Lateral formants in three Central Australian languages.

Marija Tabain [1], *Andrew Butcher* [2], *Gavan Breen* [3], *Richard Beare* [4, 5]

[1] La Trobe University, Melbourne, Australia.
[2] Flinders University, Adelaide, Australia.
[3] Institute for Aboriginal Development, Alice Springs, Australia.
[4] Murdoch Children's Research Institute, Melbourne, Australia.
[5] Monash University, Melbourne, Australia.

m.tabain@latrobe.edu.au, andy.butcher@flinders.edu.au, dictionaries@iad.edu.au, richard.beare@ieee.org

Abstract

This study examines dental, alveolar, retroflex and palatal lateral formants. Data are taken from three languages of Central Australia: Arrernte, Pitjantjatjara and Warlpiri. Results show that in relation to the alveolar lateral, the dental has a lower F1 and a higher F4; the retroflex has lower F3 and F4 and slightly higher F2; and the palatal has lower F1 and higher F2, F3 and F4. These results are discussed in light of various acoustic models of lateral production.

Index Terms: laterals, formants, Australian languages, acoustic models

10.21437/Interspeech.2014-240

1. Introduction

1.1. Basic acoustic models of the alveolar lateral

Authors on acoustic phonetics have proposed various acoustic models of lateral consonants (Fant [1], Stevens [2] and Johnson [3]). Perhaps the only point on which all three of these authors agree is that the pocket of air trapped on top of the tongue, behind the closure in the midline of the vocal tract, sets up a side-branch to the main airflow, resulting in an anti-resonance which they variously calculate as being about 2000-4000 Hz.

In addition, Fant and Stevens agree that the first formant of the lateral consonant is a Helmholtz resonance that is created by the lateral constriction and the cavity posterior to the constriction. However, whereas Stevens takes F2 to be a half wavelength resonance of the posterior cavity, Fant sets up a second Helmholtz resonance with a constriction in the uvular region, and a resonating cavity below this uvular constriction. Although both authors note a dorsal constriction in lateral production, only Fant takes the constriction to be great enough to set up a second resonating system. This is most likely due to the fact that Fant was describing Russian speech – where the lateral is strongly velarized to contrast with a phonemically palatalized lateral – while Stevens was describing English speech, where velarization varies according to various prosodic and dialectal factors. Stevens and Fant also posit different sources for the formants above F2 – however, they seem to agree that the front cavity resonance (F4 for Stevens and F3 for Fant) is effectively cancelled by the anti-resonance, with the end result that the front cavity does not contribute to the spectrum for /l/ (contra, for example, the English approximant /r/, where the front cavity plays an important role).

Johnson [3], by contrast, has a quite different approach. He suggests a schwa-like tube is appropriate for modelling /l/, with the addition of the side-branch formed on top of the tongue as a result of the main airflow along the side(s) of the tongue. Perhaps the main consequence of this assumption is that Johnson proposes quite different lateral formant values to the other two authors: assuming a uniform tube, he suggests formants at 530 Hz, 1590 Hz and 2,650 Hz, but notes that due to the smaller diameter of the cavity anterior to the lateral constriction relative to the cavity behind the constriction, the first resonance is noticeably lower than would be predicted by the uniform tube model. In addition, he suggests that velarization results in a lowering of the second resonance. Nevertheless, these values are quite different to the values posited by Fant and Stevens, who propose F1 values of about 350 Hz, F2 values of about 800-1100 Hz, and F3 values of about 2800-2900 Hz. It can be seen that the gap between F2 and F3 is quite large for both Fant and Stevens – both authors deem this to be a characteristic of lateral production, whereas the spacing of formants is much more even in Johnson's model.

Although there have been some studies on the articulatory and acoustic properties of the alveolar lateral in several languages (for example, [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]), and several sociolinguistic studies (e.g. [16, 17]), to our knowledge there has been no larger-scale acoustic study of lateral sounds other than the alveolar (but see [18] for a survey of articulatory studies that included the palatal or palatalized lateral). Since lateral production varies greatly from individual to individual (e.g. in the extent to which the lateral opening is greater or non-existent on one side or the other of the tongue – or the extent of any accompanying gestures, such as velarization – with concomitant acoustic consequences), studies of larger numbers of speakers are needed to separate out the acoustic patterns of the individual lateral phonemes from the acoustic consequences of individual speaker characteristics. This is precisely the aim of the present study.

1.2. Coronal consonants in Australian Aboriginal languages

Australian Aboriginal languages are known for their relatively large number of coronal place contrasts ([19, 20, 21]): most languages have either three or four coronal places of articulation. In any given language, the multiple coronal places of articulation typically extend across the oral stop, nasal and lateral series. A four-place system includes two apical consonants (i.e. produced with the tongue tip), which are alveolar and "retroflex" (i.e. postalveolar) in place of articulation; and two lateral consonants (i.e. produced with the tongue blade, which in practice often involves both the tip and part of the tongue body), which are dental and (alveo-)palatal in place of articulation. Central Arrernte (henceforth simply Arrernte), one of the languages studied here, is a language with a four-place contrast – namely lamino-dental, apico-alveolar, apico-postalveolar (retroflex) and lamino-(alveo)palatal. The other two languages studied here – Pitjantjatjara and Warlpiri – have three coronal places of articulation. Relative to Arrernte, they lack the lamino-dental place of articulation. Hence, the lateral inventory for Arrernte is /l̪ l ɭ ʎ/, and the inventory for Pitjantjatjara and Warlpiri is /l ɭ ʎ/.

Arrernte [22, 23, 24, 25, 26], Pitjantjatjara [27, 28, 29] and Warlpiri [30, 31] are all languages of Central Australia. Each language has a few thousand speakers, and all are still being learned by infants. Pitjantjatjara is more accurately described as a dialect of the greater Western Desert Language, which occupies about one sixth of the main Australian continent.

2. Method

Data are presented for 21 speakers from the three different Central Australian languages: seven speakers of Arrernte, nine speakers of Pitjantjatjara and five speakers of Warlpiri. Four of the Arrernte speakers, six of the Pitjantjatjara speakers, and all of the Warlpiri speakers were recorded to cassette tape in a quiet room in their home communities in about 1990 by author AB. One Arrernte speaker was recorded to reel-to-reel tape by author GB at the CAAMA radio studio in Alice Springs in the early 1980s; and two Arrernte speakers and three Pitjantjatjara speakers were recorded by author MT in professional-grade recording studios direct to computer (at Macquarie University in 2004 for Arrernte, and at La Trobe University in 2010 for Pitjantjatjara). All of the speakers are female, with the exception of one male speaker for each language. No speaker-normalization was carried out for these data.

Formants were calculated using the ESPS-based Pitch and Formant Tool in Emu – default settings were chosen with the exception of Frame-spacing, which was set to 5 ms, and Window, which was set to Hamming. Formants were sampled at the temporal midpoint of the lateral, and also 5 ms prior to the onset of the lateral, and 5 ms after the offset of the lateral. However, in the present paper, we focus only on the formants sampled at the temporal midpoint of the lateral consonant.

Stimuli consisted of single words which were repeated by the speaker three times in a row (or twice in a row in the case of the Arrernte speaker from the 1980s). Although laterals may occur as the first element of a consonant cluster in all three languages, for the present study we selected only tokens which were word-initial, word-final, or inter-vocalic. It should be noted that only Arrernte allows word-final (non-palatal) laterals phonemically (however this is relatively rare, and phonetically a schwa is likely to be appended word-finally). It should also be noted that in all three languages, the contrast between the alveolar and the retroflex (which are both apical) is neutralized in initial position – in the figures below, this neutralized initial apical is represented with a capital 'L'. However, this neutralized apical is not included in the statistical analyses, partly because the issue of neutralization is beyond the scope of this paper, and partly because initial observations suggested that the neutralized apical showed much greater variation across languages than did the non-neutralized laterals.

The reader is reminded that only Arrernte contains the dental lateral /l̪/ (written 'lh') in its inventory. In addition, whereas Pitjantjatjara and Warlpiri have a clear 3-vowel system /i, a, u/, Arrernte has the 3-vowel system /i, a, ə/, with the /i/ having a low lexical frequency/functional load - see [32] for discussion of the complexities of the Arrernte vowel system. (Pitjantjatjara and Warlpiri have an additional length contrast on the three vowels, but this length contrast is also of very low lexical frequency/functional load, and is hence ignored in the present study).

Linear Mixed Effects models were used to examine the formant results using the lme() function of the *nlme* package in R [33]. This function also estimates t- and p-values. Language, Speaker, Preceding vowel and Following vowel were included as random factors in the model, with the fixed factor Lateral. As noted above, the initial neutralized apical /L/ was excluded from these analyses. In addition, the retroflex lateral /ɭ/ (written 'rl') from Arrernte was also excluded from these analyses – this is due to the tendency for this sound to be produced as a sequence of palatal glide plus alveolar in certain environments – for instance, the word *arlenge* 'a long way away' might be pronounced [ɛjləŋə] instead of [əɭəŋə]. This is most likely due to the proximity of F2 and F3 for both of these consonants, the spectral prominence being lower in the case of retroflexes and higher in the case of palatals (cf. New York English [34]). Table 1 gives the number of tokens used in the present study.

Table 1. *<u>Number of tokens.</u> Note that shaded cells denote tokens that are include in the figures, but not included in the LME analyses. The number after each language name denotes number of speakers. Note that in this and subsequent tables and figures, 'lh' denotes the dental lateral /l̪/, 'rl' denotes the retroflex lateral /ɭ/, and 'ly' denotes the palatal lateral /ʎ/. Capital letter 'L' denotes the neutralized apical lateral found in initial position.*

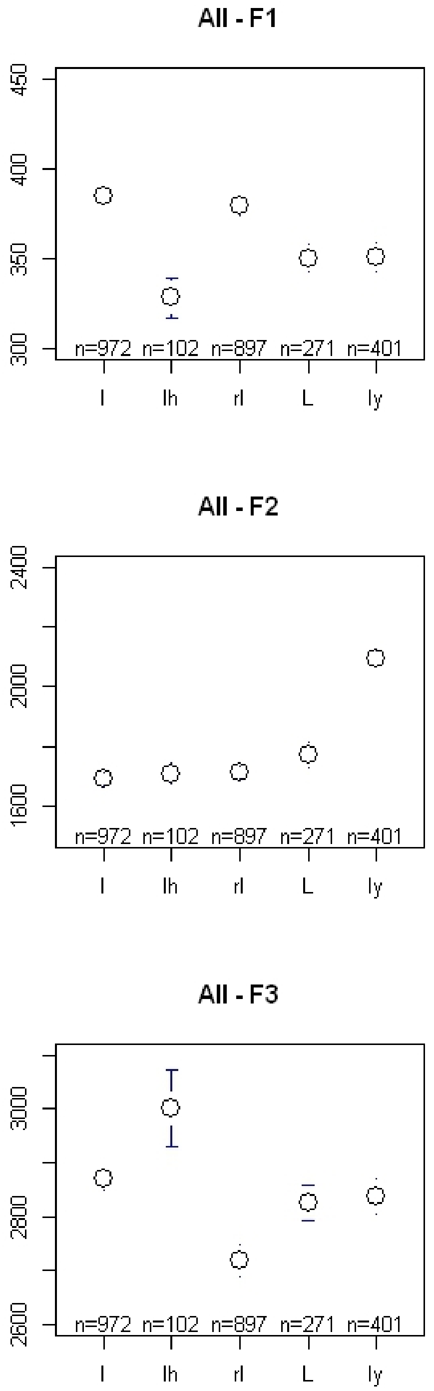
Language	**L**	**/l/**	**/ɭ/ 'rl'**	**/l̪/ 'lh'**	**/ʎ/ 'ly'**	**Total**
Arrernte (7)	11	235	105	102	49	502
Pitjantjatjara (9)	169	543	501	-	187	1400
Warlpiri (5)	91	194	291	-	165	741

3. Results

Figure 1 shows plots of means and 95% confidence intervals for the four formants measured in the present study. Table 2 gives LME results for these four formants. In the first column, a reference mean value is given for the alveolar lateral /l/; subsequent columns give LME results for comparison between the reference alveolar lateral, and the dental, retroflex and palatal laterals respectively. Each cell gives the difference between the means of the reference lateral and the comparison lateral, followed by the standard error of the difference in means, and then the t- and p-values. The reader is reminded that the initial neutralized apical is not included in these LME results, and nor are the retroflex lateral data from the Arrernte speakers. However, Figure 1 does include these data.

It can be seen that the reference formant values for the alveolar lateral given in Table 2 compare favorably with the estimates given in Johnson. The F2 and F3 values of around 1620 Hz and 2830 Hz are similar to Johnson's values of 1590

Hz and 2650 Hz, with some adjustment for the fact that the majority of our speakers are female. Our F1 value of around 370 Hz is in line with the F1 values suggested by Fant and Stevens (although it may seem lower than Johnson's estimate of 530 Hz, this higher value does not take into account perturbation resulting from a narrower tube anterior to the alveolar closure).



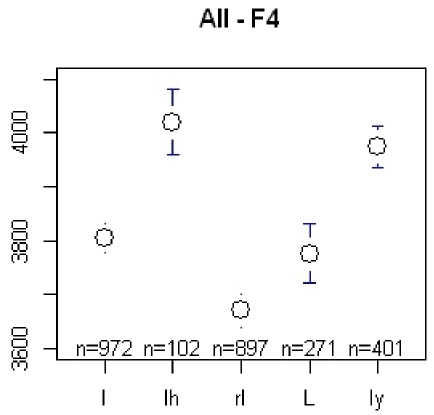


Figure 1: *Means and 95% confidence intervals for the four formants (in Hertz) measured at the temporal midpoint of the lateral.*

Table 2. *LME results. Note that shaded cells denote results that do not reach significance at $p < 0.05$.*

d.f. = 2034	/l/	vs. /l̪/ 'lh'	vs. /ɭ/ 'rl'	vs. /ʎ/ 'ly'
F1 (Hz)	374	-56 SE = 7.2 t = -7.80 p < 0.0001	-11 SE = 3.1 t = -3.53 p = 0.0004	-35 SE = 3.6 t = -9.87 p < 0.0001
F2 (Hz)	1616	67 SE = 31.5 t = 2.14 p = 0.0324	48 SE = 13.9 t = 3.45 p = 0.0006	477 SE = 15.7 t = 30.39 p < 0.0001
F3 (Hz)	2832	-3 SE = 40.5 t = -0.09 p = 0.9219	-76 SE = 17.7 t = -4.29 p < 0.0001	59 SE = 20.1 t = 2.95 p = 0.0032
F4 (Hz)	3801	195 SE = 50.2 t = 3.89 p = 0.0001	-135 SE = 22.3 t = -6.09 p < 0.0001	200 SE = 25.9 t = 7.69 p < 0.0001

If we consider the results for F1 for the other laterals, we can see that F1 is significantly lower for all three in comparison to the alveolar lateral. However, the difference is much greater for the two laminal laterals – dental 'lh' and palatal 'ly'. The difference of 11 Hz between the alveolar and the retroflex lateral, although statistically significant, may not be perceptually different given the difference in frequency is only 3% - by contrast, the difference in F1 for the laminals is around 10-15% in comparsion to the alveolar. If we consider the laminals' result in terms of Chiba and Kajiyama's [35] perturbation theory model of standing waves in the vocal tract, it is not immediately obvious why the F1 antinode located at the lips should be more constricted for these laminal sounds than for the apical sounds. One possibility is that it is due to the inherently higher jaw position for laminal sounds, which is in turn due to the inherently higher tongue body position for these sounds [36, 37, 38, 39]. A higher jaw position is accompanied by an increased approximation of the lips, and this would then lower the first resonance in comparison to a lower jaw position for the apicals – indeed, it has been shown to be the case that the jaw position for alveolar and retroflex laterals can be quite low [36]. By contrast, if we assume F1 to be a Helmholtz resonance, as do Fant and Stevens, the lower F1 value for the laminals may be due to a longer lateral constriction due to a higher tongue body position for these sounds (however, this is assuming a constant cross-sectional area of the constriction).

Turning to F2, it can be seen that by far the highest F2 value is for the palatal lateral 'ly'. It is about 400-450 Hz higher than the values for the other laterals. Although both the dental and the retroflex lateral have slightly higher F2 values than the alveolar lateral – significantly higher in the case of the retroflex – the difference in frequency is again only about 3-4%, compared to a difference of about 30% between the alveolar and the palatal. This high F2 for the palatal may be a consequence of the constriction in the palatal region, which coincides with an anti-node for the second resonance frequency if we assume a schwa-like tube – or perhaps more likely, it is the result of a smaller cavity, leading to a higher frequency half-wavelength resonance, behind the lateral constriction (see Fant's modelling of the palatalized lateral in Russian, which contains a single Helmholtz resonance).

The results for F3 are different in their turn. There is no significant difference in F3 between the alveolar and the dental, although Figure 1 suggests that F3 should be higher for the dental. However, examination of the results for Arrernte (the only language with a phonemic dental) shows that alveolar F3 is quite high for this language, hence the lack of significance in the result. (Nevertheless, a higher F3 value at the start of the following vowel transition is typically found for dentals [40], and our examination of following vowel data does suggest this is the case once the lateral is released).

There are significant differences for the retroflex and the palatal in comparison to the alveolar lateral for F3, with a lower value for the retroflex and a higher value for the palatal. However, these differences are again around 2-3%, and hence may not be perceptible. It is difficult to be certain what is the source of this lower F3 for the retroflex based on the schwa-like tube (perturbation) model, but one possibility is that the retraction of the tongue tip for the postalveolar closure is accompanied by a retraction of the tongue back/root – this retraction of the tongue root might then cause a constriction in the vicinity of the third resonance antinode, which would lower the resonance frequency. However, it is not clear why this would not then be accompanied by a lowering of F2 as well, which has an antinode in a similar region. It is perhaps simpler to explain the F3 data with reference to a Helmholtz resonance model – in this scenario, for both the alveolar and the retroflex, F3 would be a front-cavity resonance (and F2 a back cavity resonance, as suggested above). As a consequence, the slightly more back tongue-tip position for the retroflex would lead to a slightly larger front cavity relative to the alveolar.

The significantly higher palatal F3, which is not evident in the combined language data shown in Figure 1, is also difficult to explain in light of a schwa-like tube model and perturbation theory. An antinode for F3 occurs in the palatal-velar region, which should normally lower F3, rather than raise it. It is more likely that the extensive lingual contact for the palatal (and also for the dental) leads to a much smaller front resonating cavity, hence raising F3. However, it appears that there is relatively little difference in F3 between the various laterals.

Finally, differences in F4 between the various laterals appear to be greater. However, they are once again only in the order of about 5%. F4 for the retroflex 'rl' is significantly lower than for the alveolar 'l' – this may be due to the presence of fourth resonance antinodes in the postalveolar/palatal region, as well as in the uvular/pharyngeal and lower pharyngeal regions. It is difficult to reconcile a lower F4 for the retroflex, however, with a Helmholtz resonator model, since in principle the back cavity which is the likely source of F4 is smaller for the retroflex than for the alveolar – it is possible that a very different anti-resonance frequency due to a completely different tongue shape leads to these differences between the alveolar and the retroflex. Finally, F4 is significantly higher for the laminals 'lh' and 'ly' than for the two apicals (alveolar and retroflex) – again, this may be due to an overall higher jaw position and greater tongue body to palate contact for these sounds.

In summary, the laminal laterals have a relatively low F1, presumably due to the high jaw position for these sounds, as well as higher F4. In addition, the palatal has very high F2. There is relatively little difference in F3 between the four lateral places of articulation. However, the retroflex does appear to have slightly lower F3 and F4 in comparison to the other lateral sounds: this may be due to a constriction towards the uvular/pharyngeal region as the tongue back is retracted at the same time as the tongue tip, or it may be due to a completely different set of resonances due to the very different tongue shape that results from a (sub-apical) retroflex articulation.

4. Conclusions

We have seen that our lateral formant values broadly agree with the values calculated from a schwa-like tube - however, the schwa-like tube does not seem to be sufficient for describing the various formant changes that occur according to lateral place of articulation.

We have estimated formants at 374, 1616, 2832 and 3801 Hz for the alveolar lateral /l/; 318, 1683, 2829 and 3996 Hz for the dental lateral /l̪/ 'lh'; 363, 1664, 2756 and 3666 Hz for the retroflex lateral /ɭ/ 'rl'; and 339, 2093, 2891 and 4001Hz for the palatal lateral /ʎ/ 'ly'. Clearly, the largest gap is between F1 and F2, rather than F2 and F3 as suggested by Fant and Stevens (this is even more obvious when the values are converted to Bark). We would suggest that this implies an anti-resonance at a much lower frequency than has previously been estimated, which implies that the side-branch is much longer than has been estimated. We therefore encourage more precise articulatory studies and further perceptual work, in addition to further acoustic modelling work, to clarify the nature of this particular class of sounds.

5. Acknowledgements

We would like to thank the Australian Research Council for funding this research over very many years, and we would like to thank our speakers for their interest in language work. *Kele*, *palya* and *ngulajuku*.

6. References

[1] Fant, Gunnar. *Acoustic Theory of Speech Production.* The Hague: Mouton, 1960.

[2] Stevens, Kenneth. *Acoustic phonetics*. Cambridge, Mass.: MIT Press, 1998.

[3] Johnson, Keith. *Acoustic and Auditory Phonetics (3rd edition).* Maldon MA, Oxford, West Sussex: Wiley Blackwell, 2012.

[4] Gick, Bryan, Fiona Campbell, Sunyoung Oh, & Linda Tamburri-Watt. "Towards universals in the gestural organization of syllables: A cross-linguistic study of liquids", Journal of Phonetics, 34:49–72, 2006.

[5] Gick, Bryan, A. Min Kang & Douglas Whalen. "MRI evidence for commonality in the post-oral articulations of English vowels and liquids", Journal of Phonetics, 30:357–371, 2002.

[6] Giles, Stephen & Kenneth Moll. "Cinefluorographic study of selected allophones of English /l/", Phonetica, 31:206–227, 1975.

[7] Hardcastle, William & William Barry. "Articulatory and perceptual factors in /l/ vocalisations in English", Journal of the International Phonetic Association, 15:3–17, 1989.

[8] Lin, Susan, Patrice Speeter Beddor & Andries W. Coetzee. "Gestural reduction, lexical frequency and sound change: A study of post-vocalic /l/", Laboratory Phonology, 5: 9-36, 2014.

[9] Narayanan, Shrikanth, Abeer Alwan & Katherine Haker. "Toward articulatory- acoustic models for liquid consonants based on MRI and EPG data. Part I: The laterals", Journal of the Acoustical Society of America, 101:1064-1077, 1997.

[10] Proctor, Michael. "Towards a gestural characterization of liquids: Evidence from Spanish and Russian", Laboratory Phonology, 2:451-485, 2011.

[11] Punnoose, Reenu, Ghada Khattab & Jalal al-Tamini. "The contested fifth liquid in Malayalam: a window into the lateral-rhotic relationship in Dravidian languages", Phonetica, 70:274-297, 2013.

[12] Recasens, Daniel. "An articulatory-perceptual account of vocalization and elision of dark /l/ in the Romance languages", Language and Speech, 39:63–89, 1996.

[13] Scobbie, James & Marianne Pouplier. "The role of syllable structure in external sandhi: An EPG study of vocalisation and retraction in word-final English /l/", Journal of Phonetics, 38:240–259, 2010.

[14] Simonet, Miquel. "Dark and clear laterals in Catalan and Spanish: Interaction of phonetic categories in early bilinguals. Journal of Phonetics, 38:663-678, 2010.

[15] Sproat, Richard & Osamu Fujimura. Allophonic variation in English /l/ and its implications for phonetic implementation", Journal of Phonetics, 21:291–311, 1993.

[16] Horvath, Barbara M. & Ronald J. Horvath. "The geolinguistics of /l/ vocalisation in Australia and New Zealand", Journal of Sociolinguistics, 6:319–346, 2002.

[17] Stuart-Smith, Jane, Claire Timmins & Fiona Tweedie. "Conservation and innovation in a traditional dialect: L-vocalization in Glaswegian", English World-Wide, 27:71–87, 2006.

[18] Recasens, Daniel. "On the articulatory classification of (alveolo)palatal consonants", Journal of the International Phonetic Association, 43:1-23, 2013.

[19] Dixon, Robert M. W. *Australian Languages: Their Nature and Development.* Cambridge: Cambridge University Press, 2002.

[20] Dixon, Robert M. W. *The Languages of Australia*. Cambridge: Cambridge University Press, 1980.

[21] Evans, Nicholas. "Current issues in the phonology of Australian languages", in John Goldsmith (Ed.), *The Handbook of Phonological Theory* (pp. 723–761). Cambridge, MA, Oxford: Blackwell, 1995.

[22] Breen, Gavan & Veronica Dobson. "Central Arrernte", Journal of the International Phonetic Association, 35:249-254, 2005.

[23] Breen, Gavan & Rob Pensalfini. "Arrernte: a language with no syllable onsets", Linguistic Inquiry, 30:1-25, 1999.

[24] Henderson, John. *Topics in Eastern and Central Arrernte grammar*. PhD thesis, UWA, 1998.

[25] Henderson, John & Veronica Dobson. *Eastern and Central Arrernte to English Dictionary*. Alice Springs: IAD Press, 1994.

[26] Wilkins, David. *Mpwarnte Arrernte*. PhD thesis: Australian National University, 1989.

[27] Goddard, Cliff. *Yankunytjatjara Grammar.* Alice Springs: Institute for Aboriginal Development, 1986.

[28] Goddard, Cliff. *A Learner's Guide to Pitjantjatjara/Yankunytjatjara*. Alice Springs: IAD Press, 1993.

[29] Goddard, Cliff. *Pitjantjatjara/Yankunytjatjara to English Dictionary* (2nd edition). Alice Springs: IAD Press, 1996.

[30] Laughren, Mary, Robert Hoogenraad, Kenneth Hale, and Robin Japanangka Granites. *A learner's guide to Warlpiri: Tape course for Warlpiri (wangkamirlipa Warlpirilki)*. Alice Springs: IAD Press, 1996.

[31] Nash, David. *Topics in Warlpiri grammar*. New York: Garland Publishing Inc., 1986.

[32] Tabain, Marija & Gavan Breen. "Central vowels in Central Arrernte: a spectrographic study of a small vowel system", Journal of Phonetics, 39:68-84, 2011.

[33] R Core Team. *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/, 2012.

[34] Labov, William. *The Social Stratification of English in New York City*. Washington, D.C.: Center for Applied Linguistics, 1966.

[35] Chiba, T. & Kajiyama, M. (1941). *The Vowel: Its nature and structure*. Tokyo: Kaiseikan.

[36] Tabain, Marija. "Jaw movement and coronal stop spectra in Central Arrernte", Journal of Phonetics, 40:551-567, 2012.

[37] Tabain, Marija, Janet Fletcher & Andrew Butcher. "An EPG study of palatal consonants in two Australian languages", Language and Speech, 54:265-282, 2011.

[38] Recasens, Daniel. "The articulatory characteristics of palatal consonants", Journal of Phonetics, 18:267-280, 1990.

[39] Keating, Patricia, Bjorn Lindblom, James Lubker & Jody Kreiman. "Variability in jaw height for segments in English and Swedish VCVs", Journal of Phonetics, 22:407–422, 1994.

[40] Dart, Sarah. "Articulatory and acoustic properties of apical and laminal articulations", UCLA Working Papers in Phonetics, 79, 1991.