Māori /r/ Acoustics: Preliminary Analysis of the First and Second Formant

Isabella Shields, Peter J. Keegan, Catherine I. Watson

University of Auckland

isabella.shields@auckland.ac.nz, p.keegan@auckland.ac.nz, c.watson@auckland.ac.nz

Abstract

This paper describes a preliminary investigation into first and second formant (F1 and F2) behaviours of Māori /r/. A total of 607 observations of this sound are drawn from recordings of 11 fluent Māori speakers. The influence of segmental environment, word form, and phrasal context are explored using mixed-effect models. We find segmental environment impacts /r/ F1 and F2, with both preceding and following vowels modifying these formants. Word form impacts F1 and F2 only in certain segmental environments, and phrasal context has no effect. These findings provide a starting point for further investigation into Māori /r/ and coarticulation.

Index Terms: Māori phonetics, rhotics, acoustics

1. Introduction

Māori is the indigenous language of *Aotearoa* (a common Māori name for New Zealand). Aside from English, Māori is the second-most spoken language in Aotearoa: in 2018, 185,955 people reported they could hold a conversation about everyday things [1]. Colonisation of Aotearoa in the 1800s instigated a period of Māori language decline that was exacerbated by discouragement of use of the language. This resulted in a break in inter-generational language transmission and a decline in the number of speakers. The latter half of the 20th century saw a significant push to revitalise Māori, led predominantly by Māori communities who have, for example, spearheaded the development of Māori-medium and immersion schooling. Revitalisation efforts have also been supported by academic research.

The present research contributes to the overarching goal of improving our knowledge of Māori phonetics. Presently, we do not understand the extent of variation of Māori /r/. It is unclear, for example, what variants are considered 'acceptable' or as an error. This paper reports on a preliminary investigation into the formant behaviours of /r/, and considers the influence of word form, phrasal environment, and surrounding vowels.

2. Background

The phoneme inventory of Māori has 10 consonants: /p t k m n ŋ f h w r/ and five monophthongs, /i e a o u/, which have phonemically distinctive short and long qualities. In written Māori, these long vowels are usually denoted using a macron. Māori is described as a mora-timed language; mora consist of a short monophthong and an optional consonant (μ = (C)V).

Biggs' stress rules describe primary stress placement in phrases and monomorphemic words [2]. While there has been limited research into acoustic evidence of these stress rules, they have been the subject of some investigation [3], [4]. According to these rules, word stress is placed according to two factors; a hierarchy of syllables (summarised by Bauer [5]), and the number of morae in a word. These rules are not expanded upon here, but did influence the choice and form of the target words from which data is extracted in the present study. According to Biggs' rules, phrase stress is assigned based on the position of the phrase in the sentence, and may only be placed on content words. If the phrase is sentence-final, phrase stress falls on stressed syllable of the final content word. If it is not sentence-final, phrase stress falls on the penultimate mora of the phrase.

Māori /r/ is most often described as a flap [5]–[7]. Bauer provides possibly the most detailed description, calling the sound a *voiced lamino-alveolar tap* or *apico-alveolar tap* [5]. In [8], Hohepa describes trill productions of /r/, and Wilson and Harlow refer to lateral realisations of the phoneme [7], [9]. Outside of select contexts, such as when /r/ appears repeatedly with intervening unstressed vowels (e.g. in *kōrero*), Harlow notes that the presence of an approximant variant is a case of interference of New Zealand English with Māori [7].

The Māori rhotic has been the subject of phonetic analysis, most of which has focused on the MAONZE corpus [10], [11]. This corpus contains recordings of 62 bilingual Māori speakers whose birth dates span over 100 years. Maclagan and King undertook an auditory analysis of /r/ as produced by one of the historical speakers (born in 1885 and recorded in 1947) in the MAONZE corpus [10]–[12]. Their work investigated the speaker's Māori and English recordings, finding that he consistently used taps when speaking in Māori, with some approximant productions when he used Māori words in predominantly English speech. Maclagan et al. also considered the pronunciation of the word *māori* in the wider MAONZE corpus [13]. They found some indication of changes over time, with the proportion of taps used in Māori speech decreasing and the proportion used in English speech increasing.

Analysis of other corpora has also been undertaken. In an investigation of three present-day speakers from a new corpus, Shields et al. found the majority of /r/ tokens were indeed taps, and that its phonetic realisation varied [14]. They observed most tokens had at least some formant energy present throughout its production. Frication was present in a number of tokens (more often near /i/), and a smaller proportion also had release bursts. A recent study, analysing MAONZE recordings and more contemporary sources, considered the spectrographic realisation of /r/, the interaction between /r/ duration and stress, and the behaviour of the fourth formant [15].

This paper follows on from the above studies of Māori /r/ and hones in on its first and second formant (F1 and F2) behaviours. This is an area that has not yet been investigated in depth or in a wider speaker group. The present work focuses on realisations of the sound that have formant energy throughout their production, a variant identified in [14] as the most common. Formant values are considered at a single point in time in various word stress, phrase stress, and preceding/following segmental environments. We expect that these variables will have varying degrees of interaction with F1 and F2.

3. Methodology

The present study draws on a corpus of read Māori speech developed to investigate the /r/ phoneme. A preliminary analysis of this corpus was presented in [14] when it was in the early stages of development. The experimental procedure following in this study was approved by the University of Auckland Human Participants Ethics Committee (UAHPEC23198).

3.1. Kaikōrero (speakers) and materials

We present data drawn from the 11 female speakers recorded, all of whom are fluent speakers of Māori. The mean age of speakers was 35.1 years (s.d. = 11.8; range = 17 to 60 years). The oldest female speaker recorded did not explicitly state their age, indicating they were '50+' years. Their age is not included in the reported mean, although they are no older than 60 years. The majority of the speakers grew up with exposure to Māori: most of the speakers (7/11) had at least one Māori-speaking parent, and all had at least one grandparent who spoke or understood Māori. Around half of the speakers (6/11) use Māori at home as an adult, and all speakers use Māori (to varying degrees) at work or university.

In the corpus, two different frame sentences, presented below, place the /r/ token in different phrasal stress conditions (according to rules discussed in Section 2). In frame sentence 2, phrase stress is conflated with word stress of the target word. Phrase stress falls outside the target word in frame sentence 1.

(1) *I/Ka* {target word} *a* {Name}.

(2) *I kite a* {Name} *i te/ngā* {target word} *nā.*

In the present study we analyse tokens taken from three of the five word forms included in the corpus. These word forms place /r/ in different lexical stress environments and segmental environments. The word forms are as follows; WF1 /ˈCV.rV/ (such as *para*), WF2 /ˈCVː.CV.rV/ (such as *hōpara*), and WF3 /ˈrV.CV/ (such as *rapu*). The segmental environments include six /VrV/ sequences: /iri, ira, iro, ari, ara, aro/. These adjacent vowels function as point vowels in the Māori vowel space. The mid-back vowel /o/ was used in place of /u/, as the latter has become increasingly fronted and generally more rounded [16]. All target words analysed are summarised in Table 1.

3.2. Recording process and setup

Recording sessions were run in a WhisperRoom Sound Isolation Enclosure (`https://whisperroom.com`), with speakers seated at a desk in front of a computer monitor. A Rode Lavalier lapel microphone and Roland OCTA-CAPTURE were used for audio capture, pre-amplification, and digitisation. Audio was captured at a sample rate of 44.1kHz and 16-bit bit depth. Depending on the speech rate of the speaker and the speed at which they completed the recording process, up to five repetitions of each sentence were recorded. As a warm up task, speakers read aloud two passages of text in Māori shown on the monitor. This was followed by the central speech task, where sentences were displayed on the monitor and recorded one at a time. Recording sessions lasted a maximum of one hour. Of the 11 speakers analysed in the present study, one completed three repetitions, four completed four repetitions, and the remainder completed five repetitions.

3.3. Data preparation & processing

All processing, analysis, and visualisation of data was undertaken using R (version 4.2.0) [17]. Recordings were converted into *EmuR* database format using the package *EmuR* (version 2.3.0) [18]. WebMAUS General was used for a first pass at automated phonetics segmentation of recordings (language: language independent (SAMPA), otherwise default settings) [19]–[21]. Boundaries were then hand-corrected where necessary in *EmuR*. Start and end boundaries for the /r/ consonant were placed based on reduced amplitude of the waveform envelope and reduction in formant energies in the spectrogram and were placed at the nearest zero-crossing. Formant trajectories were estimated using the `forest()` function in the *wrassp* package using default settings aside from gender (gender set to '`f`' indicating 'female', which sets effective window length to 12.5 ms and nominal F1 to 560 Hz) [22]. All formant estimations were hand-adjusted by the first author.

The behaviours of first and second formants are visualised in the F1/F2 acoustic vowel space. This approach has been used to analyse formant patterns of Spanish consonants in /VCV/ sequences [23]. A similar approach is undertaken here, where three points in each /VrV/ sequence are extracted. These are (i) an approximation of the acoustic target of the preceding vowel, (ii) the temporal midpoint of /r/, and (iii) an approximation of the acoustic target of the following vowel. An approximation of vowel targets was necessary as these were not hand-labelled. Based on an analysis of present-day young speakers from the MAONZE corpus, in which vowel targets are labelled for long and short monophthongs, it was determined that, on average, the vowel target occurred 40% to 50% through the vowel production. The exact value depended on speaker and the particular vowel, and a relative position of 45% was selected to approximate the target position.

The first and second formant values (F1 and F2) were analysed using a linear mixed-effect (LME) model using the *R* package *lme4* (v. 1.1-35.3) [24]. Fixed effects were preceding vowel (either /i/ or /a/), following vowel (either /i/, /a/ or /o/), word form (WF1, WF2, or WF3), and phrase environment (P1 or P2). Separate models were constructed for F1 and F2 with model fitting informed by the `step()` function in the *lmerTest* package (v. 3.1-3) [25]. To determine significance of fixed effects, and their interactions, likelihood ratio tests (two-way ANOVA) were used. The *emmeans* package (v. 1.10.2) [26] was used for post-hoc pairwise comparisons. Speaker was added as a random effect in both models.

4. Results

First and second formant data was extracted from 607 tokens of /r/ (summarised in Table 1). The production study elicited an equal number of all segmental environments and word forms, however the proportion of tokens with formant energy differed across these.

Table 1: *Target words analysed the present study. Note WF indicates 'word form'.*

VrV	WF1		WF2		WF3		#
	word	#	word	#	word	#	
/iri/	piri	28	tāpiri	15	ripo	26	69
/ira/	hira	24	pākira	10	rapi	50	84
/iro/	piro	36	kōpiro	17	ropi	44	97
/ari/	pari	54	tōkari	34	ripa	54	142
/ara/	para	42	hōpara	15	rapu	55	112
/aro/	paro	37	tākaro	15	rotu	51	103
#	WF1	221	WF2	106	WF3	280	607

The distribution of /r/ targets in the F1/F2 space is illustrated in Figure 1, with colours differentiating the segmental environment that each /r/ is drawn from. The acoustic target approximations of the preceding and following vowels are also visualised in black, with letter label placement indicating their mean F1 and F2 values. The ellipses around vowels and /r/ targets were computed using `stat_ellipse()` in *ggplot2* (assumed t-distribution with 95% confidence level) [27]. As can be seen in the plot, there is sizeable area in the F1/F2 space in which the /r/ target occurs, and that this varies with segmental context. F1 in /r/ tends to be lowest in the when preceded by the high-front vowel /i/ (those points in dark blue, light blue, and pink) and higher when preceded by the open vowel /a/ (points in brown . When the /VrV/ sequence is a combination of the /a/ and a higher vowel, the F1 distribution is more spread across the vowel space.

We observe that F2 tends to be higher when /r/ is preceded by the high-front vowel /i/ when compared to those sequences which have only /a/ or /o/ preceding/following. There is some overlap between most segmental environments but there generally appear to be differences in all F2 distributions, save for /ari/ and /iro/ (shown in brown and pink, respectively).

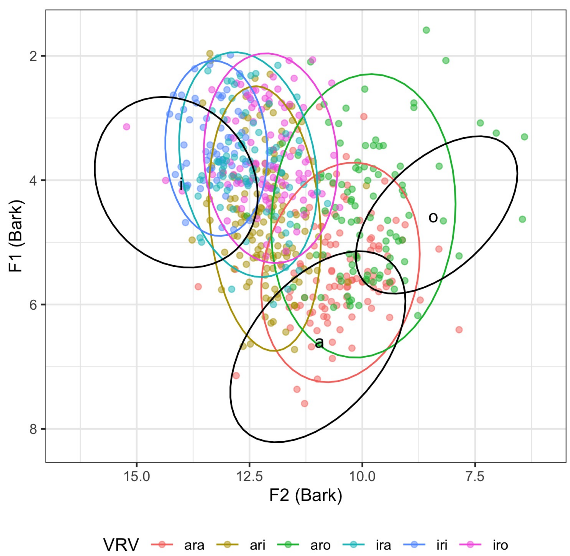

Figure 1: *F1 and F2 values (Bark-scaled) of all /r/ tokens.*

4.1. Modelling of the first formant (F1)

We used likelihood ratio tests to examine the main effects of the linear mixed-effect models. We found phrase context (described in Section 3.1) affected F1 ($\chi^2(1) = 7.41, p = 0.0065$), however post-hoc pairwise comparisons indicated there were no significant differences between phrase contexts. There were significant interactions between preceding and following vowel environment ($\chi^2(2) = 18.09, p = 0.0001$), and preceding vowel environment and word form ($\chi^2(2) = 27.05, p < 0.0001$).

Figure 2 shows the linear predictions of F1 for all levels of preceding and following vowel environment. The dots in this plot indicate the estimated marginal mean in each context, and error bars indicate the 95% confidence intervals. Both preceding and following vowel clearly influence F1. Based on these confidence intervals, preceding /i/ results in an /r/ F1 value between 3.18 and 4.03 Bark. When preceded by /a/, this value increases, ranging between 4.18 and 5.64 Bark. Post-hoc pairwise contrasts of following vowel were not significant when the preceding vowel was /i/. When the preceding vowel was /a/ and the following vowel was /i/ or /o/, pairwise contrasts with following /a/ were significant. There was no significant difference between F1 of /r/ in /ari/ and aro/. Pairwise contrasts are summarised in Table 2. The general trend we observe is that F1 of /r/ is clearly influenced by the preceding vowel, with preceding /i/ resulting in lower F1 than preceding /a/. In addition, we observe F1 in /r/ tends to be more susceptible to change due to following vowel when preceded by /a/ compared to /i/.

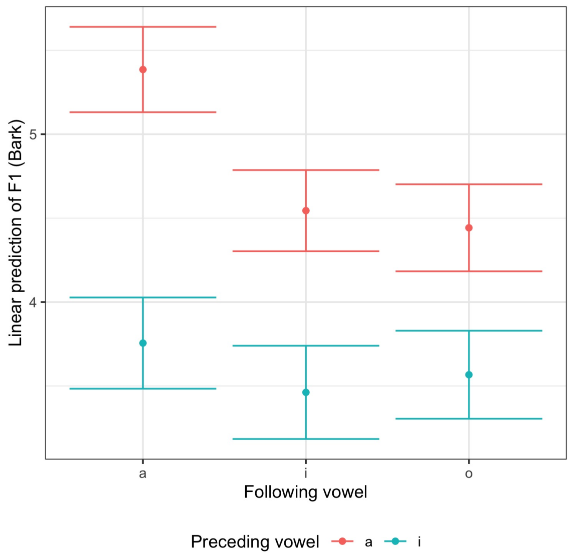

Figure 2: *Predictions of /r/ F1 for all vowel environments.*

Table 2: *Pairwise contrasts of following vowel (F1)*

Pre.	Contrast	Est. (SE)	df	t.ratio	p.value
a	a - i	0.84 (0.11)	592	7.83	$< .0001$
	a - o	0.94 (0.12)	589	8.23	$< .0001$

4.2. Modelling of the second formant (F2)

For F2, likelihood ratio tests found significant interactions between preceding and following vowel ($\chi^2(2) = 54.68, p < 0.0001$), preceding vowel and word form ($\chi^2(2) = 14.57, p = 0.0007$), and preceding vowel and phrase ($\chi^2(1) = 8.04, p = 0.0005$). Post-hoc pairwise comparisons of the latter indicated there were no significant differences between phrase contexts.

Linear predictions of F2 for all levels of preceding and following vowel are shown in Figure 3. Similar to Figure 2, this plot shows the estimated marginal mean and 95% confidence intervals. Similar to the case for F1, both preceding and following vowel environment influence F2. The general trend is for F2 to be lower when then preceding vowel is /a/ with the notable exception of /ari/, where /r/ is followed by the high-front vowel. In this case, F2 is increased to 12.16 Bark, overlapping almost totally with the range of values expected for /iro/ sequences.

For F2, pairwise contrasts of all following vowel combination were significant for both preceding /a/ and /i/. These are summarised in Table 3. The impact of following vowel on F2 appears to follow the same behaviour for preceding /i/ and /a/: F2 lowers when /r/ is followed by /a/ or /o/ (compared to /i/), and these changes are greater when /r/ is preceded by /a/.

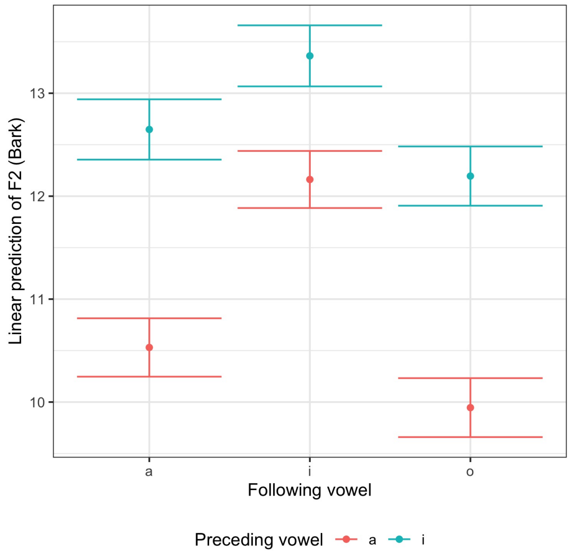

Figure 3: *Predictions of /r/ F2 for all vowel environments.*

Table 3: *Pairwise contrasts of following vowel (F2)*

Pre.	Contrast	Est. (SE)	df	t.ratio	p.value
a	a - i	-1.63 (0.09)	588	-18.77	< .0001
	a - o	0.58 (0.10)	586	6.30	< .0001
	i - o	2.22 (0.12)	587	24.95	< .0001
i	a - i	-0.72 (0.12)	586	-6.40	< .0001
	a - o	0.45 (0.10)	586	4.44	< .0001
	i - o	1.17 (0.11)	586	10.88	< .0001

As noted above, likelihood ratio tests found a significant interaction between preceding vowel and word form. Due to space constraints we do not include the full results of this analysis here. To summarise, post-hoc pairwise comparisons revealed that comparisons were only significant when the preceding vowel was /a/. This indicated that, when preceded by /a/, the F1 of /r/ in WF1 was higher than those in WF2 or WF3. The vowel preceding /r/ is stressed in WF1 and unstressed in WF2 and WF3, which may be the cause of this raising of F1. The pairwise comparisons of word form for F2 did not follow a coherent trend, with F2 of /r/ in WF1 and WF3 being higher than that in WF2.

5. Discussion

In this study we have investigated the impact of segmental environment, word form, and phrasal environment on the first and second formant behaviours of a subset of Māori /r/ realisations. These variants of the consonant have formant energy throughout their production, indicating there has not been complete closure during articulation. This realisation of the consonant has been observed to be the most common in previous work [14].

The present study has shown segmental context significantly impacts the F1 and F2 values of the consonant, providing some preliminary insight into coarticulatory changes in /r/. We can infer there are changes in constriction location (due to observed changes in F2) and of degree of constriction (due to F1). Such changes have been attested in other languages: vowel-dependent changes to closure place have been observed for taps in Catalan [28]. When preceded by the high-front vowel /i/, the F1 value at /r/ target did not change significantly, regardless of the following vowel. In the same context, F2 values did differ significantly depending on following vowel, but the influence was smaller compared to the preceding /a/ context. We may conclude then that /i/ is more restrictive than /a/ in this context, restraining /r/ F1 and F2 values to a range similar to that of the high-front vowel, although this could be natural consequence of vocal tract constraints.

As well as understanding variation in F1 and F2 behaviours of /r/, we were interested in visualising /r/ in the F1/F2 acoustic space along with targets of preceding and following vowels. This approach holds appeal as it places the unknown quantity (here, features of /r/) in a more familiar surrounding. Proctor used this approach to explore the acoustic targets of liquids in Spanish, identifying variation within and across the liquids [23]. It appears that the variation observed for the single rhotic of Māori may be greater than that observed in his study. It is possible that the variation observed here is due to the smaller consonant inventory of Māori: as there is no phoneme with which /r/ can be easily confused, more variation may be permitted. To explore this, comparison with other consonant phonemes in Māori or other languages should be considered.

This preliminary study reveals there are indeed distinctions in the F1/F2 behaviours of /r/, however we only considered these at a single point in time. The logical next step is to assess how the dynamic F1/F2 behaviours of such variants of Māori /r/ vary across segmental and word environments. This would provide more insight into the articulation of /r/, and would likely more meaningful than comparing what are effectively arbitrary points in time. We recommend further work consider these dynamic F1/F2 behaviours, as well articulatory analyses to complement such acoustic investigations.

6. Conclusions

This paper presents a preliminary investigation into F1 and F2 behaviours of Māori /r/ at a single point in time in its production. The present analysis considers only variants of the consonant with consistent formant energy during production. We consider the consonant in various segmental, word, and phrasal environments, and results suggest segmental environment impacts both F1 and F2 for all combinations of preceding and following vowels investigated. Word form also influenced F1 and F2, although only in some segmental environments. Phrasal environment was found to have no impact on either measure.

The observed influence of segmental environment on /r/ F1 and F2 indicates there is flexibility in the production of the consonant. The range of F1 and F2 values in /r/ is generally much more restricted when preceded (or followed) by /i/, suggesting there may be coarticulation processes at work. Further research is required to better understand this coarticulation and the interaction between Māori /r/ and its surrounding phones.

The findings of this study are limited as they only consider formant behaviours of Māori /r/ at a single point in time. We suggest future work consider dynamics of these formants in /r/ and adjacent vowels.

◀◀ ◀ Table of Contents for this manuscript ▶ ▶▶

7. Acknowledgements

We thank the reviewers for their insightful comments. We also express our gratitude to the kaikōrero (speakers) who took part in this study.

8. References

[1] Statistics New Zealand, *2018 Census totals by topic*. 2018.

[2] B. Biggs, *Let's learn Maori: A guide to the study of the Maori language.* 1st edition. Wellington, New Zealand: A.H. & A.W. Reed., 1969.

[3] L. Thompson, C. I. Watson, H. Charters, R. Harlow, P. Keegan, J. King, and M. Maclagan, "An experiment in mita-reading: investigating perception of rhythmic prominence in the Māori language," in *Proceedings of SST 2010*, Melbourne, Australia, 14-16 December 2010.

[4] L. Thompson, C. I. Watson, R. Harlow, M. Maclagan, H. Charters, J. King, and P. Keegan, "Adventures in mita-reading: examing stress 'rules' and perception of prosodic prominence in the Māori language," in *Proceedings of ICPhS 2011*, Hong Kong, 17-21 August 2011.

[5] W. Bauer, *Maori*, 1st edition. London, UK: Routledge, 1993.

[6] B. Biggs, "The Structure of New Zealand Maaori," *Anthropological Linguistics*, volume 3, number 3, 1961.

[7] R. Harlow, *Māori: A linguistic introduction*. Cambridge, UK: Cambridge University Press, 2007.

[8] P. W. Hohepa, "A profile generative grammar of Maori," Ph.D. dissertation, Indiana University, 1965.

[9] D. B. Wilson, "A study of spoken Māori in Awarua (Northland)," M.S. thesis, University of Auckland, 1991.

[10] J. King, M. Maclagan, R. Harlow, P. Keegan, and C. Watson, "The MAONZE Corpus: Establishing a corpus of Māori speech," *New Zealand Studies in Applied Linguistics*, volume 16, number 2, pages 1–16, 2010.

[11] J. King, M. Maclagan, R. Harlow, P. Keegan, and C. Watson, "The MAONZE Corpus: transcribing and analysing Māori speech," *New Zealand Studies in Applied Linguistics*, volume 17, number 1, 2011.

[12] M. Maclagan and J. King, "A Note on the Realisation of /r/ in the Word Maori," *New Zealand English Journal*, volume 18, pages 35–39, 2004.

[13] M. Maclagan, T. Macrae, and J. Wilson Black, "The pronunciation of the word "Māori"," *Te Reo. Journal of the Linguistic Society of New Zealand*, volume 66, number 2, pages 130–153, 2024.

[14] I. Shields, C. Watson, and P. Keegan, "Preliminary analysis of /r/ acoustics and features in three Māori speakers," in *Proceedings of SST 2022*, Canberra, Australia, 13-16 December 2022.

[15] I. Shields, C. Watson, and P. Keegan, "Ngā āhuatanga o te /r/ o te reo Māori: preliminary investigations into the acoustics of Māori /r/," *Te Reo. Journal of the Linguistic Society of New Zealand*, volume 66, number 2, pages 105–131, 2024.

[16] M. Maclagan, C. I. Watson, R. Harlow, J. King, and P. Keegan, "/u/ fronting and /t/ aspiration in Māori and New Zealand English," *Language Variation and Change*, volume 21, number 2, pages 175–192, 2009.

[17] R Core Team, *R: A language and environment for statistical computing.* R Foundation for Statistical Computing, Vienna, Austria, 2024. [Online]. Available: `https://www.R-project.org/`.

[18] M. Jochim, R. Winkelmann, K. Jaensch, S. Cassidy, and J. Harrington, *emuR: Main Package of the EMU Speech Database Management System*, R package version 2.5.0, 2024. [Online]. Available: `https://CRAN.R-project.org/package=emuR`.

[19] F. Schiel and J. J. Ohala, "Automatic Phonetic Transcription of Non-Prompted Speech," in *Proceedings of ICPhS 1999*, 10.5282/ubm/epub.13682, San Francisco, CA, USA, 1-7 August 2011, pages 607–610.

[20] F. Schiel, "A Statistical Model for Predicting Pronunciation," in *Proceedings of ICPhS 2015*, Glasgow, UK, 10-14 August 2011.

[21] T. Kisler, U. Reichel, and F. Schiel, "Multilingual processing of speech via web services," *Computer Speech & Language*, volume 45, pages 326–347, 2017.

[22] R. Winkelmann, L. Bombien, M. Scheffers, and M. Jochim, *wrassp: Interface to the 'ASSP' Library*, R package version 1.0.5, 2024. [Online]. Available: `https://CRAN.R-project.org/package=wrassp`.

[23] M. Proctor, "Gestural Characterization of a Phonological Class: the Liquids," Ph.D. dissertation, Yale University, 2009.

[24] D. Bates, M. Mächler, B. Bolker, and S. Walker, "Fitting Linear Mixed-Effects Models Using lme4," *Journal of Statistical Software*, volume 67, number 1, pages 1–48, 2015.

[25] A. Kuznetsova, P. B. Brockhoff, and R. H. B. Christensen, "lmerTest Package: Tests in Linear Mixed Effects Models," *Journal of Statistical Software*, volume 82, number 13, pages 1–26, 2017. DOI: `10.18637/jss.v082.i13`.

[26] R. V. Lenth, *emmeans: Estimated Marginal Means, aka Least-Squares Means*, R package version 1.10.2, 2024. [Online]. Available: `https://CRAN.R-project.org/package=emmeans`.

[27] H. Wickham, *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York, 2016, ISBN: 978-3-319-24277-4. [Online]. Available: `https://ggplot2.tidyverse.org`.

[28] D. Recasens and M. D. Pallarès, "A study of /J/ and /r/ in the light of the "DAC" coarticulation model," *Journal of Phonetics*, volume 27, number 2, pages 143–169, 1999. DOI: `https://doi.org/10.1006/jpho.1999.0092`.