ngeka /ŋɛka “to breathe”
nichirra /nicira/ “flying insect”
nyarlcha /ɲaɭca/ “to be weak, limp”
nyuluknyuluk /ɲulukɲuluk/ “rat”
rajarra /ɹaɟara/ “barramundi”
raka /ɹaka/ “sit down”
roba /ɹoba/ “to poke sthg. out of a hole”
rrarnba /raɳba/ “thigh”
rrayka /rajka/ “to fetch sthg.”
rrigirrga /rigirga/ “to walk around a bit”
rrurta /ruʈa/ “witchetty grub”
rurrgaka /ɹurgaka/ “to push, pull”
wagarba /wagaɹba/ “shoulder”
wakal /wakal/ “prawn”
warmbarrk /waɹmbark/ “armpit”
warn.gurra /waɳgura/ “bandicoot”
warragul /waragul/ “possum”
wartunga /waʈuŋa/ “dog”
wata /wata/ “wind”
wayanaka /wajanaka/ “lge. oyster sp.”
waykin /wajkin/ “high, on top of”
werrwerrja /wɛrwɛrɟa/ “to spread out (vi.)”
wigipa /wigipa/ “together, with”
wirrpa /wirpa/ “spill”
witich /witic/ “brown snake”
worba /woɹba/ “work magic on”
wordaja /woɖaɟa/ “to spectate”
wurja /wuɹɟa/ “whistle”
wurpa /wuɹpa/ “sum total”
wurrparn /wurpaɳ/ “emu”
yalpa /jalpa/ “to cook, burn”
yarta /jaʈa/ “for a short time”
yerrcha /jɛrca/ “mob”
yerrmba /jermba/ “husband”
yibirrich /jibiric/ “quickly”
yinda /jinda/ “where?”
yokuyoka /jokujoka/ “baby”
yopa /jopa/ “talk about, harangue”
yort /joʈ/ “road”
yukurda /jukuɖa/ “yam sp.”
yurtcha /juʈca/ “to run”

Locus Equations, F2 variability and F2 consonant loci – Gupapuyngu word list

bäba /ba:ba/ “gum nut”
bägitj /ba:gic/ “high tide”
bäka /ba:ka/ “tail, lower leg”
bäla /ba:la/ “walk”
bäpa /ba:pa/ “father”
bäpi /ba:pi/ “snake”
bäru /ba:ɹu/ “crocodile”
bäy /ba:j/ “still, until, nevermind”
babala /babala/ “wrong, by accident”
badak /baɖak/ “still”
badarr /baɖar/ “paperbark”
bakparr /bakpar/ “patch”
bakthun /bakt̪un/ “to break”
bala’ /balaʔ/ “house”
balang’ /balaŋʔ/ “male subsec.”
balangu /balaŋu/ “might, should”
baldhurr’ /bald̪urʔ/ “footmark”
balman /baɭman/ “rain”
baluka /baluka/ “robber”
balwak /balwak/ “tail”
balwur /balwuɹ/ “ripe, cooked”
bambay /bambaj/ “blind”
bambitj /bambic/ “tree”
bandja /baɲɟa/ “arm”
bangam /baŋam/ “rock”
barng.gitj /baɹŋgic/ “bee sp.”
barpuru / baɹpuɹu/ “yesterday”
barrku /barku/ “far away”
barrtjun /barcun/ “to spear, sew”
bathan /bat̪an/ “cook, burn”
batpa /baʈpa/ “reef, rocks”
bekang /bi:kaŋ/ “fishhook, line”
bidila /biɖila/ “bad”
bidjal /biɟal/ “fish”
bili /bili/ “and, because”
bindha /bind̪a/ “ribs”
bininy /biɳiɲ/ “fingernails”
binydjitj /biɲɟic/ “thin, bony”
birkpirk /biɹkpiɹk/ “kingfisher”
birrngarr /birŋar/ “turtle sp.”
biti /biʈi/ “hip, back leg”
boduk /bu:ɖuk/ “black beetle”
bolu /bu:lu/ “bamboo”
bon /bu:n/ “knee”
bopu /bu:pu/ “throat”
borrutj /bu:ruc/ “sandfly”
borum /bu:ɹum/ “ripe, cooked” [*sic*.]
bukmak /bukmak/ “all”
buku /buku/ “forehead”
buku-lup /bukuɭup/ “cleansing ceremony”
bulany /bulaɲ/ “kangaroo”
bulbulyun /buɭbuɭjun/ “to come in (tide)”
bulngu /buɭŋu/ “soft”
bulnha /buln̪a/ “slowly, wait a moment”
bulpul’yun /buɭpuɭʔjun/ “to burn (fire)”
bulu /bulu/ “again”
bulwunu /bulwunu/ “east”
bulyun /buljun/ “float, be in water”
bunbu /buɳbu/ “(abor.) house”
bung.gul /buŋgul/ “ceremony”
bunybu /buɲbu/ “shellfish sp.”
burgu /buɹgu/ “flower”
burrgutj /burguc/ “lungs”
burrpu /burpu/ “cruel, destructive”
buryun /buɹjun/ “fail, come to nothing”
buthuru /but̪uɹu/ “ear”
buyu /buju/ “weave”
däk /ɖa:k/ “hip”
däl /ɖa:l/ “strong, hard”
dakul /ɖakul/ “axe”
damba /ɖamba/ “light(weight)”
dap /ɖap/ “meeting”
detung /di:tuŋ/ “buffalo”
dhakal /d̪akal/ “cheek”
dharrpan /d̪arpan/ “to hide”
dhawada /d̪awaɖa/ “beach”
dhayka /d̪ajka/ “female”
dhika /d̪ika / “somewhere here”
dhoku’ /d̪u:kuʔ/ “paperbark”
dholu /d̪u:lu/ “mud”
dhot /d̪u:ʈ/ “folded up”
dhudi /d̪uɖi/ “buttocks”
dhulku /d̪ulku/ “sore”
dhumbul /d̪umbuɭ/ “short”
didimu /ɖiɖimu/ “parrot fish”
diltji /ɖilci/ “back, bush”
dimirr /ɖimir/ “prickle, spike”
djäga /ɟa:ga/ “to care for”
djana’ /ɟanaʔ/ “fat”

djaṉngarr /ɟaɳŋar/ “hungry”
djarrma /ɟarma/ “gossip”
djaṯam /ɟaʈam/ “centipede”
djeḏa /ɟi:ɖa/ “midnight”
djetji /ɟi:ci/ “sore, hole”
djikay /ɟikaj/ “small bird”
djimbitj /ɟimbic/ “lower back”
djinaga /ɟinaga/ “underneath”
djinmir’ /ɟinmiɹʔ/ “edge”
djirri /ɟiri/ “sin”
djolu /ɟu:lu/ “matches”
djota /ɟu:ta/ “tree sp.”
djuḏum /ɟuɖum/ “mud”
djuku /ɟuku/ “lice”
ḏogu /ɖu:gu/ “waves (sea)”
ḏopulu /ɖu:pulu/ “gambling”
ḏunu /ɖunu/ “ridge, mound”
durr’yun /durʔjun/ “push up”
gäḏany /ga:ɖaɲ/ “dew, mist”
gäna /ga:na/ “alone”
gärr’ /ga:ɹʔ/ “spider”
galnga /galŋa/ “skin, bark, money”
gaḻpan /gaɭpan/ “fr. water fish”
gang.ga /gaŋ.gu/ “carefully, gradually”
ganu’ /ganuʔ/ “ashes, dirt”
ganybu /gaɲbu/ “fishing net”
ganydjarr /gaɲɟar/ “power, strength”
gapu /gapu/ “water”
gara /gaɹa/ “spear”
garkman /gaɹkman/ “frog”
garrthan /gart̪an/ “get caught, stuck”
gaṯpurr /gaʈpur/ “wounded”
gayabak /gajabak/ “head”
gaypal /gajpal/ “wattle sp.”
getkit /gi:tkit/ “seagull”
gikina /gikina/ “tooth”
gitkit /gitkit/ “laughter”
gong /gu:ŋ/ “hand”
gorrmur’ /gu:rmuɹʔ/ “hot”
gotha /gu:t̪a/ “roof iron”
gudhal’yun /gud̪alʔjun/ “to cook”
gudjuk /guɟuk/ “male subsec.”
guḻku /guɭku/ “lots”
gumatj /gumac/ “(clan)”
gundjaḻk /gunɟaɭk/ “pandanus sp.”
gun.ga /gunga/ “pandanus sp.”
gunhu /guṉu/ “father”
guṉmul /guɳmul/ “wet season”
gurak /guɹak/ “throat”
gurrngan /gurŋan/ “shade, black, brown”
gurtha /guɹt̪a/ “fire, firewood”
gutjan /gucan/ “fem. subsec.”
guwal /guwal/ “waist”
läti /la:ti/ “knife”
ḻambarr /ɭambar/ “shoulder”
ḻikan /ɭikan/ “elbow, corner”
ḻirrgi /ɭirgi/ “ashes”
ḻuka /ɭuka/ “eat, drink”
ḻukana /ɭukana/ “eat (perf.)”
ḻukanha /ɭukaṉa/ “eat (pst.)”
ḻundu /ɭundu/ “friend, sweetheart”
ḻurrkun’ /ɭurkunʔ/ “three, a few”
mända /ma:nda/ “octopus”
manbiri /manbiɹi/ “(poisonous) catfish”
maṉḏa /maɳɖa/ “they two”
mang.gu /maŋgu/ “blood, sap”
manymak /maɲmak/ “good”
marrtji /marci/ “to go, walk”
marwat /maɹwat/ “leaf, hair”
maṯan /maʈan/ “hairbelt”
mattjurr /matcur/ “flying fox”
maypal /majpal/ “shellfish gen.”
meṉḏung /mi:ɳɖuŋ/ “snail”
miḻipi /miɭipi/ “shoulderblade”
milka /milka/ “mangrove worm”
miṉḏirr /miɳɖir/ “basket for firesticks”
mirng.guy /miɹŋguj/ “unripe, uncooked”
mitjiyang /micijaŋ/ “boat”
miṯtji /miʈci/ “mob”
moṉuk /mu:ɳuk/ “salty, bitter”
muḏuk /muɖuk/ “war”
mukthun /mukt̪un/ “to be quiet”
muṉguy /muɳguj/ “small pieces”
munydjutj /muɲɟuc/ “green pea bush food”
muta /muta/ “back”
ṉaku /ɳaku/ “canoe”
ṉepal /ɳi:pal/ “knee”
ngaḏangaṯ /ŋaɖaŋaʈ/ “collar bone”
ngalka /ŋalka/ “tooth”

ngalparr /ŋalpar/ “phlegm”
ngapa /ŋapa/ “back, top”
ngultji /ŋulci/ “dark”
ngurrng.gitj /ŋurŋgic/ “shade, ashes”
ngutu /ŋutu/ “sold (wood)”
nhepi /n̪i:pi/ “you (emph.)”
nhokal /n̪u:kal/ “to, for you (sg)”
nim’pu /nimʔpu/ “lower back”
niniku /niniku/ “shell sp.”
n̲urrku /ɳurku/ “brain”
nyika /ɲika/ “rain shower”
nyoka /ɲu:ka/ “mud crab”
räga /ɹa:ga/ “berry sp.”
räkay /ɹa:kaj/ “lily roots”
radjal /ɹaɟal/ “clean sand”
raki’ /ɹakiʔ/ “rope, string”
ralpa /ɹalpa/ “active, frisky”
ranhdhak /ɹan̪d̪ak/ “dry”
rebal’yun /ɹi:balʔjun/ “to clear”
rrätjung /ra:cuŋ/ “jellyfish”
rrupiya /rupija/ “money”
rupu /ɹupu/ “possum”
wäkngani /wa:kŋani/ “fruit sp.”
waku /waku/ “woman’s child”
wapthun /wapt̪un/ “to jump, hop”
warbunuma /waɹbunuma/ “make rain”
wargirr /waɹgir/ “urine”
warku’yun /waɹkuʔjun/ “to annoy, tease”
warrng.gul̲ /warŋguɭ/ “spear type”
warrpam /warpam/ “all, every”

wartja /waɹca/ “shellfish sp.”
wata /wata/ “wind”
watja /waca/ “pointed”
wat̲u /waʈu/ “dog”
weka /wi:ka/ “scum, sap”
weti /wi:ti/ “wallaby”
weyika /wi:jika/ “petrol, oil, fat”
wiripu /wiɹipu/ “other, different”
wititj /witic/ “python”
wopthun /wu:pt̪un/ “to smoke”
wuburr /wubur/ “sweat”
wud̲uy /wuɖuy/ “armpit”
wukun /wukun/ “cloud”
wurrdjara /wurɟaɹa/ “cabbage palm”
wurrpan̲ /wurpaɳ/ “emu”
yaka /jaka/ “no”
yalng.gi /jalŋgi/ “weak, soft”
yapa /japa/ “sister”
yiki /jiki/ “knife”
yindi /jindi/ “big”
yirritja /jirica/ “(moeity)”
yut̲a /juʈa/ “new, young”

Locus Equations, F2 variability and F2 consonant loci – Warlpiri word list

jaja /caca/ “mo. mo.”
jalany-pa /calaɲpa/ “tongue”
jamaru /camaɹu/ “mouth”
jampijin-pa /campcinpa/ “(skin name)”
jangkayi /caŋkaji/ “sg. men camp”
janmarda /canmaɖa/ “onion grass”
janyungu /caɲuŋu/ “tobacco”
jarda /caɖa/ “sleep”
jarlji /caɭci/ “frog”
jarlu /caɭu/ “huge”
jarn=ku /caɳku/ “separately”
jarn-pa /caɳpa/ “kurdaitcha”
jarralyku /caɾaʎku/ “floodplain”
jarrwara /caɾwaɹa/ “wrong way”
jiilyngarri=rni /ci:ʎŋaɾiɳi/ “pointing it out”
jilimi /cilimi/ “sg. women’s camp”
jilkarla /cilkaɭa/ “prickle”
jilyki /ciʎki/ “deaf”
jimanta /cimanta/ “shoulder”
jinarnkiji=rni /cinaɳkiciɳi/ “tripping”
jintirrjintirr-pa /cintiɾcintiɾpa/ “willy wagtail”
jirrnganjakarri /ciɾŋancakaɾi/ “standing with”
jukarra /cukaɾa/ “tomorrow”
jukurrma=ni /cukuɾmani/ “dreaming”
jukurrpa /cukuɾpa/ “dreaming”
julyurlnguna=mi /cuʎuɭŋuna/ “floating”
jumu /cumu/ “soak”
junguny-pa /cuŋuɲpa/ “mouse”
jurdu /cuɖu/ “dust”
jurlpu /cuɭpu/ “bird”
juurlpungu /cu:ɭpuŋu/ “hopped”
kakiyi /kakiji/ “elder bro.”
kakutu /kakutu/ “cockatoo”
kalaka /kalaka/ “might”
kalyakalya /kaʎakaʎa/ “bro.-in-law”
kal(y)wa /kaLwa/ “crane”
kamina /kamina/ “girl”
kampa-rru /kampaɾu/ “in front”
kanginykarrija /kaŋiɲkaɾica/ “didn’t know”
kaninjarra /kanincaɾa/ “down”
kanyarla /kaɲaɭa/ “euro”
kapan=ku /kapanku/ “quickly”
kapu /kapu/ “he will”
karlangu /kaɭaŋu/ “yamstick”
karlarnjirri /kaɭaɳciɾi/ “lizard”
karlirrya=ni /kaɭiɾja/ “turning”
karnari /kaɳaɹi/ “lizard”
karnta /kaɳʈa/ “woman”
kartaku /kaʈaku/ “billycan”
kartirdi /kaʈiɖi/ “tooth”
katarlpi /kataɭpi/ “pillow”
kilji /kilci/ “fast”
kinki /kinki/ “devil”
kinyiri /kiɲiri/ “hot coals”
kirlilkirlil-pa /kiɭilkiɭipa/ “galah”
kirntangi /kiɳʈaŋi/ “moon”
kitikiti /kitikiti/ “armpit”
kukurnu /kukuɳu/ “younger bro.”
kulkurru /kulkuɾu/ “in the middle”
kulpari /kulpaɹi/ “returning”
kultu /kultu/ “hit”
kulu /kulu/ “fight”
kunykunyngarni /kuɲkuɲŋaɳi/ “smoking pipe”
kurdu /kuɖu/ “child”
kurlpukurlpu /kuɭpukuɭpu/ “stingy”
kurnja /kuɳca/ “water in hollow tree”
kurrkara /kuɾpaɹa/ “desert oak”
kurrparu /kuɾpaɹu/ “magpie”
kutu /kutu/ “close”
kuturu /kutuɹu/ “nulla-nulla”
kuurlpari /ku:ɭpaɹi/ “constricted”
kuurrkuurr-pa /ku:ɾku:ɾpa/ “boobook owl”
kuyu /kuju/ “meat”
lam(p)urrnyina=mi /lampuɾɲinami/ “being small and round”
lapaji /lapaci/ “parrot”
luku /luku/ “heel”
maliki /maliki/ “dog”
manja /manca/ “mulga”
manjarnmanjarn-pa /mancaɳmancaɳpa/ “irritation”

marlkalypa /maɭka/ “gravel”
marnakiji /maɳakici/ “conkerberry”
marnilpa /maɳilpa/ “hair”
marrkirdi /maɾkiɽi/ “plum bush”
mata /mata/ “tired”
mijilijili /micilicili/ “navel”
milkari /milkaɹi/ “blind”
milpirri /milpiɾi/ “cloud”
mintapa /mintapa/ “ant bed”
mirdi /miɽi/ “knee”
mirriji /miɾici/ “leg”
mirta /miʈa/ “narrow shield”
miyiki /mijiki/ “for food”
mpa /mpa/ “here you are”
mukarti /mukaʈi/ “hat”
mumpulmumpulyirra=rni /mulpulmulpuʎiɾaɳi/ “gobbling it up”
murrku /muɾku/ “boy”
nantuwa /nantuwa/ “horse”
ngaanyngaanykiji=rni /ŋaːɲŋaːɲkiciɳi/ “breathing”
ngaka /ŋaka/ “soon”
ngakulyka /ŋakuʎka/ “armpit”
ngalyalki /ŋaʎalki/ “flame”
ngalyipi /ŋaʎipi/ “vine”
ngamarrkarri=mi /ŋamaɾkaɾimi/ “is a danger”
nganjurrngu /ŋancuɾŋu/ “mud”
ngapa /ŋapa/ “water”
ngapilkiri /ŋapilkiɹi/ “crested pigeon”
ngapurlu /ŋapuɭu/ “breat”
ngarntarlku /ŋaɳʈaɭku/ “fork of tree”
ngarrka /ŋaɾka/ “man”
ngiji /ŋici/ “firestick”
nguku /ŋuku/ “neck”
ngurrju /ŋuɾcu/ “good”
ngurrpa /ŋuɾpa/ “unknowing”
nguurrpa /ŋuːɾpa/ “throat”
nyinypa /ɲiɲpa/ “spit”
nyurltunyurltu /ɲuɭtuɲuɭtu/ “tangled”
nyuturrnyuturr-pa /ɲutuɾɲutuɾpa/ “(curly) hair”
paarlpa /paːɭpa/ “(calf) leg”
paarrpari=mi /paːɾpaɹimi/ “drying”
palka /palka/ “body”
pama /pama/ “beer”
pampa /pampa/ “blind”
panma /panma/ “flat stone”
panu /panu/ “many”
pararri /paɹaɾi/ “rainbow”
pardani /paɽani/ “waiting”
parduna /paɽuna/ “dry”
parlja /paɭca/ “fly”
parlpuru /paɭpuɹu/ “unhurt”
parnka=mi /paɳkami/ “running”
parra /paɾa/ “day”
parraja /paɾaca/ “coolamon”
parrparda /paɾpaɽa/ “beyond”
partari /paʈaɹi/ “blond”
pawani /pawani/ “flood”
pikirri /pikiɾi/ “woomera”
pilja /pilca/ “goanna”
pina /pina/ “knowing”
pingi /piŋi/ “ant”
pingka /piŋka/ “softly”
pinpin-pa /pinpinpa/ “flat and thin”
pirilyi /piɹiʎi/ “charcoal”
pirli /piɭi/ “stone”
puka /puka/ “rotten”
puluku /puluku/ “bullock”
pu=ngu /puŋu/ “hit (pst.)”
pun=ku /punku/ “bad”
purdangirli /puɽaŋi/ “straggling”
purdurru /puɽuɾu/ “hairstring”
purlka /puɭka/ “old man”
purturlu /puʈuɭu/ “back”
puyukuyuku /pujukujuku/ “fog, mist”
rdingki /ɽiŋki/ “gap”
rdupa /ɽupa/ “windbreak”
rurrpa /uɾpa/ “hole”
tari /taɹi/ “ankle”
tarltu /taɹitu/ “upset stomach”
tiyitiyi /tijitiji/ “mudlark”
tururru /tuɹuɾu/ “clapsticks”
wajarnpi /wacaɳpi/ “ironwood”
wanapi /wanapi/ “whole”
wangka=mi /waŋkami/ “talking”
wanta /wanta/ “sun”
wanukurdu /wanukuɽu/ “whitewood”
wapami /wapami/ “walking”

wapurnungku /wapuɳuŋku/ “ghost gum”
wardiji /waɽici/ “mulga”
wariyi /waɹiji/ “plant”
warlpa /waɭpa/ “wind”
warlungka /waɭuŋka/ “in the fire”
wartirli /waʈiɭi/ “waist”
wati /wati/ “man”
wati=ngki /watiŋki/ “man (agent)”
wiinywiiny-pa /wiːɲwiːɲpa/ “grey falcon”
wililmarda=ni /maɽani/ “whirling”
winpiri /winpiɹi/ “spearwood”
wita /wita/ “small”
wulywulypa /wuʎwuʎpa/ “late evening”
wupunwupun-pa /wupunwupunpa/ “hot (weather)”
wurlampi /wuɭampi/ “stone knife”
wurnturu /wuɳʈuɹu/ “far”
wurulypa /wuɹuʎpa/ “quiet”
wuurrwuurrwangka=mi /wuːɾwuːɾwaŋkami/ “(wind) howling”
yapa /japa/ “person”
yaparla /japaɭa/ “fa. mo.”
yardipi /jaɽipi/ “hip”
yarnunjuku /jaɳuncuku/ “hungry”
yartura /jaʈuɹa/ “root”
yawakiyi /jawakiji/ “wild plum”
yinjinmari /jincinmaɹi/ “zebra finch”
yinjiri /jinciɹi/ “spear grass”
yinka /jinka/ “laughter”
yipiri /jipiɹi/ “grass”
yirrinji /jiɾinci/ “centipede”
yitakimani /jitakimani/ “tracking”
yujuku /jucuku/ “humpy”
yuljuyulju /julcujulcu/ “elbow of tree”
yungalypa /juŋaʎpa/ “(gloss unknown)”
yungkurnu /juŋkuɳu/ “bone”
yunkurrmu /junkuɾmu/ “mistletoe”
yunpa=ka /junpaka/ “sing (imperative)”
yunparni /junpaɳi/ “singing”

A1. Locus Equation results

Table 67. CV context for Arrernte and Burarra speakers: LE Slope values in different Prosodic Contexts with intercept in brackets. Slopes involving fewer than ten tokens and unusual results are marked with an asterisk. N is given in Chapter 3.

C	**V**	**A**			**B**		
		MM	**VD**	**TR**	**DP**	**KF**	**MW**
p	**S**	0.5(538)	0.6(402)	0.3(759)	0.7(325)	0.9(-1)	0.8(127)
	W	0.7(205)	0.8(96)	0.5*(522)	0.8(260)	0.8(-3)	0.9(114)
t	**S**	0.6(738)	0.5(942)	1*(-15)	0.6(660)	0.5(927)	0.7(619)
	W	1(62)	0.5(966)	0.3*(110)	0.6(803)	0.7(586)	0.8(480)
ʈ	**S**	0.5(983)	0.5(2039)	0*(2753)	0*(1737)	0.7(491)	0*(2496)
	W	0.9(206)	0.7(586)	1(69)	0.4(1055)	0.5(1036)	0.5(855)
c	**S**	0.4(1395)	0.3(1547)	0.4(1356)	0.5(1076)	0.6(838)	0.6(888)
	W	0.5(1239)	0.3(1618)	0.5(1230)	0.5(1117)	0.2(1644)	0.55(1083)
k	**S**	1(-33)	0.9(142)	1(113)	1(20)	0.9(116)	1(-23)
	W	0.9(129)	0.7(397)	1(-208)	0.9(93)	0.9(83)	0.9(96)

Table 68. CV context for Gupapuyngu and Warlpiri speakers: LE Slope values in different Prosodic Contexts with intercept in brackets. Slopes involving fewer than ten tokens and unusual results are marked with an asterisk. N is given in Chapter 3.

C	**V**	**G**			**W**		
		AM	**BT**	**EG**	**BP**	**KR**	**RR**
p	**S**	0.9(50)	0.85(109)	0.9(-15)	0.8(141)	0.8 (171)	0.9(4)
	W	0.9(61)	0.9(23)	0.9(23)	0.8(169)	0.8(217)	0.9(55)
t	**S**	0.7*(639)	0.7(580)	N/A	0.65(610)	0.8(383)	0.6(802)
	W	0.8(378)	0.7(695)	0.5(861)	0.6(771)	0.7(582)	0.5(903)
ʈ	**S**	0.7(617)	0.7(693)	0.6*(682)	0.75*(544)	N/A	N/A
	W	0.8(463)	0.7(612)	0.6(730)	0.6(646)	0.5(813)	0.9(188)
c	**S**	0.7(731)	0.7(904)	0.7(726)	0.7(716)	0.5(1038)	0.7(714)
	W	0.7(708)	0.55(1166)	0.45(1318)	0.45(1318)	0.7(857)	0.5(945)
k	**S**	1(-39)	1(-175)	1(-133)	1(-217)	0.9(212)	1(-41)
	W	1(-93)	1(-136)	1(-326)	1(-81)	1(1)	1(-12)

Table 69. VC context: Arrernte and Burarra speakers: LE Slope values in different Prosodic Contexts with intercept in brackets. Slopes involving fewer than ten tokens and unusual results are marked with an asterisk.

		A			**B**		
V	**C**	**MM**	**VD**	**TR**	**DP**	**KF**	**MW**
S	**p**	0.6(334)	0.4(726)	0(1733)	0.7(340)	0.5(683)	0.8(316)
W		0.8(-11)	0.6(328)	0.6(348)	0.5(773)	0.5(728)	0.4(931)
S	**t**	0.7*(623)	0.5*(862)	0.5*(887)	0.8(328)	0.7(617)	0.6(788)
W		0.5(982)	0.5(1036)	0.7*(553)	0.5(762)	0*(1988)	0.6(616)
S	ʈ	0.4(1132)	0.5(956)	0.6(678)	0.6(725)	0.6(710)	0.5(818)
W		0.7(739)	0.8(482)	0.8*(372)	0.7(605)	0.4(1084)	0.5(894)
S	**c**	0.4(1430)	0.2(1676)	0.4(1163)	0.3(1276)	0.1(1850)	0.6(828)
W		0(1978)	0.2(1822)	0.2(1567)	0.5(820)	0.9*(66)	0.7(476)
S	**k**	1(36)	0.8(324)	1(-473)	0.7(350)	0.8(319)	0.9(207)
		1(-175)	0.8(270)	1(-170)	0.8(371)	0.7(404)	0.7(372)

Table 70. VC context: Gupapuyngu and Warlpiri speakers: LE Slope values in different Prosodic Contexts with intercept in brackets. Slopes involving fewer than ten tokens and unusual results are marked with an asterisk.

		G			**W**		
V	**C**	**AM**	**BT**	**EG**	**BP**	**KR**	**RR**
S	**p**	0.8(281)	0.6(472)	0.5(401)	0.7(407)	0.2(1290)	0.8(156)
W		0.6(530)	0.7(435)	1*(-5368)	0.7(330)	0.4(1116)	1(-519)
S	**t**	0.2(1022)	0.6(750)	0.4(1069)	0.8(261)	0.6(809)	0.5(981)
W		0.4*(1039)	0.5(1049)	0.3(1188)	0.8(422)	0.1*(1637)	1(100)
S	ʈ	0.6(589)	0.6(671)	0.5(971)	0.7(482)	0.6(601)	0.7(527)
W		N/A	N/A	0.6*(786)	0.4*(1157)	0.8(291)	1(-61)
S	**c**	0.9(54)	0.3(1663)	0.5(1193)	0.6(956)	0.1(1325)	0.6(695)
W		0.3(1201)	0(2148)	0.5*(1287)	0.5(1153)	0.3(1312)	0.3(1313)
S	**k**	0.7(473)	0.8(211)	1(-136)	1(-182)	0.2*(1319)	1(-203)
		0.6(506)	0.8(127)	0.5(547)	0.9(-16)	0*(1595)	1(-392)

Table 71. LE consonant locus results in the CV context per speaker, consonant and prosodic condition.

C	**V**	**A**			**B**			**G**			**W**		
		MM	**VD**	**TR**	**DP**	**KF**	**MW**	**AM**	**BT**	**EG**	**BP**	**KR**	**RR**
p	**S**	1005	992	1142	1157	-6*	896	397	710	-192*	664	863	63*
	W	690	582	1055	1125	-17*	672	422	597	163*	727	897	444
t	**S**	1742	1927	298*	1849	1903	1832	1884	2009	N/A	1760	1933	1949
	W	5742*	1845	1644	1870	1985	1978	1845	2164	1803	1782	1814	1694
ʈ	**S**	2060	2160	1811	1577	1842	1760	1912	2095	1897	2172	N/A	N/A
	W	2341	2052	1885	1754	1915	1766	1868	2190	1931	1804	1568	1450
c	**S**	2339	2316	2275	2310	2251	2190	2773	2655	2391	2703	2329	2093
	W	2481	2295	2395	2224	2138	2387	2542	2732	1596	2385	2646	2062
k	**S**	-2382*	1123	1880	499	246	-758*	-882*	5425*	15498*	2177	1791	-5564*
	W	1234	1487	1490	1161	965	1262	-23786*	2396	1826	2853	-116*	-578*

Table 72. LE consonant locus results in the VC context per speaker, consonant and prosodic condition.

		A			**B**			**G**			**W**		
V	**C**	**MM**	**VD**	**TR**	**DP**	**KF**	**MW**	**AM**	**BT**	**EG**	**BP**	**KR**	**RR**
S	**p**	802	1246	1406	1234	1258	1391	1185	1342	844	1387	1654	894
W		-59	766	958	1472	1510	1444	1107	1411	2025*	1086	1977	1545
S	**t**	1919	1809	1749	2327	1922	1769	1206	1898	1848	1464	1837	1873
W		1833	1912	1815	1584	1861	1468	1373	2117	1746	1751	1870	1868
S	ʈ	2032	1990	1656	1803	1975	1721	1289	1658	1974	1916	1550	1747
W		2192	2737	1627	1807	1952	1841	1579	N/A	1941	1901	1672	533*
S	**c**	2235	2180	2099	1943	2039	1989	1274	2478	2326	2156	1557	1970
W		2184	2195	1939	1766	925	1884	1404	2158	2499	2461	1859	1935
S	**k**	1617	1417	1456	1295	1654	1550	1234	914	-5970	2353	1720	3526*
W		1869	1565	1569	1497	1163	1281	1284	705	1208	-213*	1619	1663

Table 73. Standard deviations (SD values) at 0.1 onset of vowel. Results are marked with an asterisk if n falls below 10. N/A is given if there are fewer than two tokens. Averages (x̄) are given in grey.

C	**V**	**A**			**B**			**G**			**W**		
		MM	**VD**	**TR**	**DP**	**KF**	**MW**	**AM**	**BT**	**EG**	**BP**	**KR**	**RR**
p	**S**	241	200	91	325	428	352	427	461	434	382	478	406
	W	254	239	154*	287	271	245	407	514	413	420	440	383
t	**S**	269	164	103*	218	182	267	383*	422	N/A	309	536	311
	W	93	123	84*	205	199	219	408	418	224	271	378	159
ʈ	**S**	257	258	51*	197*	293	114*	293	370	290*	111*	257	304
	W	117	119	108	188	149	202	298	416	262	300	281	303
c	**S**	144	129	233	205	222	226	413	209	505	266	388	221
	W	103	128	267	223	154	208	434	318	238	230	430	216
k	**S**	382	282	110	364	332	367	485	566	541	423	571	411
	W	245	190	269	304	325	291	479	660	508	743	668	454
x̄		210	183	180	258	255	264	405	435	391	372	443	317

Table 74. Standard deviations (SD values) at 0.9 offset of vowel. Results are marked with an asterisk if n falls below 10. N/A is given if there are fewer than two tokens. Averages (x̄) are given in grey.

V	**C**	**A**			**B**			**G**			**W**		
		MM	**VD**	**TR**	**DP**	**KF**	**MW**	**AM**	**BT**	**EG**	**BP**	**KR**	**RR**
S	**p**	385	387	161	368	315	310	369	453	247	316	541	335
W		405	292	339	204	253	207	404	501	137*	331	496	325
S	**t**	211*	207*	134*	253	148	193	338	478	264	346	368	186
W		256	292	325*	237	91*	225	171*	333	251	548	249*	311
S	ʈ	213	188	146	186	258	213	271	411	244	264	206	323
W		285	328	155*	294	134	134	N/A	N/A	28*	49*	316	407
S	**c**	172	281	234	220	238	333	563	327	221	283	404	214
W		155	124	134	354	381	287	534	478	165*	243	521	212
S	**k**	380	326	188	320	486	394	540	616	585	494	456*	413
W		415	287	93	292	294	382	277	548	346	508	421*	464
x̄		296	278	185	273	279	268	412	461	308	370	407	319

A2. Correlation results (slopes and standard deviations)

Table 75. Correlations between LE slope and SD values per speaker.

Lang	**Sp**	**cor**	**df**	**p**
A	**MM**	0.37	18	0.09
	VD	0.36	18	0.12
	TR	0.13	18	0.6
B	**DP**	0.6	18	0.0067
	KF	0.69	18	0.0008
	MW	0.75	18	0.0006
G	**AM**	0.39	18	0.09
	BT	0.54	18	0.017
	EG	0.61	18	0.89
W	**BP**	0.67	18	0.0016
	KR	0.32	18	0.18
	RR	0.78	18	0.0001

A3. Tukey’s post-hoc comparisons for cross-speaker analyses

Table 76. Consonant - Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 (Adjusted p values reported -- single-step method)

	Estimate	**Std. Error**	**z value**	**Pr(>|z|)**
t - p	-0.172023	0.059803	-2.876	0.0329*
ʈ **- p**	-0.166073		-2.777	0.0436*
c - p	-0.268001		-4.481	<0.001***
k - p	0.154904		2.590	0.0721
ʈ **- t**	0.005949		0.099	1.000
c - t	-0.095978		-1.605	0.4942
t - k	0.326926		5.467	<0.001***
ʈ **- c**	0.101928		-1.704	0.4312
ʈ **- k**	0.320977		5.367	<0.001***
c - k	0.422905		7.072	<0.001***

Table 77. Order - Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 (Adjusted p values reported -- single-step method)

	Estimate	**Std. Error**	**z value**	**Pr(>|z|)**
CV - VC	-0.08632	0.03782	-2.282	0.0225*

A4. Consonant locus

Table 78. Consonant - Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 (Adjusted p values reported -- single-step method)

	Estimate	**Std. Error**	**z value**	**Pr(>|z|)**
t - p	945	424.99	2.22	0.17
ʈ **- p**	998		2.3	0.13
c - p	-1152		-2.7	0.05
k - p	161		0.38	0.99
ʈ **- t**	53		0.12	0.99
c - t	-208		-0.49	0.99
t - k	1106		2.6	0.07
ʈ **- c**	-154		-0.36	0.99
ʈ **- k**	1159		2.73	0.05
c - k	-1314		-3.09	0.017

A5. Comparing retroflexes and palatals

Table 79. Formant frequencies - means and SD values (Hz) for Arrernte speakers – VC in word-initial context

		MM		**VD**		**TR**	
		x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**
F1	**at**	594	98	607	141	N/A	N/A
	aʈ	415	123	561	128	543	118
	ac	434	141	546	165	548	111
F2	**at**	1650	141	1765	298	N/A	N/A
	aʈ	2106	223	2146	245	1801	72
	ac	1931	197	1886	232	1887	133
F3	**at**	2815	109	2583	132	N/A	N/A
	aʈ	2907	216	2652	215	2346	232
	ac	2954	174	2637	207	2849	137

Table 80. Formant frequencies - means and SD values (Hz) for Arrernte speakers – VC in non-word-initial context

		MM		**VD**		**TR**	
		x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**
F1	**aʈ**	603	193	630	139	N/A	N/A
	ac	522	160	571	136	603	64
F2	**aʈ**	1768	390	1608	249	N/A	N/A
	ac	1792	445	1751	365	1630	283
F3	**aʈ**	2587	213	2343	166	N/A	N/A
	ac	2916	250	2576	262	2904	123

Table 81. Formant frequencies - means and SD values (Hz) for Burarra speakers – VC

		DP		**KF**		**MW**	
		x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**
F1	**at**	640	100	667	96	663	81
	aʈ	627	106	584	119	646	81
	ac	573	86	575	96	587	112
F2	**at**	1594	184	1705	181	1644	129
	aʈ	1565	209	1658	257	1680	171
	ac	1800	180	1925	169	1890	231
F3	**at**	2824	155	2797	139	2776	148
	aʈ	2591	231	2507	257	2465	328
	ac	2898	144	3066	118	2904	255

Table 82. Formant frequencies - means and SD values (Hz) for Gupapuyngu speakers – VC

		AM		**BT**		**EG**	
		x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**
F1	**at**	732	74	704	163	541	77
	aʈ	673	129	566	182	542	168
	ac	631	124	674	148	624	179
F2	**at**	1460	182	1799	206	1465	252
	aʈ	1568	150	1766	150	1672	260
	ac	1746	362	2154	313	1822	265
F3	**at**	2805	153	2640	273	2848	65
	aʈ	2616	359	2363	180	2549	350
	ac	2973	159	2924	304	3142	100

Table 83. Formant frequencies - means and SD values (Hz) for Warlpiri speakers – VC.

		BP		**KR**		**RR**	
		x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**
F1	**at**	666	73	549	121	535	99
	aʈ	621	83	530	123	527	109
	ac	621	79	490	118	507	91
F2	**at**	1558	279	1541	266	1487	240
	aʈ	1672	224	1493	267	1524	208
	ac	1844	176	1715	243	1670	187
F3	**at**	2888	149	2935	297	2686	148
	aʈ	2528	346	2422	436	2504	252
	ac	3076	164	3027	183	2763	115

Table 84. Formant frequencies - means and SD values (Hz) for Arrernte speakers – CV (insufficient tokens for TR).

		MM		**VD**	
		x̄	**SD**	**x̄**	**SD**
F1	**ta**	643	121	694	130
	ʈa	662	106	742	106
	ca	656	141	653	136
F2	**ta**	1657	160	1618	100
	ʈa	1723	97	1615	123
	ca	1818	160	1777	201
F3	**ta**	2829	165	2462	291
	ʈa	2659	169	2470	104
	ca	2781	172	2472	166

Table 85. Formant frequencies - means and SD values (Hz) for Burarra speakers – CV.

		DP		**KF**		**MW**	
		x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**
F1	**ta**	671	133	658	109	684	78
	ʈ**a**	712	127	670	137	676	60
	ca	634	132	692	173	667	118
F2	**ta**	1662	98	1719	76	1669	59
	tʈ**a**	1607	85	1782	92	1731	103
	ca	1785	181	1866	146	1769	146
F3	**ta**	2918	208	2831	125	2773	139
	ʈ**a**	2916	154	2897	144	2766	137
	ca	2911	165	2933	166	2805	167

Table 86. Formant frequencies - means and SD values (Hz) for Gupapuyngu speakers – CV.

		AM		**BT**		**EG**	
		x̄	**SD**	**x̄**	**SD**	**x̄**	**SD**
F1	**ta**	789	127	746	90	853	199
	ʈ**a**	752	105	715	84	735	61
	ca	723	145	702	118	648	125
F2	**ta**	1613	66	1782	131	1716	56
	ʈ**a**	1625	76	1851	119	1795	49
	ca	1746	140	1955	196	1789	117
F3	**ta**	2907	104	2728	101	3155	159
	ʈ**a**	3004	113	2713	78	2712	118
	ca	2989	133	2787	109	3107	155

Table 87. Formant frequencies - means and SD values (Hz) for Warlpiri speakers – CV.

		BP		**KR**		**RR**	
		$\bar{x}$	**SD**	$\bar{x}$	**SD**	$\bar{x}$	**SD**
F1	**ta**	667	64	629	108	518	106
	ʈ**a**	670	54	600	113	579	72
	ca	718	144	631	137	498	86
F2	**ta**	1779	62	1596	113	1659	74
	tʈ**a**	1696	126	1544	140	1655	84
	ca	1837	150	1722	208	1734	131
F3	**ta**	3008	90	3136	200	2743	118
	ʈ**a**	2848	384	2713	525	2602	197
	ca	3081	90	3049	168	2749	170

A6. Vowel-dependent velar coarticulation

Table 88. Arrernte means and Standard Deviations in F2 at vowel onset and midpoint for /ki/, /ka/ and /ku/ for each speaker.

			V_{ON} **(Hz)**		V_{MID} **(Hz)**	
Lang	**Sp**		$\bar{x}$	**SD**	$\bar{x}$	**SD**
A	**MM**	**ka**	1652	144	1683	132
		ki	2411	98	2518	128
		ku	768	132	859	122
	VD	**ka**	1518	99	1524	131
		ki	2349	67	2485	20
		ku	826	132	861	167
	TR	**ka**	1770	107	1756	85
		ki	N/A	N/A	N/A	N/A
		ku	N/A	N/A	N/A	N/A

Table 89. Burarra means and Standard Deviations in F2 at vowel onset and midpoint for /ki/, /ka/ and /ku/ for each speaker.

			V_{ON} **(Hz)**		V_{MID} **(Hz)**	
Lang	**Sp**		$\bar{x}$	**SD**	$\bar{x}$	**SD**
B	**DP**	**ka**	1611	154	1639	136
		ki	2122	413	2100	407
		ku	1235	319	1300	289
	KF	**ka**	1573	138	1618	153
		ki	2055	256	2025	416
		ku	1100	240	1231	296
	MW	**ka**	1657	138	1668	135
		ki	2063	400	1990	351
		ku	1179	248	1279	309

Table 90. Gupapuyngu means and Standard Deviations in F2 at vowel onset and midpoint for /ki/, /ka/ and /ku/ for each speaker.

			V_{ON} (Hz)		**V_{MID} (Hz)**	
Lang	**Sp**		**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**
G	**AM**	**ka**	1581	140	1649	189
		ki	2176	503	2255	430
		ku	968	127	1114	214
	BT	**ka**	1806	143	1822	159
		ki	2732	127	2668	135
		ku	964	114	1158	259
	EG	**ka**	1631	110	1706	127
		ki	2409	90	2298	143
		ku	990	89	1203	281

Table 91. Warlpiri means and Standard Deviations in F2 at vowel onset and midpoint for /ki/, /ka/ and /ku/ for each speaker.

			V_{ON} (Hz)		**V_{MID} (Hz)**	
Lang	**Sp**		**$\bar{x}$**	**SD**	**$\bar{x}$**	**SD**
W	**BP**	**ka**	1660	168	1701	148
		ki	2602	231	2576	140
		ku	1019	214	1106	228
	KR	**ka**	1488	207	1471	156
		ki	2453	437	2337	428
		ku	892	254	1000	312
	RR	**ka**	1454	178	1500	179
		ki	1976	214	1994	223
		ku	1004	208	1094	227

Table 92. Standard deviation modified t-test results comparing short vowels across V1 (VC) and V2 (CV) for Warlpiri.

Sp		**df**	**t**	**p**
BP	**F1**	2	0.5921	0.61
	F2		1.2815	0.33
KR	**F1**		-2.3469	0.14
	F2		-1.6869	0.23
RR	**F1**		2.1238	0.17
	F2		0.3167	0.78

Appendix B - Vowel variability and dispersion

Vowel chapter – additional word list - Arrernte

(a)pmere /(a)ᵖməɹa/ “camp”
(a)rnakwe /(a)ɳakʷa/ “(gloss unknown)”
akwene/akune /akʷəna/ “(gloss unknown)”
ingwele /iŋʷəla/ “in the night”
kwenye /kʷəɲa/ “lacking”
lhere /l̪əɹa/ “creek”
imerneme /iməɳəma/ “showing”
lyeke /ʎəka/ “prickle”
marle /maɭa/ “girl”
merne /məɳa/ “(gloss unknown)”
metye /məca/ “blunt”
meye /məya/ “mother”
mwarre /mʷara/ “good”
name /nama/ “(gloss unknown)”
ngenhe /ŋən̪a/ “you (obj.)”
nhenhe /n̪ən̪a/ “this”
pelhe /pəl̪a/ “spit”
pmware /ᵖmʷaɹa/ “(pmwarepmware is water beetle)”
pwenge /pʷəŋa/ “blind”
pwere /pʷəɹa/ “lightning”
tharre /t̪ara/ “numb”
tneme /ᵗnəma/ “standing”
warle /waɭa/ “house”
yane /jana/ “(gloss unknown)”
yaye /jaja/ “elder sis.”

Vowel chapter – additional word list – Burarra

mala /mala/ “clan”
mela /mɛla/ “side of abdomen”
mola /mola/ “again”
mula /mula/ “hair, fur, leaves”
murna /muɳa/ “hand, finger”
muya /muja/ “fly, green ant”
ngana /ŋana/ “mouth”
ngima /ŋima/ “to paint”
nguna /ŋuna/ “give me”
ninya /niɲa/ “to sit, stay”
numa /numa/ “to smell sthg.”
nuya /nuja/ “ant sp.”
nyinya /ɲiɲa/ “your father”
rrawa /rawa/ “place, camp”
rrirra /rira/ “tooth, edge”
rruma /ruma/ “to break”
werra /wɛra/ “bad”
wola /wola/ “long time (past or future)”
worla /woɭa/ “bro./sis.”
worra /wora/ “too bad!”
wurra /wura/ “man”
yunya /juɲa/ “to sleep, be lying down”

Vowel chapter – additional word list – Gupapuyngu

dhärra /d̪aːra/ “to stand”
dhol̲u /d̪uːɭu/ “mud”
dhuyu /d̪uju/ “sacred, secret”
linyu /liɲu/ “we two (excl.)”
märi /maːɹi/ “mo. mo.”
mala /mala/ “mob”
mari /maɹi/ “trouble”
matha /mat̪a/ “tongue”
metha /met̪a/ “chest, shore”
momu /muːmu/ “fa. mo.”
ngäma /ŋaːma/ “hear, listen”
ngani /ŋani/ “really”
nganya /ŋaɲa/ “him”
ngorra /ŋuːra/ “lie down, sleep”
ngurru /ŋuru / “nose”
nhäma /n̪aːma/ “to see, look at”
nhätha /n̪at̪a/ “when”
nhina /n̪ina/ “sit, stay, be”
nhungu /n̪uŋu/ “your (sg.)”
rangi /ɹaŋi/ “beach”
rerri /ɹiːri/ “sickness”
rrothi /ruːt̪i/ “bread”
rulu /ɹulu/ “bundle”
walu /walu/ “sun”
wan̲a /waɳa/ “arm”
wänga /waːŋa/ “camp”
wanga /waŋa/ “speaker”
wanha /wan̪a/ “where”
wori /wuːɹi/ “shark”
yothu /juːt̪u/ “baby, child”

Vowel chapter – additional word list – Warlpiri

langa /laŋa/ “ear”
larra /lara/ “crack”
lawa /lawa/ “no”
lirra /lira/ “mouth”
manya /maɲa/ “soft”
maru /maɹu/ “black”
maya /maja/ “more”
mimi /mimi/ “forehead”
mina /mina/ “nest”
mulyu /muʎu/ “nose”
munga /muŋa/ “night”
nama /nama/ “ant”
ngalya /ŋaʎa/ “forehead”
ngama /ŋama/ “female”
ngarni /ŋaɳi/ “eat/drink”
ngawu /ŋawu/ “bad”
ngula /ŋula/ “that one”
nguru /ŋuɹu/ “sky”
nini /nini/ “mouse”
nyanyi /ɲaɲi/ “seeing”
nyurru /ɲuru/ “short time ago”
runyu /ɹuɲu/ “soft”
walyi /waʎi/ “headband”
warru /waru/ rock wallaby”
wurra /wura/ “not yet”
yalyu /jaʎu/ “blood”
yama /jama/ “shade”
yimi /jimi/ “language”
yiri /jiɹi/ “sharp point”

B1. Euclidean distance analyses

Table 93. Arrernte and Burarra Euclidean distances in the VC condition. Averages (x̄) across speakers are given in grey.

		VC	**V**							
Lang	**Sp**	**i**	**i:**	ɛ	ə	**a**	**a:**	**o**	**u**	**u:**
A	**MM**	273	N/A	N/A	282	459	N/A	N/A	542	N/A
	VD	241	N/A	N/A	289	682	N/A	N/A	678	N/A
	TR	202	N/A	N/A	218	291	N/A	N/A	N/A	N/A
	x̄	239	N/A	N/A	263	477	N/A	N/A	610	N/A
B	**DP**	648	N/A	187	N/A	196	N/A	381	383	N/A
	KF	701	N/A	331	N/A	259	N/A	503	526	N/A
	MW	665	N/A	215	N/A	199	N/A	434	457	N/A
	x̄	671	N/A	244	N/A	218	N/A	239	455	N/A

Table 94. Gupapuyngu and Warlpiri Euclidean distances in the VC condition. Averages across speakers are given in grey.

Lang	**Sp**	**VC**	**V**							
		i	**i:**	ɛ	ə	**a**	**a:**	**o**	**u**	**u:**
G	**AM**	700	299	N/A	N/A	311	299	N/A	570	653
	BT	771	817	N/A	N/A	326	317	N/A	609	834
	EG	N/A	907	N/A	N/A	219	281	N/A	441	660
	x̄	735	674	N/A	N/A	285	299	N/A	540	716
W	**BP**	556	N/A	N/A	N/A	266	N/A	N/A	480	N/A
	KR	584	N/A	N/A	N/A	291	N/A	N/A	609	N/A
	RR	473	N/A	N/A	N/A	230	N/A	N/A	483	N/A
	x̄	538	N/A	N/A	N/A	262	N/A	N/A	524	N/A

Table 95. All Euclidean distances in the CV condition. Averages across speakers are given in grey.

		V		
Lang	**Sp**	**i**	**a**	**u**
B	**DP**	592	231	551
	KF	389	382	N/A
	MW	728	251	641
	x̄	570	288	N/A
G	**AM**	672	315	619
	BT	906	287	697
	EG	710	306	650
	x̄	763	433	655
W	**BP**	565	266	422
	KR	732	320	708
	RR	515	224	484
	x̄	604	270	538

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