Locus equations and coarticulation in three Australian languages

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Locus equations were applied to $F_2$ data for bilabial, alveolar, retroflex, palatal, and velar plosives in three Australian languages. In addition, $F_2$ variance at the vowel-consonant boundary, and, by extension, consonantal coarticulatory sensitivity, was measured. The locus equation slopes revealed that there were place-dependent differences in the magnitude of vowel-to-consonant coarticulation. As in previous studies, the non-coronal (bilabial and velar) consonants tended to be associated with the highest slopes, palatal consonants tended to be associated with the lowest slopes, and alveolar and retroflex slopes tended to be low to intermediate. Similarly, $F_2$ variance measurements indicated that non-coronals displayed greater coarticulatory sensitivity to adjacent vowels than did coronals. Thus, both the magnitude of vowel-to-consonant coarticulation and the magnitude of consonantal coarticulatory sensitivity were seen to vary inversely with the magnitude of consonantal articulatory constraint. The findings indicated that, unlike results reported previously for European languages such as English, anticipatory vowel-to-consonant coarticulation tends to exceed carryover coarticulation in these Australian languages. Accordingly, on the $F_2$ variance measure, consonants tended to be more sensitive to the coarticulatory effects of the following vowel. Prosodic prominence of vowels was a less significant factor in general, although certain language-specific patterns were observed. © 2015 Acoustical Society of America.

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I. INTRODUCTION

A. Coarticulation

Contextual variability in the acoustics of successive consonants and vowels has been studied for many years (e.g., English: Lindblom et al., 2007; Swedish, English, and Russian: Ohman, 1966; Catalan: Recasens, 1984a,b, 1985). It is clear that this process is both universal (all languages display coarticulation), and language-specific (coarticulation is realized differently in different languages; e.g., Ohman, 1966). The extent to which a segment resists coarticulatory effects appears to relate to biomechanical constraints, and also to factors such as language-specific perceptual constraints and phonological processes, and prosodic variables, such as stress and timing patterns (e.g., Recasens, 1985; Manuel, 1999; Lindblom et al., 2007).

The coarticulatory process can occur in both directions. It has been demonstrated that the relative salience of carryover (left to right) to anticipatory (right to left) coarticulation or vice versa depends somewhat on the specific articulatory requirements of the segments involved, e.g., on the strength of biomechanical constraints and mechanico-inertial properties associated with specific articulatory gestures, and on gestural compatibility between adjacent segments (Recasens, 1999). The process complies with the principle that along a particular coarticulatory direction, there is an inverse correlation between the magnitude of consonant-to-vowel coarticulation and the magnitude of vowel-to-consonant coarticulation (Recasens and Pallarés, 2001). Carryover coarticulation is often associated with biomechanical and timing constraints, while anticipatory coarticulation is typically viewed as reflecting cognitive processing and language-specific articulatory pre-programming strategies (Recasens, 1984b). In addition, not only segmental coarticulation resistance and “aggressiveness” (the capacity to exert coarticulatory effects), but also coarticulatory directionality, can be affected by language-specific perceptual constraints (see, e.g., Beddor et al., 2002).

B. Goals of present study

The purpose of this acoustic investigation was to quantify anticipatory and carryover vowel-to-consonant coarticulation using locus equations (LEs), and to quantify consonantal coarticulatory sensitivity in the form of $F_2$ variance, in three Australian languages: Burarra, Gupapuyngu, and Warlpiri. There have been relatively few cross-linguistic studies of coarticulation in Australian languages (e.g., Tabain and Butcher, 1999). It is known that the quantification of vowel-to-consonant and vowel-to-vowel coarticulation and the comparison of anticipatory and carryover effects are effective means of characterizing coarticulatory differences between languages (e.g., Ohman, 1966; Manuel, 1999; Recasens, 1999).

One possible source of coarticulatory differences lies in the composition of segmental inventories (Manuel, 1990).
Australians are known to be unusual in possessing up to seven places of articulation in the stop series but few manners of articulation and often no more than three vowel qualities (Butcher, 2006). In the context of the present study, the most relevant differences between the three Australian languages examined are in the number of coronal categories and in the number of vowels. Burarra and Warlpiri possess three coronal categories, alveolar, retroflex (or apical postalveolar) and lamino-alveolopalatal (hereafter “palatal”), while Gupapuyngu includes an additional, lamino-dental, category. All possess two non-coronal, or “peripheral,” classes: bilabial and dorso-velar (Butcher, 2006). Burarra has five phonemic vowels, /i a o u/, and Gupapuyngu and Warlpiri, three with a length distinction, /i a u/.

Few studies have employed LEs or other acoustic measures of coarticulation to quantify the effects of prosodic variation on coarticulation (see Lindblom et al., 2007). The relationship between coarticulation and prosody is an interesting one that warrants further study, especially in the context of Australian languages. There is evidence in these languages of unusual prosodic effects on segmental realization in consonants following stressed vowels; in Warlpiri, it is these consonants that undergo localized hyper-articulation rather than the stressed vowels preceding them, resulting in an enhancement or sharpening of paradigmatic consonant contrasts (Butcher and Harrington, 2003). As is the case for most Australian languages, Warlpiri, Gupapuyngu, and Burarra are analyzed as having predominantly word-initial classes: bilabial and dorso-velar (Butcher, 2006). Burarra has five phonemic vowels, /i a o u/, and Gupapuyngu and Warlpiri, three with a length distinction, /i a u/.

Previous research conducted by Tabain et al. (2004) on Australian languages, specifically, Arrernte, Yanyuwa, and Yindjibarndi (also spelled “Yintjiparni”), has suggested that magnitudes of consonantal coarticulation by preceding and following vowels tend to be similar in these languages, which have multiple (coronal) places of articulation contrasts (see Sec. IC). It remains to be seen whether the patterns of CV (consonant-vowel) or VC (vowel-consonant) coarticulation in the three languages analyzed here are consistent with those observed in the other Australian languages examined thus far, and whether similar patterns of prosodically-driven localized hyper-articulation will be observed in CV and VC contexts.

C. Locus equation analysis

The primary metric employed in the current study is the LE (Lindblom, 1963), a linear regression metric that is typically used to measure vowel-to-stop coarticulation in CV sequences. The LE appears to reflect place of articulation in consonants, and relatedly, differences in coarticulation resistance (e.g., Fowler, 1994; Brancazio and Fowler, 1998; Löfqvist, 1999). It was Krull (1987) who first claimed a relationship between LE regression coefficients or “slopes” and the degree of coarticulation between the consonant and the vowel in a CV sequence. The LE slope indicates the magnitude of vowel-dependent coarticulation; normally, a value of 0 indicates minimal coarticulation and 1, maximal. The LE also permits the calculation of the y-intercept—the point at which the main regression, or fitted, line would cross the y axis—and the consonant “locus,” in the traditional “Haskins” sense of a theoretical point of formant origin (Delattre et al., 1955). The relevant equation is expressed by Krull (1987) as Eq. (1), where $F_{2i}$ is the second formant frequency at the onset of the vowel and $F_{2t}$, at the vowel-midpoint, where $k$ is the slope, $c$ is the intercept on the $y$ axis, and $k$ and $c$ are constants for a given consonant:

$$F_{2i} = k \times F_{2t} + c. \quad (1)$$

LE metrics have been employed to determine the effect of prosodic variation on vowel-to-consonant coarticulation on the basis that “[t]he vowel and consonant have more freedom to move in independent directions during stressed speech” (Lindblom et al., 2007, p. 3803). Several studies have demonstrated that for languages such as English, French, and Italian, coarticulation is reduced in prosodically strong locations (e.g., English: de Jong et al., 1993; Cho, 2004, 2005; French: Duez, 1992; Italian: Farnetani, 1990). In a recent LE study conducted by Lindblom et al. (2007), the authors were able to identify such an effect of emphatic phrasal stress on the vowel-dependent coarticulation of English lingual stops. It can be claimed that a prosodically strong segment should both resist and exert coarticularatory effects to a greater extent than a prosodically weak segment, on the basis that the extent to which a segment resists coarticulation appears to positively correlate with the extent to which it exerts coarticularatory effects (e.g., Recasens et al., 1997; cf. Cho, 2004).

Recent LE studies comparing multiple places of articulation in Australian languages rely on previous studies conducted by Sussman and colleagues (e.g., Sussman et al., 1991; Sussman et al., 1997). These studies typically find high slopes for the bilabial and velar consonants and low slopes for the alveolar, palato-alveolar, and retroflex or rhotic consonants, consistent with the hypothesis of Recasens (1985) that consonants are less coarticulation resistant—or more highly coarticulated—when they involve weaker constraints on the tongue dorsum (see Sec. ID). Most LE studies of Australian languages have been conducted by Tabain and colleagues (e.g., Tabain and Butcher, 1999). The findings for these languages can be summarized as follows: velar LE slopes are known to exceed 1 for these languages and bilabial slopes are also rather high, while palatal slopes tend to be relatively low (Arrernte, Yanyuwa, and Yindjibarndi: Tabain and Butcher, 1999; Tabain et al., 2004).

A relatively small number of LE studies have extended the use of LEs to the characterization of VC sequences. The majority of these are studies of American English or Swedish, e.g., by Modarresi et al. (2004), and Lindblom and colleagues (Lindblom et al., 2007; Lindblom and Sussman, 2012). In the context of Australian languages, only Tabain and colleagues have applied LEs to both CV and VC sequences (for Arrernte, Yanyuwa, and Yindjibarndi: Tabain et al., 2004). In their data, as previously mentioned (Sec. IB), magnitudes of consonantal coarticulation by preceding and following vowels inferred from the same type of acoustic measures tended to be similar. Tabain et al. suggest that this
indicates similarly “tight control” of both CV and VC trajectory periods, and argue that this is possibly “a necessary constraint on consonant production in languages which have multiple places of articulation” (Tabain et al., 2004, p. 194). Their claim regarding similar magnitudes of coarticulation by preceding and following vowels is thus consistent with Butcher’s hypothesis that there is a “Place of Articulation imperative” for Australian languages, which states that the acoustic and articulatory variability of place of articulation must be limited to ensure that perceptual contrasts involving consonant place of articulation are maintained (e.g., Butcher, 1995, 2006; see also Manuel, 1990). Such a claim about coarticulatory processes in the languages examined prior to this study (Arrernte, Yanyuwa, and Yindjibarndi) needs to be investigated across a different set of Australian languages.

D. Locus equations, coarticulation resistance, and coarticulatory sensitivity

Fowler and Brancazio (2000) were the first to strongly relate the LE method of quantifying CV coarticulation to coarticulation resistance. Their American English speakers showed more anticipatory V-to-V coarticulation for low resistant consonants (e.g., /b/) than for high resistant consonants (e.g., /d/). In other studies indicating a relationship between LE slopes and coarticulation resistance, Recasens (1984a,b, 1985) 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) were similar to rankings according to slopes. He argued that the size of the F2 standard deviations measured at the consonant-vowel boundary reflected the magnitude of the articulatory variability of the consonant, and thus its coarticulatory or context sensitivity (hereafter termed “coarticulatory sensitivity”; see also Bladon and Al-Bamerni, 1976). Both the F2 variance measure and the LE rely on the insight that “[f]ormant frequencies at the consonant-vowel boundary depend not only on the place of articulation of the consonant but also on the adjacent vowel” (Kru ll, 1987, p. 43).

Recasens argued that the extent to which segment a is sensitive to the coarticulatory effects of segment b is primarily dependent on the relative magnitudes of articulatory (principally, dorsal) constraint on a and b, and, relatedly, the degree of articulatory conflict between them. The more constrained the consonant, the smaller the magnitude of coarticulatory sensitivity. This relationship between coarticulation and articulatory constraint is formalized in the “Degrees of Articulatory Constraint,” or DAC, model, within the framework of a coproduction or gestural approach to speech production (e.g., Recasens et al., 1997). In this model, a consonant such as /p/ is specified for a minimal DAC value (DAC = 1) as it is minimally constrained, while a consonant such as a dorso-palatal /c/ is specified for a maximal value (DAC = 3) as it is maximally constrained. Coarticulatory sensitivity may also vary as a function of manner of articulation requirements and prosodic factors such as stress or position within the word (Recasens, 1999).

Despite this demonstrable relationship between coarticulation and articulatory constraint and conflict, there is some inconsistency in the results of studies comparing the LE and articulatory measures of coarticulation (see, e.g., Löfqvist, 1999). Importantly, however, recent studies have strongly supported the use of the LE as a method of measuring coarticulation (e.g., Iskarous et al., 2010; Lindblom and Sussman, 2012). Iskarous et al. (2010) demonstrated on the basis of articulatory (EMMA and x-ray microbeam) and acoustic data from American English that there were strong similarities between linear regression slopes, intercepts, and R² generated by LE and articulatory metrics, the latter regressing the horizontal position of the tongue body at consonant release over the tongue body position at the vowel-midpoint. These similarities indicated that dorsal constraint determines the magnitude of coarticulation resistance associated with a given consonant, and hence the size of the slope generated for that consonant.

In the current study, the principal hypotheses addressed by the LE and other acoustic measures were as follows. The first prediction was that (1) the place of articulation of a stop determines the extent to which it is coarticulated by an adjacent vowel in Australian languages (e.g., Tabain and Butcher, 1999; Tabain et al., 2004). If this is the case, relative slopes and estimates of context sensitivity should conform to those indicated by previous Australian language studies, and should be consistent with the DAC model (Recasens et al., 1997). Further, it was predicted that (2-a) stops undergo a similar magnitude of coarticulation by and, show similar levels of context sensitivity to, preceding and following vowels (after Tabain et al., 2004). An alternative hypothesis was that (2-b) anticipatory V-to-C effects are stronger than carryover effects, in accordance with the original predictions of Tabain et al. (2004). Finally, we predicted that (3) prosodically prominent vowels do not exert a higher magnitude of coarticulation in adjacent stops than non-prominent vowels, all else being equal. We made this prediction on the basis of previous prosodic results for Warlpiri, in which, as previously mentioned, post-tonic consonants rather than vowels were shown to be hyper-articulated in prosodically prominent contexts (e.g., Butcher and Harrington, 2003; cf., e.g., Cho, 2004). However, we anticipated that Burarra might constitute an exception to (3) given previous findings of extensive reduction in unstressed vowels in this language (Butcher, 1996). The methods by which hypotheses (1), (2) and (3) were addressed are summarized in Sec. II.

II. METHODS

A. Participants and speech samples

1. Participants

The subjects of this study were nine adult female speakers of three Australian languages: Burarra, Gupapuyngu, and Warlpiri (three speakers per language). Burarra and Gupapuyngu are spoken in central and north-eastern Arnhem Land, respectively, in the Northern Territory of Australia. Warlpiri is spoken to the north-west of Alice Springs in the same territory. The speakers were aged between 30 and 65 at
the time of recording. They were L1 speakers of these languages and spoke them on a daily basis, but as is typical in these communities, most speakers were multi-lingual and all spoke Aboriginal English. They reported no speech, language, or hearing problems and were not aware of the purposes of the research.

2. Speech samples

The larger corpus was collected and digitized by Professor Andrew Butcher. We selected only female speakers from Butcher’s corpus. Recordings were made between October 1988 and April 1991 onto a Sony (Japan) TCM-5000EV cassette recorder or a Kudelski Nagra (Switzerland) 4.2 full-track tape recorder and were digitized at a sampling rate of 22.05 kHz with 16-bit resolution using either Syntrillium Cool Edit Pro version 1.2 or Adobe Audition 1.5. Speakers were asked to repeat real words produced without a carrier phrase at a self-selected normal rate. The research record does not indicate that any instructions were given with regard to the “carefulness” of the speech (cf., e.g., Modarresi et al., 2004) or to prosodic realization. Typically, three tokens of each word type were elicited in succession. Real rather than nonsense words were elicited by Butcher for practical and cultural reasons (as discussed by Tabain et al., 2011).

The corpus collected by Butcher was originally designed to capture all consonant contrasts in each language (Butcher, 2012). The consonants analyzed in the present study comprised /p t tʃ k/ in all positions within the word and vowel environments; however, consonants were most frequently adjacent to /a/ and in word-initial or word-medial position. (More information concerning position and vowel distribution is given below.) Table I (Sec. III A) indicates the distribution of tokens according to consonant context. The Gupapuyngu lamino-dental stop was not included in the current analysis for reasons of comparability. It should be noted that the palatal is in these languages a lamino-alveolarpalatal rather than a dorso-palatal and the retroflexes are typically sub-apical (involving contact between the underside of the tongue tip and the roof of the mouth; see Butcher, 1995, 2012) or sub-laminal. Burarra and Gupapuyngu possess a fortis/lenis contrast, essentially, a length or articulatory effort distinction (see Butcher, 2004).

The tokens analyzed in this study were most often bi- or tri-syllabic words. Approximately 250 words were targeted per language: 276 for Burarra, 256 for Gupapuyngu, and 213 for Warlpiri. The 100 most frequently occurring words per language in the set of tokens analyzed are listed in the Appendix. Representative examples of word-medial alveolar, retroflex, and palatal tokens are as follows: Burarra, wata /wata/ “wind”; marda /maʃa/ “tail”; bacha /baʃa/ “to fight”; Gupapuyngu, wata /wata/ “wind”; matan /matan/ “hairbelt”: watja /waca/ “pointed”; Warlpiri, matu /matu/ “tired”; mirita /mita/ “narrow shield”; jaja /jaca/ “mother’s mother.” Additional details may be found in Graetzer (2012). As far as possible, in the present study, words were confined to the alternating consonant and vowel pattern (CV,CV.CV) in order to facilitate comparison, both because this is a common sequence in 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 (e.g., Butcher, 2006).

With regard to consonant position within the word, there was approximately equal distribution of word-initial and word-medial tokens. There were a few cases of Burarra and Gupapuyngu VC tokens in which C was word-final but typically words ended in a vowel. It was necessary to include non-word-medial tokens in order to compare CV and VC and to compare prosodic conditions. In some cases, there was an imbalance in the distribution of tokens due to the corpus comprising real words. In particular, there tended to be fewer alveolar and retroflex tokens than bilabial, palatal, and velar tokens. Additionally, there were fewer tokens available for one Gupapuyngu speaker than for the other speakers.

As LEs require sampling across vowel contexts, vowel distribution is summarized briefly here. For Burarra, /a/ comprised 64% of the vowel tokens in the CV condition and 43% of the vowels in the VC condition. Vowels /i/ and /u/ comprised between 10% and 21% of the vowel tokens, /e/

<p>| TABLE I. Locus Equation slope means (M), standard deviations (s.d.) and n per language, consonant place, trajectory period, and prosodic condition (BUR = Burarra, GUP = Gupapuyngu, WAR = Warlpiri). When marked with “NA,” statistics for 1 or more speakers have not been generated due to a low n (footnote 3). |
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<td>BUR M</td>
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<td>WAR M</td>
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comprised between 2% and 3%, and /o/ comprised between 6% and 13%, in the two conditions. For Gupapuyngu, /a/ and /æ/ comprised 43% of the vowel tokens in the CV and 39% of vowels in the VC condition, and /i/ and /a/ and their long vowel counterparts comprised between 21% and 36% of vowels in the two conditions. For Warlpiri, /a/ and /æ/ comprised 43% of vowel tokens in the CV condition and 45% of vowels in the VC condition. Vowels /i/ and /a/ and their long counterparts comprised between 26% and 29% of vowels in the two conditions. In general, /a/ was the most commonly occurring vowel, at least in non-palatal stop environments, while /u/ tended to occur less often, and /i/, least often.

B. Initial processing

Audacity Version 1.2.6 (open source software) was employed by the present authors when necessary to reduce incidental background noise (bird calls, generator noise, etc.) for those speakers recorded in the field. All acoustic measurements were carried out in the EMU Speech Database System (e.g., Cassidy and Harrington, 2004). The parameters for formant calculation comprised Linear Predictive Coding using the autocorrelation method for formant tracking and the Durbin recursion with a fixed order of 10, a pre-emphasis of 0, and a 25 ms Blackman window with a frame shift of 5 ms and a bandwidth of 300 Hz. Formant tracking errors were manually corrected. Segmentation and labeling were performed in EMU based on visual inspection of the acoustic waveform and wide-band spectrographic records.

The segmentation criteria were as follows: the intervals for plosives /p t k/ and the lenis equivalents for Burarra and Gupapuyngu were marked from (1) the offset of periodicity in the preceding vowel or the time point of an abrupt reduction in amplitude in the acoustic waveform associated with a consonantal constriction to (2) the end of the consonant release burst, if this occurred, or a abrupt increase in amplitude for the following vowel. The vowel boundaries were marked at the onset and offset of periodicity and higher formants in vowels following and preceding the closure period for stops.

The fundamental frequency signal was extracted using the EMU (tkassp/f0ana) pitch-tracker, with a range of 50 to 500 Hz and a frame shift of 5 ms. On the basis of the international analysis (which assumed that the vowel carrying a sharp F0 rise to a peak somewhere in or around the syllable rhyme was prominence-lending), vowels were identified as being prominent or non-prominent. Words were uttered in isolation and were therefore realized as full intonational phrases. This meant that prominence-lending rises were analyzed as post-lexical (or phrasal) prosodic prominence. Therefore, prosodic effects applying to both the utterance/phrase level and the word level are relevant. Additionally, as there were three repetitions of each word, there was some “listing” prosody and, typically, speakers produced a falling F0 contour on the final word in the sequence.

C. Data analysis

1. Measurement points

After time-normalization (where time was scaled between 0 and 1), F2 frequencies were measured and extracted at three time points. Vowel-midpoint data were extracted at 0.5 into the manually segmented vowel, while vowel-onset and -offset data were extracted at 0.9 in VC sequences, termed preceding vowel-offset, and 0.1 in CV sequences, termed following vowel-onset, into the vowel to approximate the release or onset of the consonant occlusion (while avoiding perturbation in the vowel formants associated with the consonant during the vowel-consonant transition). This use of time-normalization is consistent with the methods employed by Harrington (2010) and implemented in the EMU-R package (Cassidy and Harrington, 2004), with an extension of the process to the onset and offset measurements.

2. Locus equation procedures

Spectral data was analyzed in R 2.14.0 (R Development Core Team, 2011). Two sets of procedures were carried out in this study: (1) LE analyses including calculations of F2 consonant loci, and (2) F2 variance analyses. Approximately 180 LEs (typically 20 per speaker) were generated in this study, based on over 9000 CV/VC sequences extracted from real words (Table I). These were calculated per speaker, per trajectory period (a term used by Recasens, e.g., Recasens and Espinosa, 2010; CV or VC trajectory period) and prosodic condition (prominent, non-prominent) using the “locus” function in the EMU-R package, which relies on the “lm” function in the “stats” package in R. In this study, we took a “mirror image” of the standard CV LE and applied it to the VC context to ensure comparability with the study of Tabain (but cf. the work of Lindblom, e.g., Lindblom and Sussman, 2012), i.e., we extracted spectral data at vowel-midpoint and just before consonant closure in the VC period. The underlying simple linear regression function and formula within the locus function in the EMU-R package is lm(F2i ~ F2t) where F2i corresponds to F2 extracted at the vowel onset/offset and F2t corresponds to F2 extracted at the vowel-midpoint. Quantile-quantile and residuals vs fitted values plots were inspected to determine whether there were any clearly observable deviations from normality or homogeneity of variance in the distribution of residuals.

Although some past studies have calculated separate velar slopes for front and back vowel contexts (see the discussion in Iskarous et al., 2010), separate velar slopes for front and back vowel contexts were not calculated here, after, e.g., Löfqvist (1999), Tabain et al. (2004), and Lindblom et al. (2007), for three main reasons. First, listeners do not appear to perceive distinct front and back velars (Fowler, 1994; see discussion in Tabain and Butler, 1999). Second, it cannot be assumed that there are in fact two targets; there is some palatographic and acoustic evidence for threevelar constriction locations in some Australian languages, including Burarra, Gupapuyngu, and Warlpiri (Butcher and Tabain, 2004; Graetzer, 2012). Third, it remains to be seen
whether articulatory evidence can be found for continuous variation in the constriction location (see Sec. 1A).

3. Statistical procedures

A Linear Mixed Model (LMM) procedure was employed to measure the magnitude of the effects of various factors on LE slopes, after, e.g., Iskarous et al. (2010), using the “lme4” package in the R programming language (a General Linear model was not applied as in the study of Iskarous et al. given that we had the single dependent variable of LE slope). The dependent variable was the LE slope and the fixed factors were consonant place of articulation (five levels), the order of the vowel relative to the consonant or trajectory period (two levels: CV or VC), prosodic prominence in the vowel (two levels: Strong, Weak), and language group (three levels). Speaker was included as a random factor. Chi-squared (generalized likelihood-ratio) tests were used to determine whether interactions were required (Faraway, 2005). Post hoc Tukey’s HSD tests with corrected p values were used to identify significant contrasts [using the “glht” function in the R “multcomp” package, also adjusted for the random factor of speaker; see Baayen (2008) and Holthorn et al. (2008), for details of the adjustment procedure within Tukey’s tests]. LMM procedures were subsequently applied to LE slopes per language group with the fixed factors of consonant place, trajectory period, and prosodic prominence (random factor: Speaker), also with adjusted Tukey’s contrasts.

Two main methods were used to analyze variance. First, variance in F2 at the vowel-consonant boundary measurement points (preceding vowel-offset in the VC condition and following vowel-onset in the CV condition) was calculated in the form of standard deviation or s.d. (σ) values. Bonferroni corrected correlations of LE slopes and F2 s.d. values were calculated (β = 0.008) per language group and trajectory period (VC, CV). These calculations could not be performed per speaker due to insufficient tokens. Second, modified Brown-Forsythe Levene-type t-tests were used per language group and per factor of consonant place, trajectory period, and prosodic prominence to test for equality of variance between levels of each factor (Brown and Forsythe, 1974). The Brown-Forsythe Levene-type test statistic in this context is similar to an analysis of variance F statistic but applied to absolute deviations of observations from the group median, as a more robust alternative to a Levene statistic applied to deviations from the mean (i.e., robust to departures from normality; Brown and Forsythe, 1974). Arguably, the magnitude of variance (σ²) or s.d. in this context is inversely correlated with the DAC value of the consonant.

Given the choice of female speakers only and of these analytical procedures, no data transformation was necessary to control for variation in vocal tract dimensions. Throughout, α = 0.05 (before any correction).

III. RESULTS

A. Locus equation analysis

LE slopes calculated for all speakers are tabulated as language group means in Table I and summarized in Fig. 1. When group means were calculated per consonant, collapsing trajectory period, and prosodic conditions, the velar slope was the highest for Burarra and Gupapuyngu at 0.84 and 0.91, respectively (s.d. = 0.1, 0.2) and for Warlpiri at 1.03 (s.d. = 0.1). For Burarra, the retroflex and palatal slopes were the lowest at 0.5 and 0.54 (s.d. = 0.2), for Gupapuyngu, the alveolar and the palatal slopes were the lowest at 0.49 and 0.56 (s.d. = 0.1, 0.2) respectively, and for Warlpiri, the palatal slope was the lowest at 0.51 (s.d. = 0.2).

An LMM applied to the LE slopes yielded a highly significant main effect of consonant place [p t k; F(4,117) = 37.9, p < 0.0001; see Tukey’s results below]. There was little variance according to speaker (σ² < 0.001) or to residuals (σ² < 0.05). There was also a highly significant main effect of trajectory period [VC, CV; F(1,117) = 17.7, p < 0.0001]. The CV period was associated with an estimate that was 0.2 higher than that of the VC period (measured in slope or k units), i.e., there was stronger anticipatory coarticulation. There was also a relatively weak effect of language group [F(2,117) = 2.94, p < 0.01]. Burarra was associated with slightly lower slopes than the other languages (with an estimate that was 0.1 lower than Gupapuyngu and 0.06 lower than Warlpiri, in k units).

There was also no effect of prosodic prominence [F(1,117) = 1.41, p > 0.05]. There were two relatively weak interactions: consonant by trajectory period [F(4,117) = 3.3, p < 0.05] and trajectory period by group [F(2,117) = 5.7, p < 0.01]. In the case of the first significant interaction, all consonants were associated with lower slopes in the VC condition with the exception of the retroflex, for which the opposite pattern was observed. In the second interaction, the difference between the Warlpiri and Burarra speakers was greater in the VC condition, whereas the difference between the Gupapuyngu and Burarra speakers was greater in the CV condition (see Fig. 1).

The results of Tukey’s HSD multiple contrasts are presented in Table II. Across groups, peripheral consonants were associated with higher slopes (hence, stronger vowel-dependent coarticulation) than non-peripheral consonants. Velar slopes did not differ significantly from bilabial slopes. Palatal stops tended to be associated with the lowest slopes, but coronal (alveolar, retroflex, and palatal) slopes did not differ significantly from one another. No other comparisons were significant. It can be observed in Fig. 1 that slopes vary more in the VC condition, especially for the Warlpiri speakers. Stops in Warlpiri were associated with a higher magnitude of vowel-dependent coarticulation than those in Burarra at p < 0.001 (Table II), while Gupapuyngu stops were associated with a higher magnitude of such coarticulation than Burarra stops in the CV period, but not in the VC period (see Fig. 1).

When languages were examined individually, for all three groups there was a highly significant effect of consonant place [Burarra, F(4,40) = 10.3, p < 0.0001; Gupapuyngu, F(4,50) = 14.9, p < 0.0001; Warlpiri, F(4,53) = 11.6, p < 0.0001]. As noted above, consonants /p k/ were typically associated with higher slopes than the three coronals. Overall, the two sets of non-coronals and coronals did not differ within themselves. For the Gupapuyngu speakers, the CV trajectory
period was associated with higher slopes than the VC period \([F(1,50) = 36.3, p < 0.0001]\), that is, consonants tended to be more highly coarticulated by following vowels than preceding ones. The CV period was associated with an estimate that was 0.2 (k units) higher than that of the VC period. For the Burarra speakers, a similar trend merely approached significance \([F(1,40) = 3.5, p < 0.07]\), and there were significant but relatively weak interactions between consonant and trajectory period \([F(4,40) = 3.4, p < 0.05]\) and between consonant, trajectory period, and prosodic prominence \([F(4,40) = 3.9, p < 0.01]\). For these speakers, /k p t/ slopes tended to be lower in the VC context than in the CV context, but for /l/, locus slopes tended to be slightly higher in this context. Similarly, for Warlpiri, all consonants except /l/ tended to be associated with smaller slopes in the VC condition, although the effect of trajectory period did not reach significance. For Burarra, the interaction between consonant, trajectory period, and prosodic prominence appeared to relate to the fact that for /l/, the mean slope was slightly lower for weak vowels in the CV condition (\(M = 0.46\)), than in the VC condition (\(M = 0.54\)); this result is likely due at least in part to a low \(n\) in some conditions. All other comparisons were not significant.

Tukey’s post hoc analyses, presented in Table III, indicated that for the Burarra and Gupapuyngu speakers, the non-coronals and coronals did not differ within themselves. For the Burarra speakers, /k/ was associated with higher slopes than the coronal stops, and /p/ was associated with higher slopes than /t/, but other comparisons were non-significant. For the Gupapuyngu speakers, the non-coronals were associated with higher slopes than the coronals. For the

<table>
<thead>
<tr>
<th>Consonant</th>
<th>z</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>p – t</td>
<td>-3.7</td>
<td>0.005**</td>
</tr>
<tr>
<td>p – t</td>
<td>-2.7</td>
<td>0.05*</td>
</tr>
<tr>
<td>p – c</td>
<td>4.6</td>
<td>0.001***</td>
</tr>
<tr>
<td>p – k</td>
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<td>0.9</td>
</tr>
<tr>
<td>t – t</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>t – c</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>t – k</td>
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<td>0.001***</td>
</tr>
<tr>
<td>t – c</td>
<td>1.4</td>
<td>0.6</td>
</tr>
<tr>
<td>t – k</td>
<td>-3.6</td>
<td>0.005**</td>
</tr>
<tr>
<td>c – k</td>
<td>5.5</td>
<td>0.001***</td>
</tr>
</tbody>
</table>

TABLE II. Tukey’s post-hoc LE slope results for LMM across groups (with interactions; BUR = Burarra, GUP = Gupapuyngu, WAR = Warlpiri). *\(p < 0.05\), **\(p < 0.01\), ***\(p < 0.001\).
Warlpiri speakers, the non-coronals were associated with higher slopes than the palatal, and the velar was associated with higher slopes than the alveolar, retroflex, and bilabial. In sum, across the three languages, the non-coronals were typically seen to undergo a larger magnitude of vowel-to-consonant coarticulation than the coronals.

With regard to F2 consonant loci (after Delattre et al., 1955), summarized in Table IV per group, consonant, and trajectory period condition, the palatals were typically associated with the highest loci, the non-coronals with the lowest loci, and the retroflex and alveolar with intermediate loci. The velar locus was extremely variable for Gupapuyngu and Warlpiri speakers in both CV and VC conditions and for the Burarra speakers in the CV condition. The bilabial locus was primarily because of the presence of negative values, especially for /k/. There were also negative values for /p/ in Burarra and Gupapuyngu.

### Table III. Tukey’s post-hoc LE slope results for LMM per group (with interactions for Burarra only; BUR = Burarra, GUP = Gupapuyngu, WAR = Warlpiri). *p < 0.05, **p < 0.01, ***p < 0.001.

<table>
<thead>
<tr>
<th></th>
<th>p - t</th>
<th>p - t</th>
<th>p - c</th>
<th>t - t</th>
<th>t - k</th>
<th>t - c</th>
<th>c - k</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUR</td>
<td>-3.2</td>
<td>-1.6</td>
<td>1.8</td>
<td>1.2</td>
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<td>-1.4</td>
<td>-4.4</td>
</tr>
<tr>
<td></td>
<td>0.05*</td>
<td>0.5</td>
<td>0.4</td>
<td>0.7</td>
<td>0.5</td>
<td>0.6</td>
<td>0.001***</td>
</tr>
<tr>
<td>GUP</td>
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<td>4.3</td>
<td>-1.8</td>
<td>-1.2</td>
<td>1.2</td>
<td>-4.6</td>
</tr>
<tr>
<td></td>
<td>0.05*</td>
<td>0.0001***</td>
<td>0.001***</td>
<td>0.39</td>
<td>0.7</td>
<td>0.75</td>
<td>0.001***</td>
</tr>
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<td>-3.4</td>
<td>-1.3</td>
<td>2.2</td>
<td>-4.4</td>
</tr>
<tr>
<td></td>
<td>0.85</td>
<td>0.1</td>
<td>0.05*</td>
<td>0.01**</td>
<td>0.7</td>
<td>0.2</td>
<td>0.001***</td>
</tr>
</tbody>
</table>

### Table IV. F2 consonant loci—group means (M) and standard deviations (s.d.) per language. Measurement points are vowel-onset (0.1) and vowel-midpoint (0.5) in the CV condition, and vowel-offset (0.9) and vowel-midpoint (0.5) in the VC condition. * denotes an unrealistic value. n is identical to that for the LE slopes.

<table>
<thead>
<tr>
<th></th>
<th>p</th>
<th>t</th>
<th>c</th>
<th>k</th>
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<td>610</td>
<td>1822</td>
<td>1854</td>
<td>2123</td>
</tr>
<tr>
<td>s.d.</td>
<td>532</td>
<td>65</td>
<td>239</td>
<td>314</td>
</tr>
<tr>
<td>GUP</td>
<td>349</td>
<td>1918</td>
<td>2238</td>
<td>2359</td>
</tr>
<tr>
<td>s.d.</td>
<td>325</td>
<td>143</td>
<td>350</td>
<td>381</td>
</tr>
<tr>
<td>WAR</td>
<td>600</td>
<td>1755</td>
<td>1765</td>
<td>2376</td>
</tr>
<tr>
<td>s.d.</td>
<td>395</td>
<td>276</td>
<td>195</td>
<td>315</td>
</tr>
</tbody>
</table>

### B. F2 variance analysis

To investigate the effects of consonant place of articulation, trajectory period, and prosodic condition on consonantal context sensitivity, we measured F2 variance at vowel-consonant boundaries. Levene’s t-tests revealed that variation differed strongly between consonant places of articulation for all languages [Burarra, F(4,4083) = 49.5, p < 0.0001; Gupapuyngu, F(4,2662) = 25.4, p < 0.0001; Warlpiri F(4,2439) = 41.1, p < 0.0001]; there was a higher magnitude of variation in non-coronals, especially in the velar, and less variation in the coronals. For the Gupapuyngu and, in particular, Warlpiri speakers, there was greater variance at the onset of the vowel following the consonant [Gupapuyngu, F(1,2667) = 4.59, p < 0.05; Warlpiri, F(1,2442) = 22.97, p < 0.0001], i.e., consonants appeared to be more sensitive to the coarticulatory influence of following vowels. When plotted in Fig. 2, the difference between coronal and non-coronal consonants is apparent, and the trajectory period effect is perhaps more readily observable in the weak vowel context. For the Burarra speakers, however, the trend toward greater variation in the CV context did not reach significance [F(1,4086) = 2.01, p = 0.16].

With regard to prosodic effects on variance (also shown in Fig. 2), for the Burarra and Warlpiri speakers, there was a significant but relatively weak effect of prosodic context [Burarra, F(1,4086) = 4.37, p < 0.05; Warlpiri, F(1,2442) = 4.42, p < 0.05]. However, the direction of the effect differed; for Burarra, there was greater variance in the strong context, especially for the non-coronals, and for Warlpiri, in the weak context for /k/. For the Gupapuyngu speakers, the comparison was non-significant [F(1,2667) = 0.004, p = 0.84]. In general,
with the exception of Warlpiri /k/, the differences between the coronal and non-coronal consonants were reduced in the prosodically weak context.

LE slopes are plotted against standard deviations (Hz) in Fig. 3. Correlations in the CV (left panel) condition and for the Burarra speakers in the VC (right panel) conditions were moderate or high, and the linear regression models explained between 44% and 66% of the variability around the mean ($R^2$). In other words, a tendency was observed for variability at the vowel-consonant boundary to increase as coarticulation between the consonant and the vowel increased. Correlations were low and non-significant for the Gupapuyngu and Warlpiri speakers in the VC condition. One explanatory factor may be that of inter-speaker variability; one Gupapuyngu speaker showed a higher correlation ($r = 0.8$) than the other two speakers ($r = 0.3$), and one Warlpiri speaker showed a lower correlation ($r = 0$) than the other two ($r = 0.7$).

**IV. GENERAL DISCUSSION**

The results above indicate that a number of factors interact in vowel-to-consonant coarticulation and in consonantal coarticulatory sensitivity in Burarra, Gupapuyngu, and Warlpiri: consonant place of articulation, trajectory period, and, potentially, prosodic prominence. These are discussed below in order of the strength of relationship in the current data.

**A. Effects of consonant place of articulation**

The analyses presented here show clear and consistent consonant place of articulation effects on both the magnitude of consonant-vowel coarticulation and the magnitude of consonantal coarticulatory sensitivity, confirming hypothesis (1) (presented in Sec. ID). The magnitude of V-to-C coarticulatory effects tended to decrease inversely with the degree of tongue-dorsum constraint for /k/ > /p/ > /t/ ≥ /d/ > /c/, consistent with the DAC model (e.g., Recasens et al., 1997) and as found in previous studies (e.g., Lindblom et al., 2007; Recasens, 1985; Fowler and Brancazio, 2000). As might be predicted on the basis of the LE slope results, non-coronals were associated with higher magnitudes of $F2$ variance at vowel-consonant boundaries, and thus higher levels of coarticulatory sensitivity, than coronals (as observed by, e.g., Recasens, 1985, for Catalan; Tabain and Butcher, 1999, for Yanyuwa and Yindjibarndi). The velar stop was associated with a particularly high magnitude of $F2$ variance, dependent on vowel context (see also, e.g., Ohman, 1966). By extension, the non-coronals appeared to have a lower coarticulation...
resistance. A general trend was observed toward relatively low variability associated with the palatal and the retroflex, and hence higher resistance. There was some evidence of a positive association between LE slopes and s.d. values, suggesting that the LE and the $F_2$ variance measure are related measures of consonantal coarticulation resistance (as argued by Recasens, 1985; Iskarous et al., 2010; see also Fowler and Brancazio, 2000).

With regard to $F_2$ consonant loci, the coronal and non-coronal categories were once again separable, if not in absolute locus frequency, then in variability. The non-coronals were typically associated with lower consonant loci and greater locus variability, particularly for the velar, suggesting that, as in the classic consonant locus illustrations (e.g., Delattre et al., 1955), the velar stop locus is dependent on vowel context (see also Öhman, 1966). As mentioned in Sec. II C, other studies indicate that the velar in Australian languages displays not merely front and back constriction locations but as many locations as the adjacent vowel targets: front, mid or central, and back (palatographic and acoustic data: Butcher and Tabain, 2004; acoustic data: Graetzer, 2012). However, there is some evidence in certain (non-Australian) languages of a continuous change in the point of velar constriction according to the adjacent vowel (e.g., English: Dembowski et al., 1998).

In sum, with regard to both sets of results, consonant places of articulation were seen to be divisible into two main categories with respect to coarticulation: coronal and non-coronal. This is consistent with the results reported for the $F_2$ dimension by Fowler and Brancazio (2000). It has been observed that the LE measure may not capture subtle differences between places of articulation involving the same articulator, e.g., a difference between coronal stop places (e.g., Hindi, Swedish, Tamil: Krull and Lindblom, 1996) or between non-coronal stop places (e.g., Brancazio and Fowler, 1998; Sussman et al., 1991). This was confirmed in our study.

It can be inferred from the combined results that the bilabial stop involves relative independence between different articulators, whereas in the formation of a velar constriction, the dorsum is relatively free to move in the horizontal dimension, especially in coordination with the following rather than the preceding vowel (see also Recasens, 1990; Fowler, 1994; Butcher and Tabain, 2004; Fletcher et al., 2007; Graetzer, 2012). These findings for the velar are consistent with previous research in a number of languages (e.g., Swedish: Öhman, 1966; Arrernte, Yanyuwa, and Yindjibarndi: Butcher and Tabain, 2004; Warlpiri: Fletcher et al., 2007). Palatals are typically associated with relatively low slopes, which indicate a high magnitude of resistance to vowel-dependent coarticulation (as has been shown by Tabain and Butcher, 1999, among others). The DAC model (e.g., Recasens, 2012) predicts that a high magnitude of resistance to coarticulation in lamino-alveolopalatals is due to
the large amount of predorsum and jaw raising and strong coupling between the primary articulator and other tongue regions. While apicals are typically less articulatorily constrained than laminals, retroflexes are also relatively constrained; a typical retroflex stop in these Australian languages involves tongue dorsum raising and a complex and precise tip/blade articulation (e.g., Butcher, 1995).

When trajectory period and prosodic differences were collapsed, the DAC values applicable to the consonants in the current experiment were consistent with those indicated by previous experiments conducted by Recasens and colleagues (e.g., Recasens et al., 1997) and by Tabain and colleagues (e.g., Tabain and Butcher, 1999). The velar and the labial could be assigned a minimal DAC value (DAC = 1), the alveolopalatal, a maximal DAC value (DAC = 3), and the apical consonants, an intermediate DAC value (DAC = 2), although the complexity and necessary precision of a sub-apical or -laminal retroflex gesture (Butcher, 1995) can render this consonant more constrained than the alveolar gesture (hence a DAC value in the range of 2 to 3). While these data support the view that the primary determinant of a consonant’s magnitude of coarticulatory resistance is the degree of biomechanical (dorsal) constraint involved in its production, as formalized in the DAC model and as demonstrated by Iskarous et al. (2010), they are also consistent with the view that DAC values should be modifiable on the basis of language-specific articulatory patterns and constraints on consonant and vowel variability (see Bladon and Al-Bamerni, 1976). Indeed, this point has been recognized by Recasens and colleagues (e.g., Recasens et al., 1997). It is also suggested that DAC values should be modifiable so as to be able to capture several other factors, such as prosodic ones, that lead to cross-linguistic differences in coarticulation resistance (see, e.g., Recasens, 1985). More generally, the results support a coproduction model (e.g., Öhman, 1966) in which consonant gestures are adapted to the vowel context in which they occur, and in which the magnitude of this adaptation depends primarily on consonantal articulatory constraints, e.g., the involvement of the tongue dorsum in the constriction formation (see, e.g., Lindblom and Sussman, 2012).

With regard to the issue of differences between the three languages in the current study, it was found that consonants in Warlpiri tend to undergo a higher magnitude of coarticulation by adjacent vowels than those in Burarra (additionally, there was more variability in Warlpiri LE slopes). This result does not appear to be due to a difference in vowel distribution; if it were, we would expect a similar outcome for a comparison between Burarra and Gupapuyngu (as Gupapuyngu and Warlpiri share a three vowel system with a length contrast, and Burarra possesses five vowels). Nor is the result due to a difference in the number of coronal places of articulation. Hence, despite the predictions that have been made in the literature (e.g., Manuel, 1990), at this stage there is insufficient evidence of any reliable vowel-dependent coarticulation differences between the languages relating to vowel or consonant inventory composition (cf. also Manuel, 1999; Mok, 2013).

B. Trajectory period effects

While it has been shown that LE slopes typically vary primarily as a function of consonant place, evidence has also been presented of variation in slope as a function of the sequential order of the consonant and vowel, i.e., of biases in coarticulatory direction. There was a higher magnitude of anticipatory V-to-C coarticulation than carryover coarticulation on the LE measure, confirming hypothesis (2-b) and disconfirming (2-a). This pattern was independent of consonant place environment, at least for non-retroflex stops. Such a tendency toward anticipatory coarticulation is thought to indicate planned, active coarticulation (e.g., Recasens, 1989). Similarly, there was a tendency toward greater consonantal coarticulatory sensitivity on the F2 variance measure to following vowels than to preceding ones (2-b). According to a model of coarticulatory directionality (e.g., Recasens, 1999), the magnitude of anticipatory V-to-C coarticulation is inversely correlated with the magnitude of carryover C-to-V coarticulation. Hence, the tendency in the present results indicates that there is a higher magnitude of C-to-V coarticulation also in the anticipatory direction in these languages (see Graetzer, 2012).

Unlike, for example, the results of Modarresi et al. (2004) for American English, alveolars in our study did not behave differently from bilabials and velars with regard to the relative strength of anticipatory and carryover coarticulation. However, for some Burarra and Warlpiri speakers, retroflex slopes differed from those of other places of articulation in their tendency to be larger in the VC condition than in the CV condition. This is despite the fact that it has been argued that the inclusion of the retroflex in Australian language inventories may motivate greater control over the VC period in general (e.g., Steriade, 2001; Tabain et al., 2004). Of course, unlike the other consonants, the majority of retroflex-to-vowel coarticulation is manifested in F3 rather than F2, mainly in the anticipatory direction in these languages (e.g., Graetzer, 2012). This pattern of reduced vowel-dependent coarticulation in the CV period is reminiscent of results presented for two Yanyuwa speakers by Tabain et al. (2004). It appears to relate to several factors. We would suggest that there is greater gestural blending with the preceding vowel than with the following one; while the tongue tip can be curled for the retroflex consonant during the preceding vowel, the consonantal place of constriction is affected by that vowel—“front vowels having ... more anterior targets of retrofle[x]ion”—this perhaps being necessary to the attainment of the retroflex target (Krull and Lindblom, 1996, p. 73; Recasens, 1999). Presumably, retroflex production is otherwise relatively constrained, especially when sub-laminal (see, e.g., Recasens, 1999). The finding of reduced vowel-to-consonant coarticulation for Burarra in the CV period may also be ascribed to the inertial properties of the retroflex gesture, while in the case of Warlpiri, LE slopes in the CV period are similar for retroflexes and alveolars, as would be anticipated given previous articulatory descriptions for other Australian languages (e.g., Arrernte: Tabain, 2009). Finally, in part due to apical neutralization processes (Butcher, 1995), retroflexes are
relatively infrequent in certain conditions in these languages (when a prominent vowel follows, and when a non-prominent vowel precedes, as shown in Table I). While the LE is relatively robust to variation in the set of vowels involved in an equation (i.e., the slope does not appear to depend on precisely which vowel qualities occur in the context of a particular calculation; Sussman et al., 1991), it is sensitive to sample size; all else being equal, the higher the n in any linear regression, the more accurate the modeling.

The general predominance of anticipatory V-to-C coarticulation over carryover coarticulation and the tendency toward greater coarticulatory sensitivity to the following vowel is a 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. Importantly, however, the results are consistent with their predictions. By extension, it could be argued on the basis of these results—at least for the languages investigated here—that the left edge of the consonant is more protected than the right edge (i.e., the release) from the coarticulatory effects of adjacent vowels, particularly in the case of word-medial consonants, in accordance with the imperative to preserve place of articulation contrasts (Butcher, 2006). The experimental findings reported here indicate that a bias in coarticulatory directionality can be language-specific (as discussed by, e.g., Beddor et al., 2002), and not merely determined by inherent articulatory constraints on consonants (see also Modarressi et al., 2004). That is, as in many domains of speech, there is an interaction of language-particular and biomechanical factors in coarticulatory directionality.6

C. Prosodic prominence effects

With regard to prosodic effects on vowel-to-consonant coarticulation, there were no observable main effects, in support of hypothesis (3). This is consistent with the view that the LE slope is an index of consonant-vowel coarticulation that is robust to prosodic variation (Lindblom et al., 2007; Iskarous et al., 2010), in the sense that V-to-C coarticulatory effects tended to decrease in the order /k/ > /p/ > /h/ > /l/ > /c/ in both prosodic conditions. For Burarra, there was an interaction effect of prosodic prominence by consonant and trajectory period on vowel-dependent coarticulation (principally involving the retroflex stop) and a main effect on coarticulatory sensitivity; there was greater variance in the prosodically strong context, especially for the non-coronals. For Warlpiri, there was greater variance in the weak context but no other evidence of prosodic effects on coarticulation. For Gupapuyngu, there were no effects. These results for Burarra appear to be consistent with previous findings of vowel reduction in unstressed syllables (Butcher, 2006), i.e., of some effect of prominence on vowel realization. Nonetheless, it appears to be the case that the spatial effects of prosodic prominence on the nucleus are not strong in these languages, unlike the effects shown in languages such as English (e.g., de Jong et al., 1993; Cho, 2004, 2005). If there is hyper-articulation due to the effects of prosodic prominence in these languages, it may be that it occurs to a greater extent in consonants than in vowels, and especially in the post-tonic consonant (see Butcher and Harrington, 2003). This, however, requires further investigation for Burarra and Gupapuyngu.

V. CONCLUSIONS

The experiment reported here examined consonant place of articulation, trajectory period, prosodic, and language effects on vowel-to-consonant coarticulation and consonantal context sensitivity in three Australian languages. These languages differed in both the number of coronal categories (three or four) and the number of vowels (three with a length distinction, or five). With regard to metrics, the results presented here show that the LE is an effective measure of consonantal coarticulation resistance in less-well studied languages as well as in the more commonly studied European languages. The general consistency between the LE and F2 variance results, and the evidence of linear dependency between the LE and F2 standard deviations under most conditions, support the claim that the F2 variance measure can be a valuable additional measure of relative coarticulation resistance, as argued by Recasens (1985). The results support the use of this measure to test for overall gestural compatibility between a consonant and a particular vowel quality or set of qualities, given that vowels also differ in coarticulation resistance (e.g., Recasens, 2012).

The present research points to several issues for further analysis. Analyses of coarticulatory directionality should be planned in the future in such a way that consonant position within the word can be included as a factor in any model (in addition to prosodic prominence). This inclusion would be motivated by the special behavior of the word-medial consonant in these languages (e.g., Butcher, 2006). Relatedly, the matter of prosodic effects on coarticulation in Australian languages, particularly in Burarra, requires further clarification by means of an additional, more comprehensive investigation in which the effects of prosodic prominence on the post-tonic word-medial consonant can be isolated. Such an investigation would contribute to answering the larger question of whether prosodically-driven hyper-articulation in Australian languages is more likely to occur in the environment of post-tonic word-medial consonants than vowels (Butcher and Harrington, 2003). This question provides further justification for a systematic C-to-V coarticulation analysis in the three languages that would complement the LE analysis. Finally, it is important that further articulation and perception studies be carried out to clarify the relationship between coarticulation and gestural kinematics in Australian languages.

ACKNOWLEDGMENTS

The authors wish to thank Andrew Butcher for his generosity in providing the large data set from which these data are drawn, and the speakers who participated as subjects in the experiment. In addition, the authors thank Laura Koenig for her careful reading of the manuscript and for her helpful comments and suggestions. This research was primarily funded by an Australian Postgraduate Award granted to S.G.
### APPENDIX

The 100 most common words in the data set per language (in order of most to least common) with orthographic transcription, phonemic transcription ("phon.") and simplified gloss. BUR = Burarra, GUP = Gapapuyngu, WAR = Warlpiri.

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<tr>
<td>bijibijiyu</td>
<td>bijibijia</td>
<td>to be tangled</td>
<td>badak</td>
<td>ba:da:k</td>
<td>still</td>
<td>kitikiti</td>
<td>kitikiti</td>
<td>armpit</td>
</tr>
<tr>
<td>gu-derda</td>
<td>gu-de:ga</td>
<td>sickness</td>
<td>gakit</td>
<td>gakit</td>
<td>seagull</td>
<td>jampijin-pa</td>
<td>campcipina</td>
<td>(skin name)</td>
</tr>
<tr>
<td>gubardha</td>
<td>gubudga</td>
<td>road</td>
<td>gikit</td>
<td>gikit</td>
<td>laughter</td>
<td>kartirdi</td>
<td>kati:ji</td>
<td>tooth</td>
</tr>
<tr>
<td>buduracha</td>
<td>budu:ja:ca</td>
<td>bird</td>
<td>gujak</td>
<td>gujak</td>
<td>m. subsec.</td>
<td>lapaji</td>
<td>lapaci</td>
<td>parrot</td>
</tr>
<tr>
<td>gukukudhu</td>
<td>guku:ku:wa</td>
<td>to cool</td>
<td>bu:pa</td>
<td>bu:pa</td>
<td>father</td>
<td>mukarti</td>
<td>muka:ti</td>
<td>hat</td>
</tr>
<tr>
<td>jakaba</td>
<td>jaka:ba</td>
<td>to close</td>
<td>bu:pi</td>
<td>bu:pi</td>
<td>snake</td>
<td>yitakimani</td>
<td>jitakimani</td>
<td>tracking</td>
</tr>
<tr>
<td>gomkaka</td>
<td>gomkaka</td>
<td>person</td>
<td>bu:pu</td>
<td>bu:pu</td>
<td>throat</td>
<td>yu:juku</td>
<td>jacuku</td>
<td>humpy</td>
</tr>
<tr>
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<td>bo:ji:ci</td>
<td>saliva</td>
<td>buku</td>
<td>buku</td>
<td>forehead</td>
<td>yardipi</td>
<td>ja:ti:pi</td>
<td>hip</td>
</tr>
<tr>
<td>bokulcha</td>
<td>bokul:ca</td>
<td>to thunder</td>
<td>do:gu</td>
<td>dju:gu</td>
<td>waves (sea)</td>
<td>ka:ku:tu</td>
<td>ka:ku:tu</td>
<td>cockatoo</td>
</tr>
<tr>
<td>burdak</td>
<td>bu:rdak</td>
<td>yet, wait</td>
<td>witit</td>
<td>witit</td>
<td>python</td>
<td>nyuturnyuturn-pa</td>
<td>nutur:nu:rupa</td>
<td>(curly) hair</td>
</tr>
<tr>
<td>jalkaka</td>
<td>jal:ka:ka</td>
<td>to water</td>
<td>babala</td>
<td>babala</td>
<td>wrong</td>
<td>jaka</td>
<td>caca</td>
<td>mo. mo.</td>
</tr>
<tr>
<td>wordaja</td>
<td>woda:ja</td>
<td>to spectate</td>
<td>ba:gi:ti</td>
<td>ba:gi:ci</td>
<td>high tide</td>
<td>jukarra</td>
<td>cuka:ra</td>
<td>tomorrow</td>
</tr>
<tr>
<td>gapa</td>
<td>gapa</td>
<td>fa.'s sis.</td>
<td>djetji</td>
<td>ji:ci</td>
<td>sore, hole</td>
<td>kai:ki:yi</td>
<td>kaki:ji</td>
<td>elder bro.</td>
</tr>
<tr>
<td>gardabal</td>
<td>garda:bal</td>
<td>there (far)</td>
<td>dje</td>
<td>gu:kan</td>
<td>water</td>
<td>guduru</td>
<td>gu:du:ru</td>
<td>under</td>
</tr>
<tr>
<td>jicipa</td>
<td>jicipa</td>
<td>already</td>
<td>bukmak</td>
<td>bukmak</td>
<td>all</td>
<td>marnakiji</td>
<td>ma:na:ri</td>
<td>standing</td>
</tr>
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<td>jicala</td>
<td>jicala</td>
<td>to open</td>
<td>dji:mu:</td>
<td>dji:mu:</td>
<td>armpit</td>
<td>purtu:lu</td>
<td>pu:tu:lu</td>
<td>back</td>
</tr>
<tr>
<td>gajarrk</td>
<td>ga:jarrk</td>
<td>to be open</td>
<td>dju:mu</td>
<td>dju:mu</td>
<td>armpit</td>
<td>purtu:lu</td>
<td>pu:tu:lu</td>
<td>back</td>
</tr>
<tr>
<td>iganu</td>
<td>iganu</td>
<td>to spit out</td>
<td>bu:pa</td>
<td>bu:pa</td>
<td>father</td>
<td>mukarti</td>
<td>muka:ti</td>
<td>parrot</td>
</tr>
<tr>
<td>japarna</td>
<td>japarna</td>
<td>there (near)</td>
<td>yapa</td>
<td>yapa</td>
<td>sister</td>
<td>wanapi</td>
<td>wanapi</td>
<td>Whole</td>
</tr>
<tr>
<td>ikaj</td>
<td>ikaj</td>
<td>small bird</td>
<td>kuku</td>
<td>kuku</td>
<td>python</td>
<td>nyuturnyuturn-pa</td>
<td>nutur:nu:rupa</td>
<td>(curly) hair</td>
</tr>
<tr>
<td>igapal</td>
<td>igapal</td>
<td>flood plain</td>
<td>bi:qi:la</td>
<td>bi:qi:la</td>
<td>bad</td>
<td>wajurnpi</td>
<td>waci:ni</td>
<td>ironwood</td>
</tr>
<tr>
<td>igi:ci</td>
<td>igi:ci</td>
<td>thin, bony</td>
<td>werti</td>
<td>werti</td>
<td>hair</td>
<td>maliki</td>
<td>maliki</td>
<td>dog</td>
</tr>
<tr>
<td>i:ci</td>
<td>akici</td>
<td>conkerberry</td>
<td>tijiti</td>
<td>tijiti</td>
<td>bony</td>
<td>maliki</td>
<td>maliki</td>
<td>dog</td>
</tr>
<tr>
<td>imbi</td>
<td>imbi</td>
<td>to be swollen</td>
<td>ngapa</td>
<td>ngapa</td>
<td>ridge</td>
<td>wai:ki:ru</td>
<td>wa:ki:ru</td>
<td>reef, rocks</td>
</tr>
<tr>
<td>bangfiru</td>
<td>bangfur</td>
<td>sun</td>
<td>jatu</td>
<td>jatu</td>
<td>sun</td>
<td>djarumbir</td>
<td>witchiri</td>
<td>djarumbir</td>
</tr>
<tr>
<td>jukuru</td>
<td>jukuru</td>
<td>to run</td>
<td>gurak</td>
<td>gu:ra:k</td>
<td>throat</td>
<td>mirra</td>
<td>mirra</td>
<td>liver</td>
</tr>
<tr>
<td>bakala</td>
<td>bakala</td>
<td>hair, leaves</td>
<td>mu:dju</td>
<td>mu:dju</td>
<td>water</td>
<td>ngaanynnga</td>
<td>ma:na:yi</td>
<td>breathing</td>
</tr>
<tr>
<td>bugula</td>
<td>bugula</td>
<td>to be swollen</td>
<td>muta</td>
<td>muta</td>
<td>back</td>
<td>ngaka</td>
<td>ngaka</td>
<td>soon</td>
</tr>
<tr>
<td>bu:la:ja</td>
<td>bu:la:ja</td>
<td>to be swollen</td>
<td>ngapa</td>
<td>ngapa</td>
<td>back, top</td>
<td>ngalipi</td>
<td>na:zi:pi</td>
<td>vine</td>
</tr>
<tr>
<td>djalala</td>
<td>da:la:la</td>
<td>to knock</td>
<td>rebal'yun</td>
<td>rebal'yun</td>
<td>to clear</td>
<td>ngapikiri</td>
<td>ngapikiri</td>
<td>crested pigeon</td>
</tr>
<tr>
<td>divi:ja</td>
<td>divi:ja</td>
<td>be open</td>
<td>wata</td>
<td>wata</td>
<td>wind</td>
<td>ngapulu</td>
<td>ngapulu</td>
<td>breast</td>
</tr>
<tr>
<td>gaba</td>
<td>gaba</td>
<td>there (near)</td>
<td>wa:tu</td>
<td>wa:tu</td>
<td>dog</td>
<td>pardinj</td>
<td>paranj</td>
<td>waiting</td>
</tr>
<tr>
<td>gapa</td>
<td>gapa</td>
<td>there (far)</td>
<td>wi:ti</td>
<td>wi:ti</td>
<td>wallaby</td>
<td>puluku</td>
<td>puluku</td>
<td>bullock</td>
</tr>
<tr>
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<td>garada</td>
<td>there (near you)</td>
<td>yaka</td>
<td>jaka</td>
<td>no</td>
<td>rdapu</td>
<td>tudju</td>
<td>windbreak</td>
</tr>
<tr>
<td>gutuwa</td>
<td>gutuwa</td>
<td>to pick up</td>
<td>yapa</td>
<td>yapa</td>
<td>sister</td>
<td>wanapi</td>
<td>wanapi</td>
<td>whole</td>
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<tr>
<td>moruku</td>
<td>mo:ju:ki</td>
<td>bag/mullet</td>
<td>baba</td>
<td>baba</td>
<td>gum nut</td>
<td>wapami</td>
<td>wapami</td>
<td>walking</td>
</tr>
<tr>
<td>yibirr</td>
<td>jibir</td>
<td>quickly</td>
<td>buku-ju:pu</td>
<td>buku-ju:pu</td>
<td>ceremony</td>
<td>wairirlju</td>
<td>wairilju</td>
<td>waist</td>
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<tr>
<td>gu-lootok</td>
<td>gu-lootok</td>
<td>to open</td>
<td>da:ku</td>
<td>da:ku</td>
<td>hip</td>
<td>wa:ti</td>
<td>wa:ti</td>
<td>man</td>
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<tr>
<td>japa:ra</td>
<td>japa:ra</td>
<td>dry</td>
<td>dahak</td>
<td>dahak</td>
<td>cheek</td>
<td>yapa</td>
<td>yapa</td>
<td>person</td>
</tr>
<tr>
<td>yakurdu</td>
<td>juku:ra</td>
<td>yam</td>
<td>dahdi</td>
<td>dahdi</td>
<td>butts</td>
<td>yartura</td>
<td>ja:tu:ra</td>
<td>root</td>
</tr>
<tr>
<td>kupaku</td>
<td>kupak</td>
<td>to be open</td>
<td>dju:mu</td>
<td>dju:mu</td>
<td>armpit</td>
<td>purtu:lu</td>
<td>pu:tu:lu</td>
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</table>

The y-intercepts and speaker specific means and standard deviations are not included in this paper for brevity. Speaker-specific descriptive statistics are also not included because the aim of this paper is to discuss language-specific behavior. These details can be found in Graetzer (2012).

1Values smaller than 0 or greater than 1 are statistically unrealistic, that is to say, the data cannot be modeled reliably by the lm function in R and/or the locus frequency cannot be calculated by lm, but are reported in the scientific literature more generally. In the vast majority of cases in Australian language studies, Tabain (2004), and are reported in the context of Graetzer (2012).

2The high variability in the retroflex slopes, particularly for Warlpiri (Fig. 1), is due at least in part to multiple cases of a low n in the regression model.

3This non-linearity is at least partly due to cases of slopes of <0.1. In two cases, the slopes were for palatal stops, and n was not low. In the case of one retroflex and one alveolar slope, the regression method appeared to be unable to reliably fit the data because n was very low.

4A reviewer raised the matter of potential issues in cross-linguistic LE comparisons arising from the choice of time-normalized onset and offset frequencies (0.1 into the vowel following the consonant and 0.9 into the vowel preceding the consonant), which was made in the current study to avoid errors introduced by consonant perturbation and thus to increase the reliability of the data at those time points (see Secs. II B and II C). The majority of the claims we make are made on the basis of intra-systemic
patterns. Furthermore, the slight refinement in our approach is relatively minor and does not prevent us from making reliable comparisons with other studies.

“A reviewer pointed out that the slight differences between the languages with regard to coarticulatory directionality, and the differences between these results and those found for other, non-Australian, languages (e.g., Modaresi et al., 2004), indicate that we are not observing a general biomechanically-driven asymmetry in directionality but language-specific effects.


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Title: Locus equations and coarticulation in three Australian languages

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