Phonetic typology and articulatory constraints:
The realisation of secondary articulations in Scottish Gaelic rhotics

Claire Nance
Lancaster University
c.nance@lancaster.ac.uk
Department of Linguistics and English Language
County South
Lancaster University
LA1 4YL
United Kingdom

Sam Kirkham
Lancaster University
s.kirkham@lancaster.ac.uk
Department of Linguistics and English Language
County South
Lancaster University
LA1 4YL
United Kingdom

Phonetic typology and articulatory constraints:
The realisation of secondary articulations in Scottish Gaelic rhotics

ABSTRACT. Much progress has been made in the last 200 years about understanding the origins and mechanisms of sound change. It is hypothesised that many sound changes originate in biomechanical constraints on speech production, or in the misperception of sounds. These production and perception pressures explain a wide range of sound changes across the world's languages, yet we also know that sound change is not inevitable. For example, similar phonological structures have undergone change in many languages yet remained stable in others. In this study, we examine how typologically unusual contrasts are maintained in the face of intense pressures, in order to uncover the potential biomechanical, perceptual and sociolinguistic factors that facilitate the maintenance of typologically unusual contrasts. We focus on secondary articulation contrasts in Scottish Gaelic rhotics, triangulating auditory, acoustic and articulatory data in order to better understand the maintenance of contrast in the face of multi-dimensional typological challenges. Here, individual-level articulatory strategies are combined with contextual prosodic information in order to maintain acoustic and auditory distinctiveness across three rhotic phonemes. We highlight the need to more comprehensively consider typologically unusual and minority languages in order to test the limits of generalisations about cross-linguistic phonetic typology.*

Keywords: rhotics, palatalisation, Scottish Gaelic, Celtic, sound change, ultrasound

*Thank you very much to the participants who gave their time for this research! We are very grateful to Andries Coetzee, Meredith Tamminga, and the anonymous reviewers for their extremely helpful and constructive feedback on earlier versions of the manuscript. Thank you to our research assistants: Lois Fairclough for hand-correcting the ultrasound splines, and Chloe Cross and Dom Moran for assisting in the auditory and acoustic analysis.

1 INTRODUCTION. One of the major challenges in the study of sound change is determining when and how a sound change begins. Sound change actuation is widely hypothesized to be the result of either listeners misperceiving sounds and then eventually recategorising them (Ohala 1981), or patterns of variability in speech production becoming phonologised (Ohala 1989). Such constraints on speech perception and production can be used to explain a wide variety of changes and patterns of sounds cross-linguistically (Blevins 2009). While such models are extremely powerful in their ability to describe typological patterns, sound change is not inevitable. Many languages have sound systems that have not undergone the predicted changes seen in other languages with similar systems, despite the existence of similar production and perception pressures. How are typologically unusual structures maintained in some languages, despite similar structures being widely lost in a range of other languages? This is the central question of the present study and we propose that answering this question is fundamental to our understanding of cross-linguistic typology and change.

As a case study for testing the stability of typologically unusual and complex contrasts, we focus on secondary articulations in rhotics. While the majority of the world's languages have some kind of rhotic consonant, large rhotic systems are rare, especially those contrasting multiple secondary articulations. Secondary articulations in rhotics are perhaps most widely studied in Indo-European, especially Russian. Across the wider Slavic family, palatalised rhotics appear prone to reduction and loss. Previous articulatory studies of Russian have commented on the articulatory challenge of producing a trill with secondary articulation, specifically palatalisation, which explains why secondary articulations in rhotics are comparatively rarer than, for example, secondary articulations in laterals (Kochetov 2005; Iskarous & Kavitskaya 2018). In addition to these biomechanical constraints, there is also evidence that large rhotic inventories present a perceptual challenge for listeners, especially when such contrasts involve overlapping acoustic properties (Howson & Monahan 2019).

Rhotic secondary articulations present an intriguing and exciting prospect, as Spajić et al. (1996) put it, 'for the trill-seeking phonetician'. They are biomechanically disfavoured and perceptually challenging to maintain. In this study, we present data on complex rhotic contrasts from Scottish Gaelic,[1] a language that maintains three phonemic rhotics which are contrasted in terms of palatalisation and velarisation. Our aim is to examine the phonetic realisation of secondary articulatory contrasts in a context where they appear to be diachronically, perceptually and articulatorily disfavoured: rhotic consonants. We examine how speakers achieve these contrasts despite apparent pressures from articulatory, perceptual and sociolinguistic constraints. Our analysis consists of auditory and acoustic data on the production of rhotics from twelve L1 Lewis Gaelic speakers, and ultrasound tongue imaging of seven of the same speakers. In doing so, we advance our understanding of the typology of secondary rhotic articulations and examine the realisation of an unusual consonant inventory which appears to exist in relative stability despite a diachronic tendency towards loss.

In the remainder of this section we first explore previous accounts of how speech articulation and perception can lead to larger typological patterns emerging (Section 1.1). We then apply these models to the case of secondary articulations in rhotics (Section 1.2). Section 1.3 explores how these typological patterns are manifested in the history of Indo-European focusing on the Goidelic languages, and Section 1.4 introduces the specific sociolinguistic context of Scottish Gaelic, before our summary in Section 1.5.

1.1 SOUND CHANGE AND PHONETIC TYPOLOGY. Ohala's (1989; 2012) influential model of the role of perception in sound change suggests that change may arise from the listener misperceiving the speech signal. Ohala's famous example is that back vowels in the environment of coronal plosives may be produced as more front. A listener hears the realisation of back vowels as front in this context and they may fail to perceptually compensate for the coarticulatory effects of a coronal sound, eventually recategorising a back vowel such as /u/ as a front /y/ vowel. 'Misperception' can cover a variety of possible scenarios. For example, a listener may genuinely mishear what has been spoken due to phonetic similarity; e.g. hearing a bilabial fricative as labiodental. Or a listener may interpret a potentially ambiguous signal as another unit in their perception grammar, due to a lack of compensation for coarticulatory effects (as in Ohala's example above). Alternatively, a listener may encounter multiple forms of a particular phonological unit, but due to the effects of statistical learning in an exemplar-based phonology, their representation of a particular phonological unit might shift away from the original speaker over time (Blevins 2009, pp. 32–33).

The variation that exists – and allows the possibility for misperception – stems from variation in speech production (Ohala 1989). All spoken languages are subject to the effects of speech production in a vocal tract, which is subject to anatomical and biomechanical constraints, as well as the potential for speech planning and production errors. These constraints may form weak biases that can be amplified given the right linguistic or social conditions, leading to a potential sound change. For example, Seoul Korean tonogenesis may be driven by production factors, such as the intrinsically higher f_0 in aspirated stops compared with lower f_0 following lenis stops (Kang & Han 2013). Typologically unusual sounds may also be susceptible to reduction and loss over time due to biomechanical constraints on articulation. For example, the production of nasalised fricatives poses a significant aerodynamic challenge, as air must flow through the nasal cavity while simultaneously creating the aerodynamic conditions required for frication noise in the oral cavity

(Ohala 1993; Warner et al. 2015). These examples point towards biomechanical or aerodynamic factors yielding biases towards or against particular phonetic realisations, but there also exist more general phenomena that can lead to small biases in production over time. For example, speakers are observed to dynamically adapt their speech along a hyper- or hypo-articulation continuum over the production of utterances. Varying degrees of over- or under-articulation may lead to consistent and perceptually noticeable variation in the speech signal, presenting another potential source of sound change that can be consolidated and stabilise into a community-wide change (Lindblom 1990).

Recent methodological developments have facilitated a more detailed examination of the role of speech articulation and vocal tract biomechanics, which has led to an enhanced understanding of how articulatory variation may contribute to change. Such change can progress via individual differences in articulatory strategies, or we may see community-level gradual shifts in articulatory configuration, which then lead to a more noticeable acoustic change (Bybee 2001, p. 58). For example, Lawson et al. (2013) demonstrate that socially stratified variation in rhotic tongue shape has contributed to the merger of several vowels in middle-class Glaswegian English speech. One likely possibility is that there exist quantal relationships between acoustics and articulation, whereby gradual shifts in articulation may produce few acoustic differences in some vocal tract regions but large acoustic differences in other regions (Stevens 1989). The quantal nature of the acoustic-articulatory relationship seems to us to be a highly significant factor in understanding the progression of ongoing sound changes, whereby production patterns in articulation could point towards potential acoustic change once such articulatory change stabilises. This explanation has been proposed in recent studies of pre-lateral vowel fronting in English (Strycharczuk & Scobbie 2017; Gorman & Kirkham 2020) and it stands to reason that a detailed examination of speech articulation can only enhance our knowledge of how synchronic variation may potentially represent a precursor to diachronic change.

The above models go a long way to describing many possible processes and historical developments in sound systems cross-linguistically, with a small number of possible exceptions discussed in (Blust 2005). There remains a gap, however, in accounting for how typologically unusual systems sometimes remain stable despite the pressures of production biases, perception biases and other pressures towards system change, such as language contact and endangerment (Dorian 1981; Thomason 2001). Presumably, all language systems and all speakers are subject to similar processes of misperception and articulatory biases. Yet in some cases, sound change occurs, while in other cases, sounds that might be predicted to undergo change do not. Our study considers the phonetic realisation of secondary articulations in rhotics, a typologically unusual phenomenon, which appears cross-linguistically prone to change. We now address the nature of secondary articulation contrasts in rhotics and why such contrasts are particularly likely to undergo reduction or loss.

1.2 Secondary articulation contrasts in rhotics. The majority of the world's languages contrast one or more rhotic consonants (76% in Maddieson 1984's sample). Most languages have a single rhotic, which is commonly a trill (P. Ladefoged & Maddieson 1996, p. 217). While 183 out of 317 languages in Maddieson (1984)'s sample had one rhotic, only 51 had two rhotics, 8 had three rhotics and 1 language had four rhotics. Languages contrasting three or more rhotics constituted 2.8% of the sample. While not included in Maddieson (1984), it is also worth noting that Toda (Dravidian) has six contrastive rhotics: at three different places of articulation and each can be palatalised or plain (Spajić et al. 1996). Of the 316 rhotic phonemes analysed in Maddieson (1984, p. 81), only 11 have a secondary articulation. Eight are palatalised, two velarised and one pharyngealised. Other rhotic secondary articulation contrasts may include labialisation as in Marshallese and Kusaien (Micronesian, Bender 1968; Lee 1975, p. 25).

Considering the small number of languages with rhotics contrasting in secondary articulations in Maddieson's sample and other literature, the contrast described in Gaelic involving three rhotics contrasting in secondary articulations is typologically unusual. The most commonly reported secondary articulation in rhotics is secondary palatalisation. Hall (2000) provides an overview of secondary palatalisation in rhotics across the world's languages and shows that this feature is found in a range of language families including Uralic, Niger-Congo, Dravidian, Afro-Asiatic and Mongolian among others. Across the Indo-European language family, there appears to be a trend towards losing palatalisation in rhotic consonants as a phonemic feature. Note this is not always the case; for example, palatalised rhotics are not found in Proto-Dravidian (Krishnamurti 2003, p. 120), but appear to be an innovative feature in Toda (Spajić et al. 1996).

The tendency towards loss of palatalised rhotics in Indo-European, however, may stem from two sources. Firstly, palatalised rhotics may be disfavoured by biases rom articulatory constraints. As stated above, the most common manifestation of rhotics is a trill. Several authors have commented on the articulatory incompatibility between trilling and palatalisation (P. Ladefoged & Maddieson 1996; Kavitskaya 1997; Kavitskaya et al. 2009; Iskarous & Kavitskaya 2010; Stoll 2017). This incompatibility rises in the production of a trill, where optimal aerodynamic conditions are needed for the Bernoulli effect to produce vibration. In trill production, the tongue body is retracted and stabilised (McGowan 1992; Recasens 2013). When the tongue body is also raised and fronted for palatalisation, this produces additional constraints on the production of vibrations necessary for trilling. In order to overcome this fundamental incompatibility between trilling and palatalisation, Stoll (2017) shows that Russian speakers delay the palatalisation gesture in palatalised rhotics compared with the same gesture in palatalised laterals (see Kochetov 2005 for a similar finding). This temporal delay may lead to increased gestural overlap and, therefore, increases potential for increasing degrees of gestural overlap, which can lead to sound change. Stoll also shows that the tongue tip gesture in trilled rhotics is slower than the tongue tip gesture in laterals, so may be subject to gliding. Stoll and Kochetov interpret these articulatory findings from contemporary Russian to suggest that these factors may have led to sound change and loss of palatalised rhotics in other Slavic languages.

Another potential bias against the production of palatalised rhotics is perceptual constraints. Howson & Monahan (2019) show that rhotics occupy a small perceptual space and are acoustically and perceptually more similar to each other than other sound classes. In their experiment, listeners were worse at distinguishing three different rhotic segments than three different laterals, stops, nasals or fricatives. Howson & Monahan (2019) suggest that the perceptual similarities across the class of rhotics has led to (1) common occurrence of changes from one rhotic to another; for example, /r/ > /ʀ/ in Sorbian (Howson 2017); (2) allophonic alternations across rhotics; for example, [ɾ r ɹ ɽ] as allophones in Brazilian Portuguese (Veloso 2015); and (3) frequent attestation of free variation in rhotics; for example, [r] ∼ [ʀ] in Swedish (Lindau 1985).

Taken together, these articulatory and perceptual mechanisms are frequently used to explain the loss of palatalised rhotics, especially in Slavic. In the next section, we consider the realisation of secondary articulations in rhotics in more detail in order to track their evolution across Indo-European, especially Goidelic, and eventually explain how they are maintained or have been lost.

1.3 Secondary articulations in rhotics across Indo-European. In the above section, we explained how biases in production and perception might lead to change in rhotic systems, especially towards loss of secondary articulations in rhotics. We now examine in more detail how these biases have impacted the typology of rhotic systems across Indo-European with a particular focus on Balto-Slavic and Goidelic. Slavic is the most widely studied context of secondary palatalisation, and Goidelic is of most immediate relevance to the contemporary Gaelic context.

Slavic and Baltic. Secondary articulations in rhotics are most widely studied in the context of palatalisation in Russian and other Slavic languages. Originally present in Proto-Slavic, palatalised rhotics are now found to varying extents in the modern languages (Carlton 1990). They occur in all environments in Russian (Kochetov 2005; Iskarous & Kavitskaya 2010; Stoll 2017), and also in Lower Sorbian (Howson 2018), and are partially present in some environments in Ukranian, Upper Sorbian and Bulgarian. An overview table in Iskarous & Kavitskaya (2010, p. 627) shows that palatalised rhotics have been lost in languages such as Belarusian, Slovak, Serbian, Croatian and Macedonian. Two languages have spirantised palatalised rhotics into a post-alveolar fricative /ʒ/ in

Polish, and a trill-fricative in Czech /r̝/ (Howson, Komova, et al. 2014). Finally, palatalised rhotics have changed into a rhotic + /j/ in Slovenian (Stoll 2017). Similarly, palatalised rhotics appear to have been present in Proto-Baltic, but are reduced in the modern Baltic languages. Lithuanian contrasts palatalised and non-palatalised rhotics (Augustaitis 1964), and they are marginal in Latvian (Zalite 2015).

GOIDELIC. Here, we explain how the contemporary Gaelic system evolved from Gaelic's ancestor language, Old Irish (also known as 'Early Gaelic'), and trace the development of rhotic systems across the language family in order to ultimately demonstrate how they are maintained in some Goidelic varieties but not others. Old Irish/Early Gaelic is described as having a four-way contrast in sonorants, which is usually shown in Celtic Studies literature as L l L' l'. The apostrophe denotes palatalisation and the capitalisation show a 'fortis/lenis' contrast (Russell 1995; Stifter 2006). In the Archaic Irish period around 400-600CE, it is thought that the 'fortis/lenis' distinction was one of geminate/singleton, and is shown in orthography with a double/single grapheme (Hickey 1995, p. 149). 'Lenition' refers to a sound change that happened pre-Old Irish (i.e. pre-600CE). In lenition changes in Goidelic, intervocalic consonants spirantised, voiced, or degeminated. This sound change resulted in the system of word initial consonant alternations (mutations) found in the modern Goidelic languages (e.g. Ball & Müller 2009). In early Old Irish, a lenited sonorant changed from geminate to singleton (Hickey 1995, p. 154) and palatalisation became gradually phonemic during the Old Irish period (Greene 1973). Towards the end of the Old Irish period around 800-900CE, it is thought that gemination was lost as a contrastive aspect of the language (Hickey 1995, p. 150). Thurneysen (1946, p. 84) suggests that at this stage, the 'fortis' sonorants were produced with a laminal advanced articulation and the 'lenis' sonorants were produced with an apical retracted articulation. We interpret this suggested place of articulation contrast as a contrast between alveolar (advanced) and retroflex (retracted) rhotics, but this is speculative given the differences in terminology.

Around 900CE, Irish had contrastive palatalisation, a system of consonant mutations including lenition, and a former geminate/singleton contrast. Hickey 1995 suggests that in Middle Irish the whole consonant system realigned to contrast palatalised versus velarised counterparts and the sonorants were included in this system of oppositions. Where they occurred in synchronic and diachronic contexts of lenition, the former geminate/singleton ('fortis/lenis') contrast in sonorants was replaced by a 'depolarisation' contrast. By this, Hickey means that palatalised sonorants in lenition contexts become non-palatalised, and velarised sonorants become non-velarised (Hickey 2014, p. 46). This results in the three-way contrast found in most dialects of Scottish Gaelic between palatalised, 'plain' and velarised sonorants. The Middle Irish period is significant as this is when we can linguistically state that Scottish Gaelic can be regarded as a separate language from

Irish, with the distinction being dated to the 1100s by Ó Maolalaigh (2008). The entire development of the rhotic system in early forms of Irish and Gaelic is summarised in Table 1.

<INSERT TABLE 1 ABOUT HERE>

In the modern Goidelic dialects, this system has undergone further change in some cases. The most conservative manifestation is in some dialects of Gaelic where three rhotics are reported. Specifically, in Lewis (Bernera) Gaelic, Borgstrøm (1940, p. 24) describes (1) a velarised rhotic which is trilled, 'strongly hollow' sounding and retroflex in articulation; (2) a plain alveolar tap/trill with 1-2 taps; and (3) a dental fricative that is not strongly palatal. Oftedal (1956, pp. 126–9) also refers to (1) an alveolar trill with a 'hollow timbre'; (2) a plain tap without 'hollow timbre'; and (3) a dental or alveolar fricative, which is sometimes palatalised. In their phonetic study of Gaelic, P. Ladefoged, J. Ladefoged, et al. (1998) report formant differences between the plain and velarised rhotics suggestive of a palatalisation contrast, and state that the palatalised phoneme was realised as a dental fricative. In a wide-ranging dialect survey of Gaelic speakers collected in the mid twentieth century, Ó Dochartaigh (1997) largely confirm these reports above, yet the auditory transcription data have not been systematically analysed in the phonetic literature. We address this by presenting such a re-analysis in this article. Finally, Nance, McLeod, et al. (2016) conducted an auditory analysis of word-final rhotics in L2 Gaelic speakers. They found that phonemically palatalised rhotics were more likely to be produced with palatalisation or spirantisation, but that the velarised rhotics were comparatively rare in spontaneous speech and it was, therefore, difficult to conclusively determine their phonetic realisation and phonological status.

The three-way contrast in Middle Irish rhotics has been reduced to a two-way contrast in several Goidelic dialects. For example, in Applecross Gaelic, Ternes (2006, p. 25) suggests that the alveolar and palatalised rhotic have merged, leaving a velarised vs. 'unmarked' rhotic. A two-way contrast is similarly described for modern Irish. Ní Chasaide (1999) reports a distinction between palatalised and velarised taps, which is neutralised in word-initial context and produced as an approximant. Similarly, Ní Chiosáin & Padgett (2012) and Bennett et al. (2018) show a contrast between palatalised and velarised trills. Finally, Hickey (2014, p. 93) suggests a contrast between a trill and a palatalised trill, which is neutralised in word-initial context. The most innovative Goidelic dialects in terms of rhotics are East Sutherland Gaelic and Manx. In East Sutherland, Dorian (1978, p. 45) reports one rhotic sound which is typically realised as a tap or trill. Similarly, there is one rhotic in Manx, though Broderick (2009, p. 310) reports 'traces' of palatalised rhotics in some relic words. Broderick's description is based on Classical Manx (mid 1700s). The above information is summarised in Table 2.

<INSERT TABLE 2 ABOUT HERE>

The above discussion suggests that the three-way phonemic contrast in contemporary Lewis Gaelic rhotics is a particularly strong case study for examining the maintenance of typologically unusual contrasts in the face of considerable biomechanical, perceptual, and sociolinguistic pressures. Lewis Gaelic was chosen for this study as it is a traditional dialect with a relatively large speaker base, where the first author has been conducting fieldwork for some time. Other island varieties such as Uist or Barra could also have been chosen to represent contemporary Gaelic here. These conservative Goidelic dialects represent an unusual case where there has not been recent reported loss or simplification of the rhotic system. This provides us with an ideal opportunity for testing (1) whether this distinction does indeed remain intact in present-day Scottish Gaelic; (2) the nature of complex rhotic contrasts in terms of their auditory, acoustic and articulatory correlates; and (3) how such a typologically unusual system persists in the face of diachronic pressures that would predict its loss. Before we advance our method for analysing this system, we briefly outline the status of contemporary Scottish Gaelic, which helps to further contextualise the unusual maintenance of the complex rhotic contrasts that we observe.

1.4 SCOTTISH GAELIC TODAY. Gaelic is spoken by approximately 58,000 people in Scotland (approximately 1% of the population). The densest concentration of Gaelic speakers is found in the chain of islands off Scotland's north-west coast, the Outer Hebrides, where around 60% of the population can speak Gaelic, according to the most recently available census data (Scottish Government 2015). A map showing the concentration of Gaelic speakers in Scotland is shown in Figure 1. While it is now the case that Gaelic is spoken by only a small proportion of the Scottish population, in around 1000-1100 it was spoken by the majority of people in what is now Scotland and used as the language of the Scottish nobility (MacKinnon 1974). Due to political shifts in allegiance towards the English-speaking south, the Highland Clearances and twentieth century depopulation, the number of Gaelic speakers as a proportion of Scottish people has declined since this time (McLeod 2020). At the same time, a revitalisation movement, which gathered pace at the end of the twentieth century, has led to the expansion of Gaelic into new domains such as education, media and politics. This revitalisation has contributed to the linguistic expansion of the language and its use in new domains such as technical policy documentation (Lamb 2008; Dunmore 2019).

<INSERT FIGURE 1 ABOUT HERE>

The sociolinguistic context described above points towards fertile conditions for sound change in the Gaelic rhotic system. Previous research into language shift and obsolescence shows reduction of complex or typologically unusual systems (Dorian 1981; Jones 1998) and a reduction in the number of contrasts not found in the societally-dominant language (Campbell & Muntzel 1989; Thomason 2001). In the case of Gaelic, the language has been in intense contact with English in the Outer Hebrides for at least the past 100 years and all Gaelic speakers, apart from the very old and very young, are bilingual in English (Macleod 2010). As such, it might be expected that a typologically unusual and diachronically unstable system such as a three-way contrast in rhotics would be subject to change, especially as it is larger and very different from the single rhotic phoneme in English.

1.5 SUMMARY AND REMAINING QUESTIONS. Thus far, previous research suggests that typologically complex sound systems may undergo simplification or reduction due to a series of biomechanical pressures on speech production, as well as the fact that dense contrasts are perceptually vulnerable to misperception. We have highlighted, however, that some typologically disfavoured sound systems are maintained despite these pressures. In this study, we examine how some languages maintain unusual contrasts despite their loss or simplification in other languages. In doing so, we simultaneously provide documentation of an unusual system in a minority endangered language.

Our study provides a multi-dimensional analysis of the auditory, acoustic and articulatory characteristics of a three-way contrast in Scottish Gaelic rhotics. We are thus able to track the group-level and individual speaker strategies used to produce this phonemic contrast, as well as identify patterns in articulation that may be indicative of pressure towards a future change in progress (Lawson et al. 2013). In order to contextualise our findings in terms of the broader diachronic situation of Gaelic, we compare our data to a dialect survey from speakers born at the turn of the twentieth century, allowing us to further assess the possibility of stability or change in Gaelic rhotics.

2 METHODS.

2.1 SPEAKERS. The participants recorded for this study are speakers who grew up on the Isle of Lewis, Outer Hebrides, with Gaelic as their L1. Due to the availability of higher education and employment opportunities, all the speakers had spent some time living on the Scottish mainland, but had returned to Lewis to further their careers. All reported using more Gaelic than English in their daily lives and were employed in Gaelic-essential work, or retired from work involving Gaelic. The speakers in this study are aged 21-80, mean age 40. While the sample is age-diverse, the speakers are consistent in identifying as Gaelic-dominant bilinguals. In the minoritised context of

Gaelic, this is increasingly rare and our sample represent an important proportion of Gaelic-dominant adults in an island community. Fifteen speakers were recorded for this study; we present auditory and acoustic data from the twelve who meet the criteria outlined above. For the ultrasound analysis, we present data from the seven speakers who imaged clearly and where there were no technical recording difficulties. Our auditory analysis also provides some comparison to the Lewis speakers in the Survey of the Gaelic Dialects of Scotland (Ó Dochartaigh 1997). This extensive survey includes data from nine participants from Lewis born between 1892-1922 and recorded in 1961-1963.

2.2 DATA COLLECTION. Data for this study were collected in a community centre in Stornoway, Isle of Lewis, or in a quiet room in the participant's workplace. The acoustic data were collected using a Beyerdynamic Opus 55 microphone, with the signal being pre-amplified and digitised using a Sound Devices USBPre audio interface and then recorded to a laptop computer at 44.1 kHz with 16-bit quantisation. The microphone was attached to a headset used to stabilise the ultrasound probe (Articulate Instruments 2008). The stimuli were presented to participants using the Articulate Assistant Advanced (AAA) software on a laptop computer screen (Articulate Instruments 2018).

Midsagittal B-mode ultrasound images were recorded using a Telemed MicrUs system, with a 64 element probe of 20 mm radius. We used a 2 MHz probe frequency, 80 mm depth, 90% field of view and 57 scan lines, which resulted in a frame rate of $\sim$92 Hz. The probe was stabilised throughout the experiment using the Articulate Instruments metal headset (Articulate Instruments 2008). Each speaker also produced an occlusal plane reference recording at the beginning of the session, by biting down on a plastic bite plate fixed behind the upper incisors and pushing their tongue up against the plate. Audio-ultrasound synchronisation was carried by recording the TTL pulse that the ultrasound hardware emits at the completion of each frame onto a simultaneous audio track, which gives very high-accuracy frame-level synchronisation between audio and the ultrasound image.

The stimuli used for this study are in Table 3. We also recorded data containing Gaelic laterals and nasals, as well as English sonorants which are not reported here, but see Nance & Kirkham (2020) for details of the Gaelic lateral and nasal acoustic analysis. The list was repeated three times in random order without a carrier phrase.[2] The word list aimed to elicit the three rhotic phonemes in /i a u/ vowel contexts in word-initial and word-medial position. Due to the fatigue resulting from recording while wearing the ultrasound headset, we were unable to elicit data on the word-medial context. The occurrence of /r^{j}/ in word-initial position is extremely limited to a small handful of words. We chose to elicit the word *ri* 'to' as it is reliably produced with /r^{j}/, but the limited context for /r^j/ in word-initial position is further discussed in Section 4. In word-initial position, the 'plain' phonemes are usually triggered by initial consonant mutation. As such, we elicited them by using the possessive *mo* 'my' which triggers mutation. The auditory and acoustic analyses were conducted on 1088 tokens (from 12 speakers) and the ultrasound analysis was conducted on 399 tokens (from 7 speakers).

<INSERT TABLE 3 ABOUT HERE>

2.3 DATA SEGMENTATION. The duration of the rhotic was manually labelled in Praat (Boersma & Weenink 2021) by a research assistant and then checked by the first author. Due to the long-range acoustic effects of rhotics, it is not always straightforward to segment a clear beginning and end of rhoticity (Plug & Ogden 2003). In word-initial position, taps and trill were relatively easy to segment and the vowel was segmented beginning at a clear change in waveform periodicity and increase in intensity, as well as spectrographic clues. Approximants were segmented as ending where there was a clear change in the second formant on the spectrogram and/or the third formant, as well as auditory clues. These cues were also used to segment voiced rhotics in word-final position. The majority of word-final rhotics were, however, largely voiceless and appeared on the spectrogram as similar to voiceless fricatives. In these cases, the rhotics were segmented where there was a change in formant structure and based on changes in the amplitude of the waveform. Examples of the segmentation and realisation of different rhotic phonemes are shown in the spectrograms and waveforms in Appendix A.1, Figures 13, 14, 15.

2.4 AUDITORY ANALYSIS. Auditory analysis was carried out using a narrow phonetic transcription of the rhotic using the SAMPA alphabet in Praat. Two phonetically trained research assistants, Chloe Cross and Dom Moran, conducted the first transcription independently. The transcribers had no knowledge of Gaelic and were unaware of the phonemic category of each rhotic. As discussed in Stuart-Smith et al. (2014), auditory transcription of rhotics can be problematic and vary between transcribers. After this initial transcription, the data were collapsed into broader categories and inter-rater reliability carried out. The collapsing of narrow transcriptions into broader categories is detailed in Appendix A.2, Table 14. Initial inter-rater reliability between the two sets of transcriptions was conducted using Cohen's Kappa (Cohen 1960; Gisev et al. 2013). Cohen's Kappa was obtained using the irr package (Gamer et al. 2019) in R (R Core Team 2021) run in RStudio (RStudio team 2020). The k value was 0.65, z = 30.6, $p < .001$, suggesting moderate reliability (McHugh 2012). Disagreement occurred most commonly on word-final taps with palatalisation, which one transcriber counted as taps and the other categorised as palatalised fricatives. The first author of the current paper then checked all tokens where the transcribers disagreed and made a final decision based on previous experience of working on Gaelic rhotics (Nance, McLeod, et al. 2016). When organising these data and all the data described below, we made extensive use of the tidyverse suite of R packages (Wickham et al. 2019).

As a comparison, we also include data from the Survey of the Gaelic Dialects of Scotland (SGDS) (Ó Dochartaigh 1997). The survey materials include examples of word-final rhotics and were auditorily transcribed. We have interpreted the transcriptions from the nine Lewis speakers in Ó Dochartaigh (1997) into the same broad categories used for our analysis. Details of the exact process used are in Appendix A.3 in Table 15.

The data from the SGDS can provide an interesting insight into language change (or lack thereof). However, an important point to keep in mind when comparing the two auditory transcriptions is that our method involved a first transcription by phonetically trained people with no knowledge of Gaelic and what the rhotics were 'supposed to be'. We felt this would give the most unbiased picture of the realisation of these particular sounds. As such, our transcription scheme focussed on potential differences between major manners and place of articulation. The SGDS fieldwork on Lewis was conducted mainly by Magnus Oftedal who had already published a monograph on the topic (Oftedal 1956), and would have had a very strong idea of what he was likely to hear.

2.5 ACOUSTIC ANALYSIS. Previous acoustic work on palatalisation and rhotics has considered measures of the first three formants (Spajić et al. 1996), F2−F1 (Iskarous & Kavitskaya 2010; Howson 2018), whole spectrum analysis (Iskarous & Kavitskaya 2018), and SSANOVAs fitted to the first three formants (Howson 2018). As noted by Iskarous & Kavitskaya (2018, p. 62), palatalisation contrasts may be greater during the vowels surrounding the consonant than in the consonant itself. Similarly, Kochetov (2017) found substantial spectral differences in the vowels surrounding palatalised and non-palatalised fricatives in Russian. As such, our acoustic analysis considers the rhotic and the vowel following/preceding it. A final point to consider is that the palatalisation gesture in rhotics occurs relatively late (as compared to laterals) in the duration of the segment (Kochetov 2005; Stoll 2017).

Considering this previous research, our analysis includes static measures of F2−F1 and F3−F2 at 80% duration of the word-initial rhotics. We also measured F2−F1 and F3−F2 in the vowel following word-initial rhotics at 20% duration of the vowel, and in the vowel preceding word-final rhotics at 80% duration of the vowel. Formants were estimated in Praat using a 25ms Gaussian window and the LPC Burg method, which was set up to find five formants up to 5500 Hz (female speakers) or 5000Hz (male speakers). The resulting values were within-speaker z-scored. The z-scores allow us to quantify within-speaker contrast while projecting each speaker's data onto the same scale, thus enhancing the possibility of comparing across speakers.

In word-final rhotics, it would not make sense to attempt to obtain formant measures from largely voiceless segments, where LPC analysis cannot reliably estimate formants. As such, we measured spectral Centre Of Gravity (COG) instead of extracting formants, following Kochetov (2017). For this analysis, sound files were band pass filtered at 2000-11,000Hz, and downsampled to 22,050Hz. COG was obtained from a 40ms Hamming window centred on 80% of the rhotic duration and then values were within-speaker z-scored. We used Praat scripts to extract both formant values and spectral moments. These scripts were run directly from R using the speakr package (Coretta 2021b).

2.6 ULTRASOUND ANALYSIS. Splines were automatically batch-fitted to every ultrasound frame in the data set using AAA's batch fit function. We then selected regions of interest, based on the labelling of the acoustic sonorant-vowel interval, and a paid research assistant, Lois Fairclough, manually checked and corrected any obvious errors in the splines where appropriate. Note that we did not correct for very minor tracking errors. All splines were then rotated and scaled to the occlusal plane, based on a trace of the bite plate recording for each speaker. Data were exported from AAA and manipulated in R using the rticulate package (Coretta 2021a).

The ultrasound analysis includes two components. Our first analysis presents Generalized Additive Models (GAMs) of tongue splines from each speaker so that the reader can conceptualise the different tongue shapes used for these rhotics. We fitted separate GAMs to each speaker and the models were fitted using polar coordinates (Mielke 2015). The model featured spline Y values as the outcome variable and a smooth term of X values by an interaction variable comprising phoneme, vowel and position. We set the autocorrelation parameter at 0.4, which we found to reduce autocorrelation for a substantial degree for all speakers. After model fitting, we then split the interaction variable back into its component parts, which allows us to examine how tongue shapes different according to phoneme, position and vowel context. Visualisation was carried out using the tidymv package (Coretta 2021c).

Our second analysis involves Principal Component Analysis (PCA) of the tongue splines to reduce the dimensionality of the data and allow comparison of the main patterns in production employed across speakers (Stone 2005; Johnson 2011; Turton 2017; Bennett et al. 2018). The PCA was run on all of the x and y coordinates of the tongue splines extracted at rhotic midpoint. As the ultrasound tracks tongue splines along 42 fanlines, this leads to a data frame with 84 possible axes of variation (x and y values for each fanline). The PCA reduces these 84 potential areas of variation into a smaller number of components which characterise each tongue shape. Prior to running the PCA, data from each speaker were *z*-scored to better facilitate inter-speaker comparison. The PCA was calculated using the princomp() function in R. The first four components accounted for 88% of the variation in the dataset, with PC4 only accounting for 7% of the variation. Following Baayen (2008, p. 130) and Turton (2017) we report PCs which capture >5% of the data. PC5 explains 4% of the variation in the data so is not included. Subsequent PCs explain less and less of the variation. In order to interpret the aspects of tongue splines which the PCs represent, the loadings of the PCs of interest were plotted on top of an average tongue spline for the data. Each PC is a linear function explaining variation in the dataset, and the loading is the intercept of this function. In order to show the extent of the variation each PC explains, we plotted the mean coordinates of the dataset $\pm$ the standard deviation of each PC times the loading. For more details see Johnson (2011, pp. 95–102).

2.7 STATISTICAL TESTING. This section outlines our overall approach to statistical testing, with more specific details provided in the relevant results sections. Our modelling uses mixed effects regression analysis via the lme4 R package (Bates et al. 2015). After listening to the data and conducting some initial visualisation, we found that word-initial and word-final data behaved quite differently so we have modelled the two word positions separately (except in the auditory analysis, see below). Phoneme (velarised, plain, palatalised) and vowel context (/i/, /a/, /u/) were included as independent variables. We have used the IPA symbols to refer to the three phonemic categories (/rˠ/, /r/, /rʲ/) in order to clearly disambiguate from phonetic auditory perception of palatalisation and velarisation. Our random effects structure was as follows: we included by-speaker random slopes for the effect of vowel and phoneme wherever possible. In cases where such models did not converge, we first changed the optimiser to the bobyqa method using the Optimx package (Nash & Varadhan 2011; Nash 2014). If this model would also not converge, we included only a by-speaker random slope for phoneme and, if even this model would not converge, we only included a random intercept of speaker. These cases are indicated in the relevant results sections. We did not test for interactions between vowel and phoneme context due to the increased demand on statistical power for detecting such interactions (Harrrell 2015) which was not possible in all aspects of our dataset. Instead, we discuss the results of possible interaction between factors via data visualisation.

For significance testing of the main effects, we tested a full model as described above against a model not containing the predictor of interest via likelihood ratio testing. We are therefore modelling whether or not a particular variable significantly improves model fit, and thus significantly predicts variation in the data (Winter 2020, p. 260). In order to conduct significance testing of the different levels in each predictor, we conducted post-hoc tests of all pairwise comparisons between levels of the categorical predictors, corrected for multiple comparisons within each set of contrasts using the Tukey method. This was implemented using the the emmeans R package (Lenth 2021). Full model formulae and measures of model fit are in Appendix A.4 Table 16. All data and code used in our analysis are available at `https://osf.io/jsa7k/`.

3 RESULTS. Our aim here is to examine how palatalisation and velarisation contrasts are produced in Gaelic, in light of current models of sound change predicting pressures towards reduction in the system. We first present results of the auditory analysis in order to identify the distinguishing perceptual characteristics of rhotics. We follow this by examining the acoustic correlates of phonological contrast, before examining the tongue shapes used in speech production. All data visualisation was conducted using the ggplot2, gridExtra, ggpubr, and ggpattern R packages (Wickham 2016; Auguie 2017; Kassambara 2020; Cheng & Davis 2021).

3.1 AUDITORY ANALYSIS. The results of our broad auditory labelling are shown in Figure 2. The figure shows clear differences according to word position, especially for /rˠ/: in word-initial position these are usually realised as approximants, but in word final position a tap is the most common realisation. There are also more approximants for /r/ in word-initial position compared to word-final position. In word-initial position, taps represent about half the tokens of /r/ and /rʲ/, but there are also a large number of palatalised fricative/rhotic realisations in the /rʲ/ category. In word-final position, most /rˠ/ and /r/ tokens are taps, but /rʲ/ is frequently realised as a palatalised fricatives/rhotic.

<INSERT FIGURE 2 ABOUT HERE>

Statistical testing was carried out to model the likelihood of a rhotic being produced as a palatalised fricative/rhotic in our broad transcription scheme. This variable was modelled via mixed effects logistic regression modelling as described in Section 2.7. Word-initial and word-final rhotics were modelled together. Although overall word-initial and word-final positions behave quite differently, in terms of the number of productions of palatalised fricative/rhotic they are comparable. This method allowed us to obtain a higher token count for the modelling. The results are shown in Table 4. The results clearly show a significant effect of phoneme and that there are more palatalised rhotics/fricatives in the /rʲ/ phoneme category compared to /r/ and also /rˠ/. There is a significant difference for vowel context overall, and the comparison of /i/ and /u/ results suggests that this may come from more palatalised fricative/rhotic realisations in /u/ contexts.

<INSERT TABLE 4 ABOUT HERE>

In order to investigate the realisation of /r^{j}/ further, we listened to these sounds again to analyse in more detail. We wished to ascertain which ones are produced with audible rhoticity and which ones are produced with some kind of non-rhotic fricative. Previous literature suggests that the phonemic /r^{j}/ is produced as a dental fricative (Borgstrøm 1940; P. Ladefoged, J. Ladefoged, et al. 1998). We found, however, that a large number of tokens (52/204) were produced with audible rhoticity. This usually took the form of a rhotic off-glide to the vowel followed by voiceless frication. These are the tokens that we consider to be phonetically palatalised rhotics in the dataset. A breakdown of this labelling by word containing a phonemic /r^{j}/ is in Figure 3. Words with the vowel /i/ (*fir* and *sir*) seem more likely than others to be produced with a phonetically palatalised rhotic, but we have not tested this statistically due to small token counts.

<INSERT FIGURE 3 ABOUT HERE>

Tokens in Figure 3 coded as ‘fricative no rhoticity’ were generally dental or alveolar fricatives but this represented only 38 of the 204 /r^{j}/ tokens. In terms of the 52 tokens we heard as phonetically palatalised rhotics, these were realised as a short tap followed by voiceless palato-alveolar frication. This could be represented as [^{ɾ}ɕ] in word-final position. In our word-initial phonemically palatalised rhotic word *ri*, tokens we heard as phonetically palatalised rhotics were also usually realised as a tap and palato-alveolar frication; i.e. [ɾɕ]. An example of a word-final token in the word *fir* ‘men’ /fir^{j}/ is in Figure 4. In this token, the word is produced as [fi^{ɾ}ɕ].

<INSERT FIGURE 4 ABOUT HERE>

A breakdown of /r^{j}/ realisation by speaker is shown in Figure 5. The figure shows that every speaker except lf04 produced some instances of phonetically palatalised rhotics. Speaker lf04 consistently produced dental fricatives, approximants or non-palatalised taps. In Figure 5, the speakers have been ordered by age with the youngest speakers on the left. There is a trend towards more audible palatalisation among the older speakers, and more phonetically palatalised rhotics among older speakers. We have not tested this statistically due to small token counts but this would be an interesting area to investigate in the future.

<INSERT FIGURE 5 ABOUT HERE>

The results of our comparison to the Lewis datapoints in the Survey of the Gaelic Dialects of Scotland is shown in Figure 6. Note these data consider word-final rhotics only. The SGDS data show a very clear three-way split with the /r^{ɣ}/ realised as trills, the /r/ as taps and the /r^{j}/ as palatalised fricatives/rhotics. We have not attempted to break down the palatalised fricative/rhotic category any further as we cannot be confident that we have interpreted the version of IPA used in the SGDS consistently enough at this more fine-grained level.

<INSERT FIGURE 6 ABOUT HERE>

To summarise: our auditory analysis reveals differences in realisation of the three phonemic categories, with /r^j/ demonstrating audible palatalisation, and /r^ɣ/ a greater number of word-initial approximants and word-final trills. There are substantial differences between word-initial and word-final rhotics in terms of manner of articulation. Comparison to the SGDS data shows that our data are largely consistent with the previous auditory survey, but our data appear to show less clear-cut distinctions between phonemic categories. We return to this finding in Section 4.2. We now turn to the acoustic characteristics of the rhotics in order to further explore contrast in the system.

3.2 ACOUSTIC ANALYSIS. In this section, we now report on the acoustic differences between the three rhotic phonemes. As described above, in word-initial position we measured (1) F2−F1 at 80% of rhotic duration; (2) F3−F2 at 80% of rhotic duration; (3) F2−F1 at 20% of vowel duration; and (4) F3−F2 at 20% of vowel duration. In word-final position, we measured (1) F2−F1 at 80% of vowel duration; (2) F3−F2 at 80% of vowel duration; and (3) Centre of Gravity (COG) centred on 80% of rhotic duration. These results are shown in Figure 7 for word-initial tokens and Figure 8 for word-final position. A breakdown of results according to the three vowel contexts is in Appendix A.5, Figures 16 and 17.

<INSERT FIGURE 7 ABOUT HERE>

<INSERT FIGURE 8 ABOUT HERE>

Statistical testing as detailed in Section 2.7 was carried out on each of the seven acoustic measures described above. In each case the acoustic measure was the dependent variable, while the effects of phonemic category and vowel context were tested via model comparison, and the comparison of the levels within the main effects were tested via post-hoc testing. The results of these models are shown in Tables 5, 6, 7 and 8.

<INSERT TABLE 5 ABOUT HERE>

<INSERT TABLE 6 ABOUT HERE>

<INSERT TABLE 7 ABOUT HERE>

<INSERT TABLE 8 ABOUT HERE>

Table 5 shows that in word-initial position at 80% of rhotic duration, here is a significant effect of rhotic phoneme on F2−F1 and F3−F2. All comparisons between phoneme categories were significant. The data in Figure 7 show that /rˠ/ has the lowest F2−F1 and /rʲ/ the highest. /rˠ/ has the highest F3−F2 and /rʲ/ the lowest. Following vowel phoneme also significantly predicts formant values during the rhotic phase, though /i/ and /u/ are similar.

In Table 6 we can see that at 20% duration of the vowel following word-initial rhotics, there is also a significant effect of rhotic phoneme category on F2−F1 and F3−F2. All comparisons between phoneme categories were significant. Similar to the measures during the rhotic itself, vowels following /rˠ/ have the lowest F2−F1 and the highest F3−F2. Vowel phonemic identity also predicts formant values though /u/ and /i/ were not significantly different from each other, and /a/ and /i/ were not significantly different in F3−F2.

Table 7 indicates that at 80% duration of the vowel preceding word-final rhotics, there is a significant effect of phonemic category. All phoneme comparisons were significantly different in both F2−F1 and F3−F2. Figure 8 shows that vowels preceding /rˠ/ have the lowest F2−F1 and the highest F3−F2. Vowel phonemic identity also predicts formant values though /u/ and /i/ were not significantly different from each other in F3−F2. Table 8 considers COG measures at 80% of word-final rhotic duration. There is a significant effect of phoneme and /rʲ/ has a significantly different COG compared to /r/. Vowel phoneme also significantly predicts COG, but not for in differentiating /u/ and /i/.

To summarise: There are significant effects of rhotic phonemic identity on the F2−F1 and F3−F2 of word-initial rhotics, vowels following word-initial rhotics, vowels preceding word-final rhotics, and word-final rhotic COG. In formant values, F2−F1 is significantly lower in the context of /rˠ/ and F3−F2 is significantly higher. /rʲ/ has the highest F2−F1 and lowest F3−F2. COG is significantly different in /rʲ/ compared to /r/. We now consider how these contrasts are realised in articulation via examination of mid-sagittal tongue shape.

3.3 Ultrasound analysis. So far, the acoustic analysis shows significant differences in formant and COG values between phonemic categories, both in the rhotic itself and also in the vowel. This analysis now considers the articulatory strategies used to produce phonemic contrast in rhotics. We first present GAMs fitted to each individual's data to explore individual variation in tongue shapes used. We then report a principal components analysis that aims to summarise the most salient dimensions of tongue shape variation between speakers, which helps to form generalisations across the data set.

Figure 9 shows GAMs fitted to each speaker's midsagittal tongue data, comparing phoneme types within different positions and vowel contexts. The most striking finding from this analysis is that the speakers appear to employ one of two distinct tongue shapes: either a bunched rhotic articulation or a tongue tip/front up (Delattre & Freeman 1968; Mielke et al. 2016; Heyne et al. 2020; King & Ferragne 2020). Figure 9 groups the speakers according to this pattern: bunched speakers are on the top row and tip up speakers are on the bottom row.[3] We have added each speaker's age to the plots, which shows that there is no clear age-related pattern. We also do not observe a clear gender-based pattern (speaker codes containing 'f' are female and 'm' for male), but we note that our small sample size makes it difficult to make such generalisations. Accordingly, we propose that that this is likely to represent speaker-specific variation, as reported for rhotics in other languages (Mielke et al. 2016). In Figure 10 we have plotted the auditory coding from the same speakers as shown for the ultrasound analysis. Similar to the results in Mielke et al. (2016), we do not find a straightforward relationship between auditory perception and tongue shape. We suggest that these differences in strategy may be covert and non-perceptible, perhaps representing motor equivalent strategies for producing an audibly similar output. We discuss this possibility in much greater detail in the Discussion section.

With respect to the phonemic contrasts in the Gaelic rhotic system, overall most speakers display a pattern whereby /r^j/ is produced with fronted and raised tongue shapes, and /$r^ɣ$/ is produced with lowered and retracted tongue shapes. In general, the word-initial phonemes are more articulatorily distinct than the word-final phonemes.

<INSERT FIGURE 9 ABOUT HERE>

<INSERT FIGURE 10 ABOUT HERE>

Our second ultrasound analysis uses Principal Components Analysis in order to summarise and quantify overall patterns in tongue shapes used. Data reduction in this manner allows for aggregation of data across speakers, which we did not do in the GAM analysis above. The first four principal components together explain 88% of the data. The respective proportions were: PC1 49%, PC2 21%, PC3 11%, PC4 7%. The loadings of the first four Principal Components and extent of the variation captured are plotted in Figure 11. From this figure we can draw the following interpretations: PC1 appears to represent variation in tongue frontness/backness. PC2 captures variation in tongue tip and the middle of the tongue, PC3 shows tongue dorsum height, and PC4 appears to capture variation in tongue root movement. The values of the first four PCs are plotted in Figure 12.

<INSERT FIGURE 11 ABOUT HERE>

<INSERT FIGURE 12 ABOUT HERE>

The values of the first four PCs were tested via linear mixed effects regression modelling as described in Section 2.7. Each PC was tested separately in word-initial and word-final context and in each case the independent variables were rhotic phoneme and vowel phoneme. The results are shown in Tables 9-12.

<INSERT TABLE 9 ABOUT HERE>

<INSERT TABLE 10 ABOUT HERE>

<INSERT TABLE 11 ABOUT HERE>

<INSERT TABLE 12 ABOUT HERE>

In word-initial position, there is a significant effect of rhotic phoneme on PC1, PC2 and PC3. For PC1, /r$^{\text{ɣ}}$/ has the lowest value and /r^{j}/ significantly the highest. For PC2, /r^{j}/ has the highest values but /r$^{\text{ɣ}}$/ and /r/ rhotics are not significantly different. For PC3, /r$^{\text{ɣ}}$/ rhotics again have the lowest value and /r^{j}/ the highest. Following vowel phoneme context significantly affects tongue shape for PC3 only, with /i/ vowel contexts differing significantly from /u/. In word-final position, there are significant effects of rhotic phoneme on PC1 only. For PC1, /r/ and /r^{j}/ have significantly higher values than /r$^{\text{ɣ}}$/. Preceding vowel phoneme context significantly affects tongue shape for PC1 and PC2, where /u/ and /i/ have significantly higher values than /a/.

From these results, and the interpretation of the PCs in Figure 11, we can make the following generalisations. In word-initial position, /r$^{\text{ɣ}}$/ has a backer tongue shape, /r^{j}/ is more fronted and /r/ lies somewhere in the middle. /r^{j}/ has a higher tongue middle, and /r/ and /r$^{\text{ɣ}}$/ are similar. /r$^{\text{ɣ}}$/ has the lowest overall tongue shape, /r^{j}/ the highest, and /r/ somewhere in-between. In word-final position /r$^{\text{ɣ}}$/ has a backer tongue shape, but /r^{j}/ and /r/ rhotics are generally similar. In summary, our ultrasound analysis shows some individual differences in tongue shape strategy to achieve the Gaelic phonemic contrast. Across the dataset though, there is a general tendency to produce /r^{j}/ with a fronting gesture and /r$^{\text{ɣ}}$/ with tongue lowering and backing. The phonemic differences are greatest in word-initial position.

4 DISCUSSION. Our aim in this paper is to examine how a typologically unusual system is maintained despite apparent articulatory, perceptual, and sociolinguistic pressures towards

reduction and loss. To do this, we examined the auditory, acoustic and articulatory characteristics of three rhotic phonemes in Gaelic, and provided some comparison to dialect survey data from speakers born over 120 years ago. In this discussion section, we summarise the results of our three analyses and then consider the overall evidence for maintenance of the three-way contrast in Gaelic. Finally, we return to debates about the articulatory and perceptual origins of sound change and how these data can help us to identify and explain how phonological systems can remain stable despite these pressures.

4.1 SUMMARY OF RESULTS: SECONDARY ARTICULATIONS IN GAELIC RHOTICS. Our results provide evidence for different realisations of phonemic rhotics in both word-initial and word-final contexts. The auditory analysis (Figure 2) suggests that word-initial /rˠ/ is most frequently an approximant, /r/ is an approximant or tap, and /rʲ/ is mainly a tap or a palatalised fricative/rhotic. In word-final position, taps are the most common realisation for /rˠ/ and /r/. /rʲ/ tokens are either taps, palatalised rhotics, or a fricative with some kind of palatalisation. Almost all word-final rhotics are voiceless, similar to the word-final laterals in Nance & Kirkham (2020). There are a small number of trills in every context. This is similar to results from other languages where it is noted that fully trilled productions are rare, especially in palatalised contexts (Lindau 1985; Spajić et al. 1996; Iskarous & Kavitskaya 2010; Stoll 2017).

A summary of the results from the acoustic and articulatory (PCA) analysis are shown in Table 13, focussing on the significant differences between phonemic categories. In word-initial position there are significant acoustic differences for the three categories in all measures. In word-final position, there were differences in the vowel preceding the rhotic, but in the rhotic itself there was only a significant difference between /rʲ/ compared to the /r/ and /rˠ/ together. These results closely pattern with other studies of palatalisation across rhotics and other segments, indicating that the acoustic signature for palatalisation extends substantially into the surrounding vowels (Kochetov 2017; Howson 2018; Iskarous & Kavitskaya 2018).

In general, our ultrasound analysis shows that /rʲ/ is produced with fronted and raised tongue shapes, and /rˠ/ is produced with backed and lowered tongue shapes. This is demonstrated by the significant differences between rhotic phoneme categories in PC1 in both word-initial and word-final position. However, we found substantial differences in articulatory strategies for rhotic production. Broadly speaking, our participants either produce rhotics with a tip/front raising gesture, or a tongue body bunching gesture similar to previous studies (Delattre & Freeman 1968; Lawson et al. 2011; Heyne et al. 2020; King & Ferragne 2020). We did not find that these two strategies are correlated with sociolinguistic variation in our sample, and they do not appear to have consistently different auditory realisations. It could be the case that a larger sample is needed in order to observe variation along sociolinguistic dimensions, but we think it likely that these strategies are more speaker-specific, given that the variation does not correspond to audible differences in production (Mielke et al. 2016).

<INSERT TABLE 13 ABOUT HERE>

Our method involved triangulating evidence from auditory, acoustic and articulatory analyses. These perspectives allow us to build up a holistic picture, yet do not always produce identical results. For example, we found more significant differences for phoneme category in the acoustic analysis as compared to the PCA analysis. Also, as shown by comparing 9 and Figure 10, the auditory impressions do not always align perfectly with differences in tongue shape. However in other respects there are strong correspondences between the different sources of data in that generally there were more differences between phoneme categories in word-initial position compared to word-final position (discussed in detail in Section 4.3). It is likely that much of the variability in the PCA data stems from individual differences in anatomy and the strategies speakers adopt to produce phonemic contrast despite these differences. We further explore this proposal in Section 4.3.

4.2 Evidence for the three-way contrast in Gaelic. The auditory, acoustic and articulatory evidence we present here largely support proposals for a three-way contrast in Gaelic rhotics, albeit with some caveats. In word-initial position, all analyses show clear three-way differences in acoustics, articulation and auditory characteristics. However, it must be noted that there is only one word that is reliably produced with a /r^j/ in word-initial position, the very common preposition *ri* ‘to’. We used the non-conjugated form, which has a high front vowel following and thus perhaps makes the rhotic susceptible to a high, front, palatalised tongue shape. Classic accounts of Gaelic phonology, such as Borgstrøm (1940) and Oftedal (1956), see the word-initial palatalised rhotic as a separate phoneme despite its highly limited context. Our analysis demonstrates that there is a separate phonetic realisation for this sound, albeit in a limited setting. We suggest that these findings are evidence of acquiring word-specific pronunciations of particular sounds, which can then lead to category formation (Bybee 2001; Renwick & Ladd 2016). Indeed, several previous phonetic studies of Gaelic have noted the scarcity of traditional minimal pairs and triplets, and state that it may not be possible to find examples of all phonemes in all contexts (Shuken 1980; P. Ladefoged, J. Ladefoged, et al. 1998). Our account provides further support that evidence from less prototypical and minority languages such as Gaelic is important for understanding full nature of phonological typology, as well as the structure of the world’s languages.

We observed in Figure 5 that there might be a pattern according to speaker age, whereby younger speakers produce fewer phonetically palatalised fricatives/rhotics and especially fewer palatalised rhotics. It is possible that this may indicate change in the future, but we cannot say conclusively due to the size of the current dataset, despite the fact that our data represents a sizeable sample of the very small community under study. The inclusion of data from the Survey of the Gaelic Dialects of Scotland does, however, allow some comparison to speakers born at the turn of the twentieth century. The youngest participant in this sample was twenty years older than our oldest participant. Word-final rhotics in the SGDS sample show a clear picture where place and manner of articulation distinguish the three categories, which was less clear in our data. The SGDS sample was collected mainly by Magnus Oftedal who wrote his monograph on Lewis Gaelic a few years before collecting the SGDS data (Oftedal 1956). The SGDS uses auditory transcription to record results. Our auditory results are similar to the results from the word-final rhotics in the SGDS, but the phonemic categories are less clearly defined. We do not find variants that are not attested in the SGDS, such as a high number of approximants in word-final position. We suggest that the differences between the two datasets probably do not represent sound change, but instead a transcriber bias in the SGDS towards what rhotics are 'supposed to be' in Oftedal's decisions about the phonemic structure of Gaelic. The elicitation methods in the SGDS also included several repetitions and explicit instruction towards a canonical production, after which the fieldworkers selected a 'representative' variant. We do not criticise the SGDS in this respect, but instead suggest that the different methodology employed in our study is more likely to be responsible for differences in results, rather than sound change in this case. In summary: we do not find evidence that this system has substantially changed from the data in Ó Dochartaigh (1997), or the early dialect descriptions of Borgstrøm (1940) and Oftedal (1956). In fact, it appears that the Gaelic system has remained relatively stable since Gaelic became a distinct language from Middle Irish in around 1100CE.

A remaining question relates to possible representation. While taps and approximants are the most common manners of articulation, we also found trilled productions in every phoneme and word position. Unlike some previous descriptions (Borgstrøm 1940; P. Ladefoged, J. Ladefoged, et al. 1998), we did not find that /r^{j}/ was always produced as a dental fricative. Instead, approximately half of the tokens were produced as taps, and around half were produced as some kind of fricative with palatalisation, including some dental fricatives, or a (phonetically) palatalised rhotic. We also found some approximants and trills. As such, we suggest that the palatalised category should be considered as a /r^{j}/ due to a high incidence of tokens involving rhoticity, rather than a dental fricative. This may well not be the case in all dialects of Gaelic, but we suggest that a palatalised rhotic is a common realisation of this phonemic category in Lewis.

Discussion about the differences between taps and trills suggests that speakers who aim to produce a tap are unlikely to produce a trill 'by accident'. It has been suggested that, unlike taps, trills are characterised by a current of air passing over a narrow aperture and producing a vibration via the Bernoulli effect (McGowan 1992; P. Ladefoged & Maddieson 1996, p. 217). Taps, on the other hand, are characterised by one muscular movement of the tongue tip/blade which is not extended to include multiple vibrations. As stated by Recasens & Dolors Pallarès (1999), trills are not geminate versions of taps. Languages that have phonological trills often have a variety of surface representations. This is noted in Lindau (1985)'s cross-linguistic analysis, as well as in Spajić et al. (1996), alongside some detailed studies of Russian trills (Iskarous & Kavitskaya 2010; Stoll 2017). In Russian, the palatalised rhotics in particular are less likely to be realised as full trills than non-palatalised rhotics (Iskarous & Kavitskaya 2010, p. 630). Our data do contain some trilled realisations across contexts and across phonemes. The evidence above suggests that these are unlikely to be underlying taps that surface as trills. As such, we suggest that a suitable representation for Gaelic rhotics would be as trills with secondary articulations; i.e. /$r^{ɣ}$ r r^{j}/.

4.3 Sound change and phonetic typology. Classic models of sound change, such as Ohala (1981), Ohala (1989), and Ohala (2012), and more recent developments, such as Blevins (2009), suggest that there are perceptual and articulatory explanations for how and why features such as palatalised rhotics may be lost. Specifically, perceptually ambiguous sounds may be misperceived, while articulatorily challenging segments are disfavoured over time. Indeed, the research summarised in the Introduction suggests that large rhotic systems are typologically unusual and that palatalised rhotics are particularly subject to loss in Indo-European and in other Goidelic varieties. In Slavic, palatalised rhotics are maintained in all positions in Russian and Lower Sorbian, maintained to some extent in Ukranian, Upper Sorbian and Bulgarian, spirantised in Polish and Czech, changed to a rhotic + /j/ in Slovenian, and lost in most southern Slavic languages (Iskarous & Kavitskaya 2010). In this study, we aimed to ascertain what characteristics of the Gaelic rhotic system allow it to remain stable despite cross-linguistic tendency towards loss (Iskarous & Kavitskaya 2010), possible perceptual ambiguity (Howson & Monahan 2019), articulatory complexity (Kochetov 2005; Stoll 2017), and sociolinguistic pressures (Dorian 1981). While there is some variation in our data, overall we find evidence that the three-way contrast is largely stable and is maintained by our speakers. We now propose four mechanisms that help to explain why Gaelic appears to maintain a robust three-way contrast in phonemic rhotics, despite considerable pressures to lose this distinction.

First, as discussed above, our rhotics are rarely realised as full trills and are more commonly realised as an approximant, tap, or tap plus voiceless frication. In particular, we were interested in how speakers might resolve the articulatory conflict between palatalisation and trilling in order to distinguish the phonemically palatalised rhotic. It appears that one strategy for resolving the articulatory conflict between trilling and palatalisation is simply not to produce a full trill with several vibration cycles. This is not uncommon in languages that maintain palatalised rhotics, and even those described as having palatalised trills such as Toda and Russian (Lindau 1985; Spajić et al. 1996; Iskarous & Kavitskaya 2010). For example, Iskarous & Kavitskaya (2010, p. 630) report for Russian that 26% of the plain rhotics were fully trilled, but only 1% of the phonemically palatalised rhotics. It is appears, therefore, that adaptation of articulatory strategies to preserve palatalisation are used by speakers of Scottish Gaelic, reducing the incompatibility between primary and secondary articulations. That said, this strategy alone does not eliminate the challenges posed by simultaneous rhoticity and palatalisation, which we now address further.

A second mechanism behind how the contrasts are maintained in Gaelic rhotics is that individuals appear to adopt articulatory strategies that produce similar acoustic and perceptual outcomes. This can be seen in the different individual articulatory strategies shown in Figure 9, which lead to substantial differences in the acoustics of each phonemic category. This may represent motor equivalent ways of addressing the articulatory challenges posed by simultaneous rhoticity and palatalisation. Motor equivalence in speech concerns the use of variable articulatory strategies that produce equivalent acoustic outputs. This can typically be achieved via covariation of articulatory gestures in order to constrain acoustic variability (Perkell et al. 1993), or the modification of an articulatory plan in response to a perturbation (Honda et al. 2002; Tremblay et al. 2003). While such variation can be highly structured and language-specific (Kirkham & Nance 2017), it often represents speaker-specific variation in how an equivalent acoustic goal is reached (Perrier & Fuchs 2015; Carignan 2019). In this case, we propose that the different articulatory strategies (tip up or bunched rhotics) represent different paths to achieving a similar degree of acoustic and auditory contrast between phonemes. Notably, each speaker consistently uses their individual bunched or tip up strategy across different rhotic phonemes. This could represent speakers adapting an articulatory strategy that best fits their individual vocal tract anatomy and allows them to achieve the specific phonetic implementation of the contrast. The latter point is a particularly important one, with previous studies showing that, even under considerable perturbation, speakers do not only aim to produce maximal contrast but also try to produce sounds with the rich phonetic detail appropriate to that language (Brunner & Hoole 2012). Notably, we did not find any obvious social differentiation in articulatory strategies, which have been suggested in studies of Scottish English rhotics (Lawson et al. 2013). Instead, our results show greater similar to studies of American English rhotics, with a small set of idiosyncratic patterns that do not appear to correlate with speaker characteristics such as age or gender, yet do allow for speaker-level flexibility in the production of contrast (Mielke et al. 2016). Previous work such as as Strycharczuk & Scobbie (2017) and Gorman & Kirkham (2020) has suggested that articulatory change may sometimes precede acoustic change due to the quantal nature of speech, whereby small changes in articulation lead to larger acoustic differences (Stevens 1989). Here, we instead see that speakers individually manipulate the flip-side of quantal theory: different articulatory strategies can produce similar acoustic outcomes.

A third mechanism behind the maintenance of contrast in Gaelic despite considerable pressure is that Gaelic rhotics are produced quite differently in word-initial and word-final position. This was the case in all three analyses. Gaelic sonorants appear to be largely devoiced in word-final position (Nance & Kirkham 2020), so it is likely that Gaelic speakers have adopted specific strategies for voiced (initial) and voiceless (final) environments in order to retain contrast despite perceptual similarities among rhotic consonants (Howson & Monahan 2019). Cross-linguistically, it is very common for rhotics to behave quite differently in syllable onset and coda position. For example, Standard German rhotics are frequently vocalised in coda position, but not vocalised in onset position (Simpson 1998; Wiese 2003). Similarly, Netherlandic Dutch rhotics vary widely across syllable contexts and may be, for example, a uvular trill in onset position and a retroflex approximant in coda position (Sebregts 2014). In Turkish, syllable-initial rhotics are voiced but syllable-final rhotics are frequently a voiceless fricative (Kopkallı 1993, p. 29). Gaelic is described as a VC language so may behave slightly differently from patterns described in other languages (Hammond et al. 2014). However, our stimuli were such that the word-initial tokens corresponded to syllable onsets and word-finals tokens syllable codas. We argue that the devoicing in word-final position in Gaelic has necessitated new strategies for maintaining phonemic contrasts. For example, we found comparatively few approximants in word-final position and we argue that speakers adapt their production and produce more taps, trills or rhotic fricatives instead as these articulations may be more perceptually distinct in a voiceless environment. This is quite different from the context of Modern Irish (see below), where the three-way distinction has been lost.

The explanations so far point to how Gaelic maintains this contrast, but our discussion now turns to understand why these strategies are deployed by speakers. Accordingly, a fourth and final factor is the production aims of the speakers themselves. As discussed in the Introduction, Gaelic is a language undergoing obsolescence, which might be expected to lead to reduction and simplification in phonology (Dorian 1981; Jones 1998). However, Gaelic is also undergoing revitalisation. Speakers such as those recorded for our study are well aware of their role in the revitalisation movement. Additionally, they all worked or had worked in occupations requiring the use of Gaelic. Gaelic's status as a revitalising language may involve some conservative retention of phonemic contrast in speakers who are very aware of the language's endangered status. There are some indications of this in the sociolinguistic analysis reported in Nance, McLeod, et al. (2016). Here, fluent L2 users of Gaelic showed that individual accent aim and overt production goals correlated with rhotic production. It is possible that awareness of phonological structure in highly educated speakers such as those in our sample may lead to greater retention of phonemic contrast. These factors demonstrate that sociolinguistic considerations may mean that language contact and obsolescence outcomes are far from a 'forgone conclusion' as noted by Ravindranath (2015).

It is reasonable to ask how Lewis Gaelic has maintained the three-way contrast but other Goidelic varieties such as Modern Irish have not. Modern Irish appears to represent a stage between Middle Irish and contemporary Lewis Gaelic. Authors agree that the Middle Irish three-way rhotic contrast has been reduced in modern dialects to a two-way distinction between palatalised and non-palatalised (Ní Chasaide 1999; Ní Chiosáin & Padgett 2012; Hickey 2014). Hickey (2014, pp. 95–96) suggests that the contrast in Modern Irish is neutralised in word-initial position, with an approximant being the most common variant. In word-final position, spirantisation and devoicing of the palatalised phoneme to [z̧] or [ş̥] is very common, especially in western Irish dialects. Hickey (2014, p. 97)'s phonological analysis states that while the nasals and laterals in Irish maintain aspects of the Middle Irish three-way distinction, this is not the case in rhotics. A final recent development is that non-palatalised word-final rhotics are produced as [ɻ] due to influence from Irish English (Hickey 2014, p. 97). There are several points of difference here with the Lewis Gaelic context. First, in word-initial position Gaelic has continued to distinguish the /r/ in mutation contexts, while Irish does not, and also a /$\mathrm{r^j}$/ in a small subset of words. Second, in word-final position, all Gaelic rhotics are devoiced rather than just /$\mathrm{r^j}$/. This factor may have led to Gaelic speakers developing some of the strategies discussed above in order to distinguish their phonemes in a way that was not necessary in Irish due to the voicing contrast, which could be used as the cue to indicate palatalisation or non-palatalisation. Third, Lewis Gaelic is not influenced by a voiced retroflex production in the same way that Irish might be as the Lewis English rhotic is heavily influenced by historical contact with Gaelic (Shuken 1984).

The above suggests that languages may maintain contrasts under pressure when a specific set of conditions converge to facilitate stronger phonetic differentiation between phonemes. We note that there is not a single 'silver bullet' listed above that explains the preservation of contrast. Instead, it appears that the greater articulatory compatibility between the phonetic implementation of rhotics and the palatalisation gesture allows for a more flexible set of motor equivalent aims in achieving acoustic contrast. The existence of different phonetic pressures according to word position also facilitates the development of auditorily distinctive realisations that are not subject to the same syllable structure pressures seen in many other languages. While the above factors are common in many contexts, we suggest that the above factors interact with Gaelic's existing phonology and facilitate the preservation of a complex and diachronically unstable phonological contrast. This is despite the fact that Gaelic is a minority language undergoing rapid change in other areas of the sound system such as prosody (Nance 2015). As a consequence, the stability we find in this study is far from inevitable and may even represent an exceptional case for Gaelic. Moreover, it remains possible that the minority status of Gaelic actually aids the maintenance of contrast, as professional Gaelic speakers, such as those in our study, may have high levels of metalinguistic awareness and may seek to use any available strategies to maintain traditional phonological contrasts.

5 CONCLUSION. In this study, we examined the production of secondary articulations in Gaelic rhotics in order to understand how this unusual system is maintained, despite predictions from sound change models indicating that such contrasts are prone to loss. Our analysis shows that the rhotic system of Lewis Gaelic has largely retained the three-way phonemic contrast inherited from Middle Irish, unlike other Goidelic dialects such as Irish and East Sutherland Gaelic. While there is some individual variation in production, we do not see evidence of large-scale change or widespread differences compared to survey data collected in the middle of the twentieth century. We propose that Gaelic speakers have instead adopted a variety of strategies to circumvent perceptual and biomechanical pressures on contrast, such as the use of fewer full trills and adapting production strategies within wider linguistic prosodic constraints in order to potentially maximise perceptual distance. We suggest that this individual variability may assist the production of contrast via motor equivalent strategies for acoustically similar outcomes. We demonstrate that examining the use of such strategies in typologically unusual contexts can better refine the predictions of models of cross-linguistic phonological typology and sound change. And finally, we argue that such a process is essential for testing the limits of sound change models beyond majority languages.

A Appendix.

A.1 Example spectrograms and waveforms.

<INSERT FIGURE 13 ABOUT HERE>

<INSERT FIGURE 14 ABOUT HERE>

<INSERT FIGURE 15 ABOUT HERE>

A.2 Auditory coding categories.

<INSERT TABLE 14 ABOUT HERE>

A.3 Interpreting the SGDS transcriptions. The table below shows the transcriptions published in Ó Dochartaigh (1997) and how we interpreted them. The symbols used in the survey for rhotics are explained in the introductory volume to the survey pp130-134. We have focussed on the conventions used by the two fieldworkers in Lewis: Oftedal and McCaughey. Oftedal also uses a subscript $<$ at times to indicate partial devoicing. We have included these tokens as ‘devoiced’.

<INSERT TABLE 15 ABOUT HERE>

A.4 Extra information on regression models.

< INSERT TABLE 16 ABOUT HERE >

A.5 Acoustic measures according to vowel context.

<INSERT FIGURE 16 ABOUT HERE>

<INSERT FIGURE 17 ABOUT HERE>

REFERENCES.

ARTICULATE INSTRUMENTS. 2008. *Ultrasound stabilisation headset: Users manual revision 1.5*. Edinburgh: Articulate Instruments.

ARTICULATE INSTRUMENTS, ed. 2018. *Articulate Assistant Advanced version 2.17*. Edinburgh: Articulate Instruments.

AUGUIE, BAPTISTE. 2017. *gridExtra: Miscellaneous Functions for "Grid" Graphics*. R package version 2.3. URL: `https://CRAN.R-project.org/package=gridExtra`.

AUGUSTAITIS, DAINE. 1964. *Das litauische Phonationssystem*. Munich: Sagner.

BAAYEN, R. HARALD. 2008. *Analyzing linguistic data: A practical introduction to statistics*. Cambridge: Cambridge University Press.

BALL, MARTIN and NICOLE MÜLLER, eds. 2009. *The Celtic languages*. 2nd. London: Routledge.

BATES, DOUGLAS, MARTIN MACHLER, BEN BOLKER, and STEVE WALKER. 2015. Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software* 67. 1–48.

BENDER, BYRON. 1968. Marshallese phonology. *Oceanic Linguistics* 7. 16–35.

BENNETT, RYAN, MÁIRE NÍ CHIOSÁIN, JAYE PADGETT, and GRANT MCGUIRE. 2018. An ultrasound study of Connemara Irish palatalization and velarization. *Journal of the International Phonetic Association*. 1–44.

BLEVINS, JULIETTE. 2009. *Evolutionary phonology: The emergence of sound patterns*. Cambridge: Cambridge University Press.

BLUST, ROBERT. 2005. Must sound change be linguistically motivated? *Diachronica* 22. 219–269.

BOERSMA, PAUL and DAVID WEENINK. 2021. *Praat: Doing phonetics by computer [computer program]. Version 6.1.53*. URL: `http://www.praat.org/`.

BORGSTRØM, CARL. 1940. *The dialects of the Outer Hebrides*. Vol. 1. Olso: Norsk Tidsskrift for Sprogvidenskap.

BRODERICK, GEORGE. 2009. Manx. *The Celtic languages,* ed. by MARTIN BALL and NICOLE MÜLLER. London: Routledge. 305–356.

BRUNNER, JANA and PHILIP HOOLE. 2012. Motor equivalent strategies in the production of German /ʃ/ under perturbation. *Language and Speech* 55. 457–476.

BYBEE, JOAN. 2001. *Phonology and language use*. Cambridge: Cambridge University Press.

CAMPBELL, LYLE and MARTHA MUNTZEL. 1989. The structural consequences of language death. *Investigating obsolescence: studies in language contraction and death,* ed. by NANCY DORIAN. Cambridge: Cambridge University Press. 181–197.

CARIGNAN, CHRISTOPHER. 2019. A network-modeling approach to investigating individual differences in articulatory-to-acoustic relationship strategies. *Speech Communication* 108. 1–14.

CARLTON, TERRENCE. 1990. *Introduction to the phonological history of the Slavic languages*. Bloomington: Slavica.

CHENG, MIKE and TREVOR L DAVIS. 2021. *ggpattern: Geoms with Patterns*. http://github.com/coolbutuseless/ggpattern, https://coolbutuseless.github.io/package/ggpattern/index.html.

COHEN, JACOB. 1960. A coefficient of agreement for nominal scales. *Educational and Psychological Measurement* 20. 37–46.

CORETTA, STEFANO. 2021a. *rticulate: Ultrasound Tongue Imaging in R*. R package version 1.7.2. URL: `https://CRAN.R-project.org/package=rticulate`.

CORETTA, STEFANO. 2021b. *speakr: A wrapper for the phonetic software 'Praat'*. R package version 3.2.0. URL: `https://CRAN.R-project.org/package=speakr`.

CORETTA, STEFANO. 2021c. *tidymv: Tidy Model Visualisation for Generalised Additive Models*. R package version 3.2.1. URL: `https://CRAN.R-project.org/package=tidymv`.

DELATTRE, PIERRE and DONALD FREEMAN. 1968. A dialect study of American r's by x-ray motion picture. *Linguistics* 6.

DORIAN, NANCY. 1978. *East Sutherland Gaelic: The dialect of the Brora, Golspie, and Embo fishing communities*. Dublin: Dublin Institute for Advanced Studies.

DORIAN, NANCY. 1981. *Language death: The life cycle of a Scottish Gaelic dialect*. Philadelphia: University of Pennsylvania Press.

DUNMORE, STUART. 2019. *Language revitalisation in Gaelic Scotland: Linguistic practice and ideology*. Edinburgh: Edinburgh University Press.

GAMER, MATTHIS, JIM LEMON, and IAN FELLOWS. 2019. *irr: Various Coefficients of Interrater Reliability and Agreement. R package version 0.84.1.* URL: `https://CRAN.R-project.org/package=irr`.

GISEV, NATASA, J. SIMON BELL, and TIMOTHY CHEN. 2013. Interrater agreement and interrater reliability: Key concepts, approaches, and applications. *Research in Social and Administrative Pharmacy* 9. 330–338.

GORMAN, EMILY and SAM KIRKHAM. 2020. Dynamic acoustic-articulatory relations in back vowel fronting: Examining the effects of coda consonants in two dialects of British English. *Journal of the Acoustical Society of America* 148. 724–733.

GREENE, DAVID. 1973. The growth of palatalisation in Irish. *Transactions of the Philological Society* 72. 127–136.

HALL, TRACY. 2000. Typological generalisations concerning secondary palatalization. *Lingua* 110. 1–25.

HAMMOND, MICHAEL, NATASHA WARNER, ANDRÉA DAVIS, ANDREW CARNIE, DIANA ARCHANGELI, and MURIEL FISHER. 2014. Vowel insertion in Scottish Gaelic. *Phonology* 31. 123–153.

HARRRELL, FRANK. 2015. *Regression Modeling Strategies: With Applications to Linear Models, Logistic and Ordinal Regression, and Survival Analysis*. 2nd. Basel: Springer Verlag.

HEYNE, MATTHIAS, XUAN WANG, DONALD DERRICK, KIERAN DORREEN, and KEVIN WATSON. 2020. The articulation of /ɹ/ in New Zealand English. *Journal of the International Phonetic Association* 50. 366–388.

HICKEY, RAYMOND. 1995. Sound change and typological shift: Initial mutation in Celtic. *Linguistic typology and reconstruction,* ed. by JACEK FRISIAK. Berlin: Mouton. 133–182.

HICKEY, RAYMOND. 2014. *The sound structure of Modern Irish*. Berlin: Mouton de Gruyter.

HONDA, MASAAKI, AKINORI FUJINO, and TOKIHIKO KABURAGI. 2002. Compensatory responses of articulators to unexpected perturbation of the palate shape. *Journal of Phonetics* 30. 281–302.

HOWSON, PHIL. 2017. Upper Sorbian. *Journal of the International Phonetic Association* 28. 1–9.

HOWSON, PHIL. 2018. Rhotics and palatalization: An acoustic examination of Upper and Lower Sorbian. *Phonetica* 75. 132–150.

HOWSON, PHIL, EKATERINA KOMOVA, and BRYAN GICK. 2014. Czech trills revisited: An ultrasound EGG and acoustic study. *Journal of the International Phonetic Association* 44. 115–132.

HOWSON, PHIL and PHILIP MONAHAN. 2019. Perceptual motivation for rhotics as a class. *Speech Communication* 115. 15–28.

HUNT, TYLER. 2020. *ModelMetrics: Rapid Calculation of Model Metrics*. R package version 1.2.2.2. URL: `https://CRAN.R-project.org/package=ModelMetrics`.

ISKAROUS, KHALIL and DARYA KAVITSKAYA. 2010. The interaction between contrast, prosody, and coarticulation in structuring phonetic variability. *Journal of Phonetics* 38. 625–639.

ISKAROUS, KHALIL and DARYA KAVITSKAYA. 2018. Sound change and the structure of synchronic variability: Phonetic and phonological factors in Slavic palatalization. *Language* 94. 43–83.

JOHNSON, KEITH. 2011. *Quantitative methods in linguistics*. Oxford: Blackwell.

JONES, MARI. 1998. *Language obsolescence and revitalization: Linguistic change in two sociolinguistically contrasting Welsh communities*. Oxford: Clarendon Press.

KANG, YOONJUNG and SUNGWOO HAN. 2013. Tonogenesis in early Contemporary Seoul Korean: A longitudinal case study. *Lingua* 134. 62–74.

KASSAMBARA, ALBOUKADEL. 2020. *ggpubr: 'ggplot2' Based Publication Ready Plots*. R package version 0.4.0. URL: `https://CRAN.R-project.org/package=ggpubr`.

KAVITSKAYA, DARYA. 1997. Aerodynamic constraints on the production of palatalized trills: The case of the Slavic trilled [r]. *Proceedings from the 5th European conference on speech communication and technology*. 751–754.

KAVITSKAYA, DARYA, KHALIL ISKAROUS, AUDE NOIRAY, and MICHAEL PROCTOR. 2009. Trills and palatalization: Consequences for sound change. *Proceedings of the formal approaches to Slavic linguistics*. Yale University. 97–110.

KING, HANNAH and EMMANUEL FERRAGNE. 2020. Loose lips and tongue tips: The central role of the /r/-typical labial gesture in Anglo-English. *Journal of Phonetics* 80. 1–19.

KIRKHAM, SAM and CLAIRE NANCE. 2017. An acoustic-articulatory study of bilingual vowel production: Advanced tongue root vowels in Twi and tense/lax vowels in Ghanaian English. *Journal of Phonetics* 62. 65–81.

KOCHETOV, ALEXEI. 2005. Phonetic sources of phonological assymetries: Russian laterals and rhotics. *Proceedings of the 2005 annual conference of the Canadian Linguistic Association*. Ed. by CLAIRE GURSKI. University of Western Ontario. London, Ontario.

KOCHETOV, ALEXEI. 2017. Acoustics of Russian voiceless sibilant fricatives. *Journal of the International Phonetic Association* 47. 321–348.

KOPKALLI, HANDAN. 1993. *A phonetic and phonological analysis of final devoicing in Turkish*. PhD thesis. Ann Arbor: University of Michigan.

KRISHNAMURTI, BHADRIRAJU. 2003. *The Dravidian languages*. Cambridge: Cambridge University Press.

LADEFOGED, PETER, JENNY LADEFOGED, ALICE TURK, KEVIN HIND, and ST JOHN SKILTON. 1998. Phonetic structures of Scottish Gaelic. *Journal of the International Phonetic Association* 28. 1–41.

LADEFOGED, PETER and IAN MADDIESON. 1996. *The sounds of the world's languages*. Oxford: Blackwell.

LAMB, WILL. 2008. *Scottish Gaelic speech and writing: Register variation in an endangered language*. Belfast: Cló Ollscoil na Banríona.

LAWSON, ELEANOR, JAMES M. SCOBBIE, and JANE STUART-SMITH. 2011. The social stratification of tongue shape in postvocalic /r/ in Scottish English. *Journal of Sociolinguistics* 15. 256–268.

LAWSON, ELEANOR, JAMES M. SCOBBIE, and JANE STUART-SMITH. 2013. Bunched /r/ promotes vowel merger to schwar: An ultrasound tongue imaging study of Scottish sociophonetic variation. *Journal of Phonetics* 41. 198–210.

LEE, KEE-DONG. 1975. *Kusaiean reference grammar*. Honolulu: The University Press of Hawaii.

LENTH, RUSSELL V. 2021. *emmeans: Estimated Marginal Means, aka Least-Squares Means*. R package version 1.6.3. URL: `https://CRAN.R-project.org/package=emmeans`.

LINDAU, MONA. 1985. The story of /r/. *Phonetic Linguistics: Essays in honor of Peter Ladefoged,* ed. by VICTORIA FROMKIN. Orlando, FA: Academic Press. 157–168.

LINDBLOM, BJÖRN. 1990. Explaining Phonetic Variation: A Sketch of the H and H Theory. *Speech production and speech modelling,* ed. by WILLIAM HARDCASTLE and ALAIN MARCHAL. Dordrecht: Springer Verlag. 403–439.

MACKINNON, KENNETH. 1974. *The Lion's Tongue*. Inverness: Club Leabhar Limited.

MACLEOD, MICHELLE. 2010. Language in society: 1800 to the present day. *The Edinburgh Companion to the Gaelic language,* ed. by MORAY WATSON and MICHELLE MACLEOD. Edinburgh University Press. 22–46.

MADDIESON, IAN. 1984. *Patterns of sounds*. Cambridge: Cambridge University Press.

MCGOWAN, RICHARD. 1992. Tongue-tip trills and vocal-tract wall compliance. *Journal of the Acoustical Society of America* 91. 2903–2910.

MCHUGH, MARY. 2012. Interrater reliability: the kappa statistic. *Biochemia Medica* 22. 276–282.

MCLEOD, WILSON. 2020. *Gaelic in Scotland: Policies, movements and ideologies*. Edinburgh: Edinburgh University Press.

MIELKE, JEFF. 2015. An ultrasound study of Canadian French rhotic vowels with polar smoothing spline comparisons. *Journal of the Acoustical Society of America* 137. 2858–2869.

MIELKE, JEFF, ADAM BAKER, and DIANA ARCHANGELI. 2016. Individual-level contact limits phonological complexity: Evidence from bunched and retroflex /ɹ/. *Language* 92. 101–140.

NANCE, CLAIRE. 2015. Intonational variation and change in Scottish Gaelic. *Lingua* 160. 1–19.

NANCE, CLAIRE and SAM KIRKHAM. 2020. The acoustics of three-way lateral and nasal palatalisation contrasts in Scottish Gaelic. *Journal of the Acoustical Society of America* 147. 2858–2872.

NANCE, CLAIRE, WILSON MCLEOD, BERNADETTE O'ROURKE, and STUART DUNMORE. 2016. Identity, accent aim, and motivation in second language users: New Scottish Gaelic speakers' use of phonetic variation. *Journal of Sociolinguistics* 20. 164–191.

NASH, JOHN C. 2014. On Best Practice Optimization Methods in R. *Journal of Statistical Software* 60. 1–14.

NASH, JOHN C. and RAVI VARADHAN. 2011. Unifying Optimization Algorithms to Aid Software System Users: optimx for R. *Journal of Statistical Software* 43. 1–14.

NÍ CHASAIDE, AILBHE. 1999. Irish. *Handbook of the International Phonetic Association,* Cambridge: Cambridge University Press.

NÍ CHIOSÁIN, MÁIRE and JAYE PADGETT. 2012. An acoustic and perceptual study of Connemara Irish palatalization. *Journal of the International Phonetic Association* 42. 171–191.

Ó DOCHARTAIGH, CATHAIR, ed. 1997. *Survey of the Gaelic dialects of Scotland*. Dublin: Dublin Institute for Advanced Studies.

Ó MAOLALAIGH, ROIBEARD. 2008. The Scottishisation of Gaelic: A reassessment of the language and orthography of the Gaelic notes in the Book of Deer. *Studies on the Book of Deer,* ed. by KATHERINE FORSYTH. Dublin: Four Courts Press. 179–275.

OFTEDAL, MAGNUS. 1956. *A linguistic survey of the Gaelic dialects of Scotland. Vol III: The Gaelic of Leurbost, Isle of Lewis*. Oslo: Norsk Tidsskrift for Sprogvidenskap.

OHALA, JOHN. 1981. The listener as a source of sound change. *Papers from the parasession on language and behaviour, University of Chicago,* ed. by CARRIE MASEK, ROBERTA HENDRICK, and MARY FRANCES MILLER. Chicago: University of Chicago. 178–203.

OHALA, JOHN. 1989. Sound change is drawn from a pool of synchronic variation. *Language Change: Contributions to the study of its causes,* ed. by LEIV EGIL BREIVIK and ERNST HÅKON JAHR. Berlin: Mouton de Gruyter. 173–198.

OHALA, JOHN. 1993. The phonetics of nasal phonology: theorems and data. *Phonetics and Phonology Series,* ed. by MARIE HUFFMAN and RENA KRAKOW. Vol. 5. San Diego, CA: Academic Press. 225–249.

OHALA, JOHN. 2012. The listener as a source of sound change: An update. *The Initiation of Sound Change: Perception, production, and social factors,* ed. by MARIE-JOSEP SOLÉ and DANIEL RECASENS. Amsterdam: John Benjamins. 21–36.

PERKELL, JOSEPH S., MELANIE L. MATTHIES, MARIO A. SVIRSKY, and MICHAEL I. JORDAN. 1993. Trading relations between tongue-body raising and lip rounding in production of the vowel /u/: A pilot 'motor equivalence' study. *Journal of the Acoustical Society of America* 93. 2948–2961.

PERRIER, PASCAL and SUSANNE FUCHS. 2015. Motor equivalence in speech production. *The Handbook of Speech Production,* ed. by MELISSA A. REDFORD. Wiley. Chap. Chichester. 225–247.

PLUG, LENDEERT and RICHARD OGDEN. 2003. A parametric approach to the phonetics of postvocalic /r/ in Dutch. *Phonetica* 60. 159–186.

R CORE TEAM. 2021. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria. URL: `www.R-project.org`.

RAVINDRANATH, MAYA. 2015. Sociolinguistic Variation and Language Contact. *Language and Linguistic Compass* 9. 243–255.

RECASENS, DANIEL. 2013. Coarticulation in Catalan dark [l] and the alveolar trill: General implications for sound change. *Language and Speech* 56. 45–68.

RECASENS, DANIEL and MARIA DOLORS PALLARÈS. 1999. A study of /ɾ/ and /r/ in the light of the 'DAC' coarticulation model. *Journal of Phonetics* 27. 143–169.

RENWICK, MARGARET and D. ROBERT LADD. 2016. Phonetic Distinctiveness vs. Lexical Contrastiveness in Non-Robust Phonemic Contrasts. *Laboratory Phonology: Journal of the Association for Laboratory Phonology* 7. 1–29.

RSTUDIO TEAM. 2020. *RStudio: Integrated Development Environment for R*. RStudio, PBC. Boston, MA. URL: `http://www.rstudio.com/`.

RUSSELL, PAUL. 1995. *Introduction to the Celtic languages*. London: Longman.

SCOTTISH GOVERNMENT. 2015. *Scotland's Census 2011: Gaelic report (part 1)*. Edinburgh: National Records of Scotland.

SEBREGTS, KOEN. 2014. *The sociophonetics and phonology of Dutch /r/*. Utecht: Netherlands Graduate School of Linguistics.

SHUKEN, CYNTHIA. 1980. *An instrumental investigation of some Scottish Gaelic consonants*. PhD thesis. Edinburgh: University of Edinburgh.

SHUKEN, CYNTHIA. 1984. Highland and Island English. *Language in the British Isles,* ed. by PETER TRUDGILL. Cambridge: Cambridge University Press. 152–167.

SIMPSON, ADRIAN. 1998. Accounting for the phonetics of German r without processes. *ZAS Papers in Linguistics* 11. 91–104.

SONDEREGGER, MORGAN. 2021. *Regression modeling for linguistic data v. 0.91*. URL: `https://doi.org/10.17605/OSF.IO/PNUMG`.

SPAJIĆ, SINIŠA, PETER LADEFOGED, and P. BHASKARARAO. 1996. The trills of Toda. *Journal of the International Phonetic Association* 26. 1–21.

STEVENS, KENNETH. 1989. On the quantal nature of speech. *Journal of Phonetics* 17. 3–45.

STIFTER, DAVID. 2006. *Sengoidelc: Old Irish for beginners*. New York: Syracuse University Press.

STOLL, TAJA. 2017. *Articulatory analysis of palatalised rhotics in Russian: Implications for sound change*. PhD thesis. Munich: Ludwig–Maximilians–Universität München.

STONE, MAUREEN. 2005. A guide to analysing tongue motion from ultrasound images. *Clinical Linguistics and Phonetics* 19. 455–501.

STRYCHARCZUK, PATRYCJA and JAMES M. SCOBBIE. 2017. Fronting of Southern British English high-back vowels in articulation and acoustics. *Journal of the Acoustical Society of America* 142. 322–331.

STUART-SMITH, JANE, ELEANOR LAWSON, and JAMES M. SCOBBIE. 2014. Derhoticisation in Scottish English: a sociophonetic journey. *Advances in Sociophonetics,* ed. by CHIARA CELATA and SILVIA CALAMAI. Amsterdam: John Benjamins. 59–96.

TERNES, ELMAR. 2006. *The phonemic analysis of Scottish Gaelic*. 3rd. Dublin: Dublin Institute for Advanced Studies.

THOMASON, SARAH GREY. 2001. *Language contact: An introduction*. Edinburgh: Edinburgh University Press.

THURNEYSEN, RUDOLF. 1946. *A grammar of Old Irish*. Dublin: Dublin Institute for Advanced Studies.

TREMBLAY, STÉPHANIE, DOUGLAS M. SHILLER, and DAVID J. OSTRY. 2003. Somatosensory basis of speech production. *Nature* 423. 866–869.

TURTON, DANIELLE. 2017. Categorical or gradient? An ultrasound investigation of /l/-darkening and vocalization in varieties of English. *Laboratory Phonology: Journal of the Association for Laboratory Phonology* 8. 1–31.

VELOSO, JOÃO. 2015. The English r is coming! The never ending story of Brazilian Portuguese rhotics. *Oslo Studies in Language* 7. 323–336.

WARNER, NATASHA, DANIEL BRENNER, JESSAMYN SCHERTZ, ANDREW CARNIE, MURIEL FISHER, and MICHAEL HAMMOND. 2015. The aerodynamic puzzle of nasalized fricatives: Aerodynamic and perceptual evidence from Scottish Gaelic. *Laboratory Phonology: Journal of the Association for Laboratory Phonology* 6. 197–241.

WICKHAM, HADLEY. 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. ISBN: 978-3-319-24277-4. URL: `https://ggplot2.tidyverse.org`.

WICKHAM, HADLEY, MARA AVERICK, JENNIFER BRYAN, WINSTON CHANG, LUCY D'AGOSTINO MCGOWAN, ROMAIN FRANÇOIS, GARRETT GROLEMUND, ALEX HAYES, LIONEL HENRY, JIM HESTER, MAX KUHN, THOMAS LIN PEDERSEN, EVAN MILLER, STEPHAN MILTON BACHE, KIRILL MÜLLER, JEROEN OOMS, DAVID ROBINSON, DANA PAIGE SEIDEL, VITALIE SPINU, KOHSKE TAKAHASHI, DAVIS VAUGHAN, CLAUS WILKE, KARA WOO, and HIROAKI YUTANI. 2019. Welcome to the tidyverse. *Journal of Open Source Software* 4. 1686.

WIESE, RICHARD. 2003. The unity and variation of German /r/. *Zeitschrift für Dialektologie und Linguistik* 70. 25–43.

WINTER, BODO. 2020. *Statistics for linguistics: An introduction using R*. London: Routledge.

ZALITE, LINDA. 2015. *The incidence and evolution of palatalized consonants in Latvian*. MA thesis. New York: City University of New York.

FOOTNOTES.

[1]We henceforth refer to the language spoken in Scotland as 'Gaelic' as is customary in the Gaelic-speaking community. The language spoken in Ireland is referred to as 'Irish'. The language family including Gaelic, Irish and Manx is referred to as 'Goidelic' in order to avoid potential ambiguity.

[2]A carrier phrase was not used for two reasons: first, in previous fieldwork, Gaelic speakers reported that carrier phrases were a very unnatural and odd way to use Gaelic. We think it might be the case that there is little experience of using minority languages for specific data elicitation in an experimental setting. Second, the lack of a carrier phrase reduced the time spent wearing the ultrasound probe and headset, which can become quite tiring.

[3]A colour version of this figure is available at https://osf.io/xvfpw/.

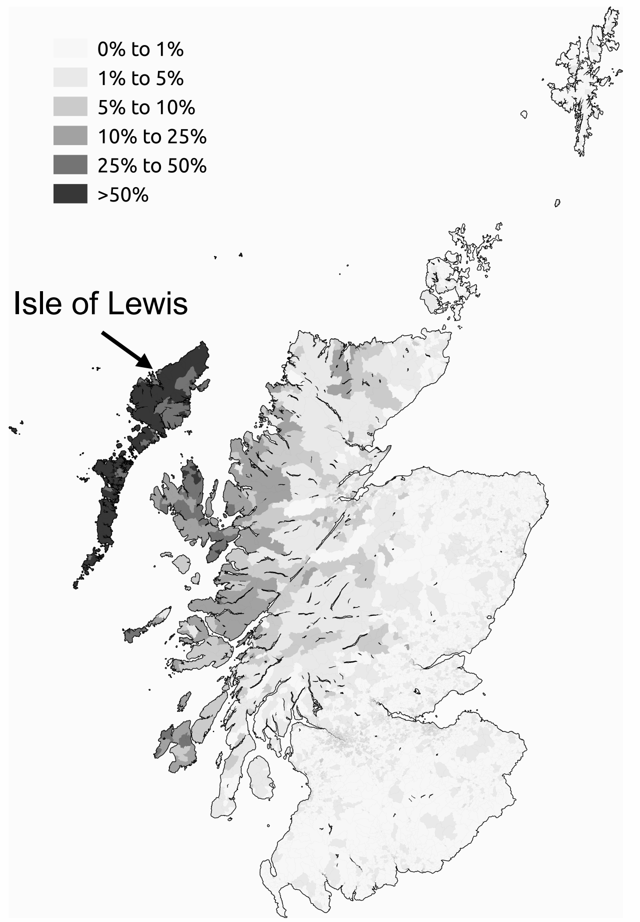

Figure 1: Map showing the concentration of Gaelic speakers across Scotland using data from the 2011 UK Census (most recent available results). Attribution: By SkateTier - Own work, CC BY-SA 3.0, https:commons.wikimedia.orgwindex.php?curid=31996352. (Converted to grayscale here).

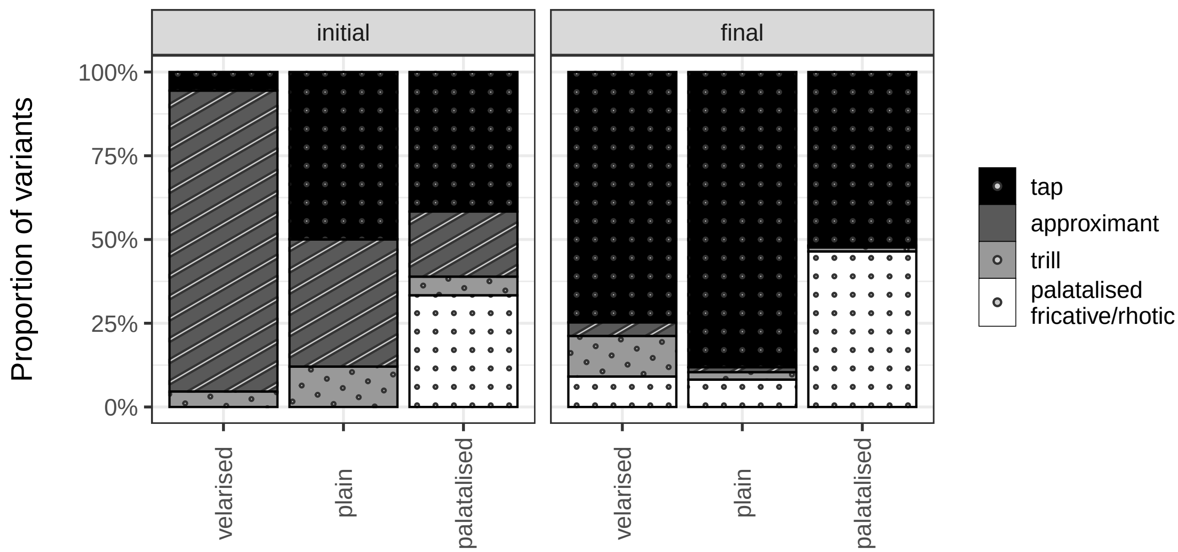

Figure 2: Auditory transcription of rhotic phonemes.

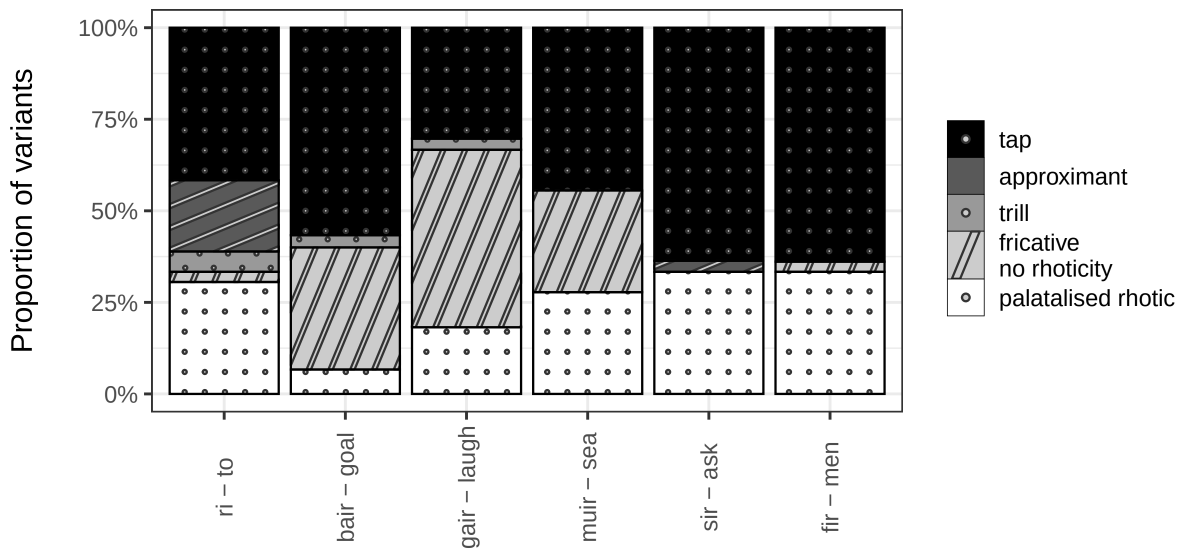

Figure 3: More detailed auditory labelling of /r^{j}/ tokens only, word by word.

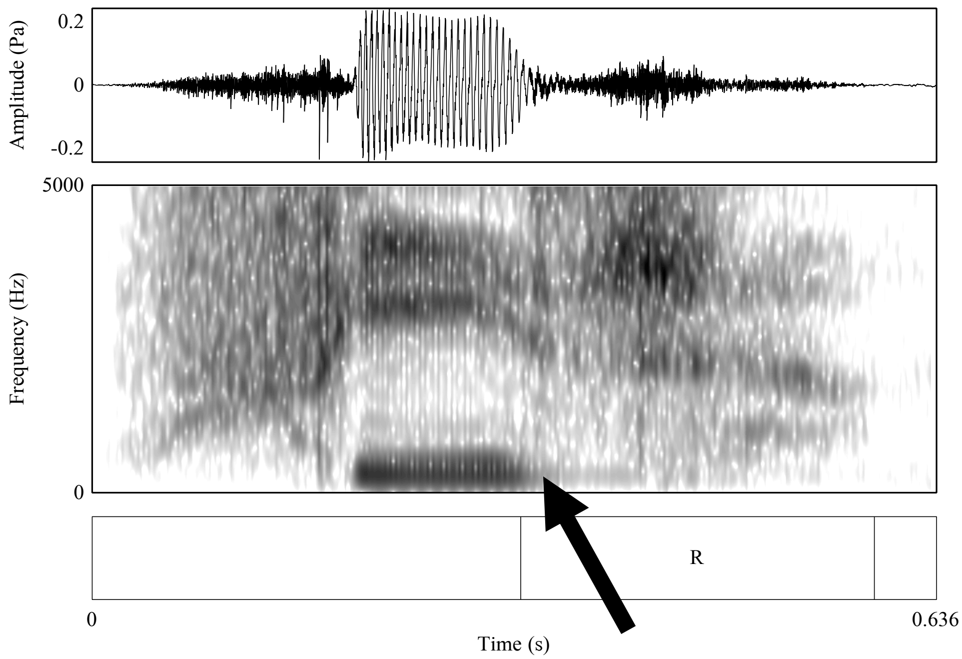

Figure 4: Example waveform and spectrogram of a word-final /rʲ/ in the word *fir* ‘men’ spoken by a female speaker lf03. Arrow shows the location of a tap-like transition between the vowel and voiceless fricative [ç], which is audibly rhotic.

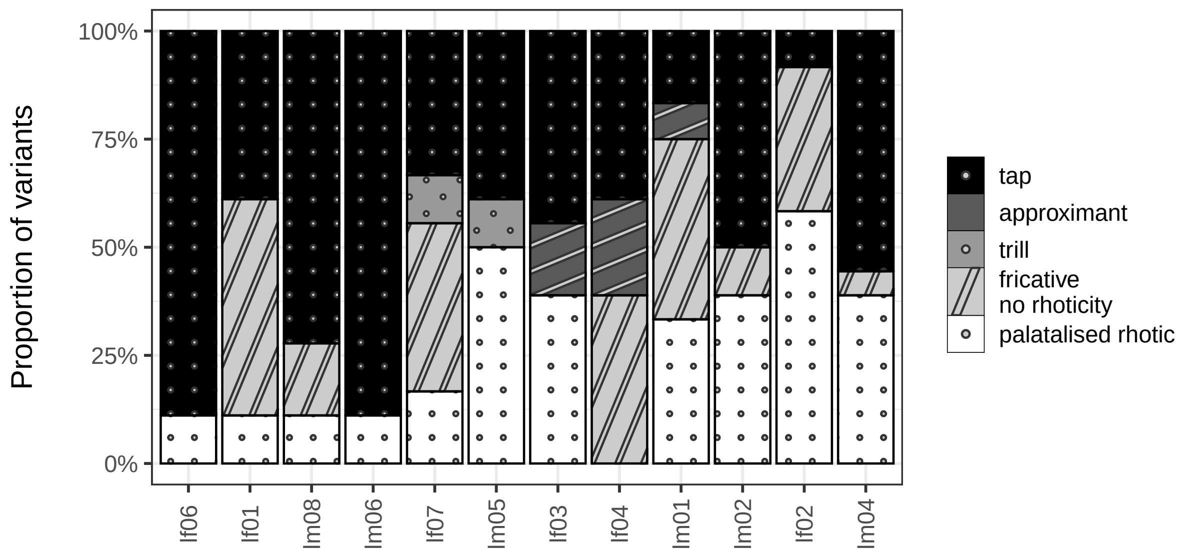

Figure 5: More detailed auditory labelling of only /r^j/ according to speaker. Speakers are ordered by age (youngest on left, oldest on the right).

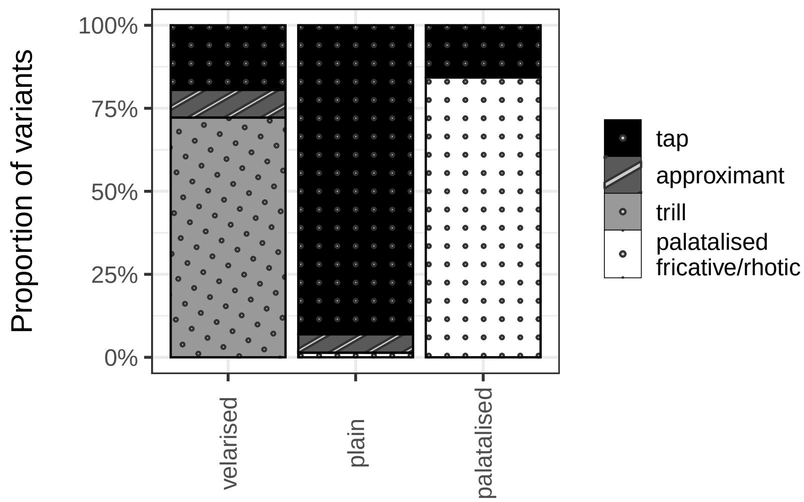

Figure 6: Word-final rhotics in the Survey of the Gaelic Dialects of Scotland.

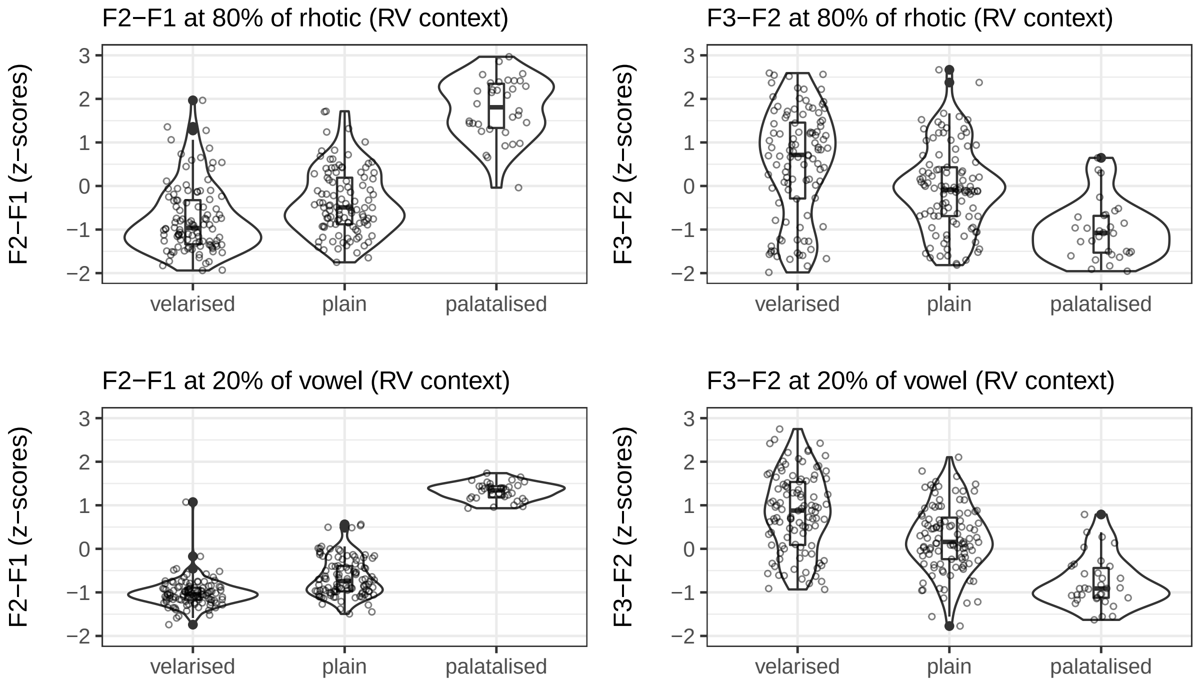

Figure 7: Acoustic measures on word-initial rhotics and following vowels.

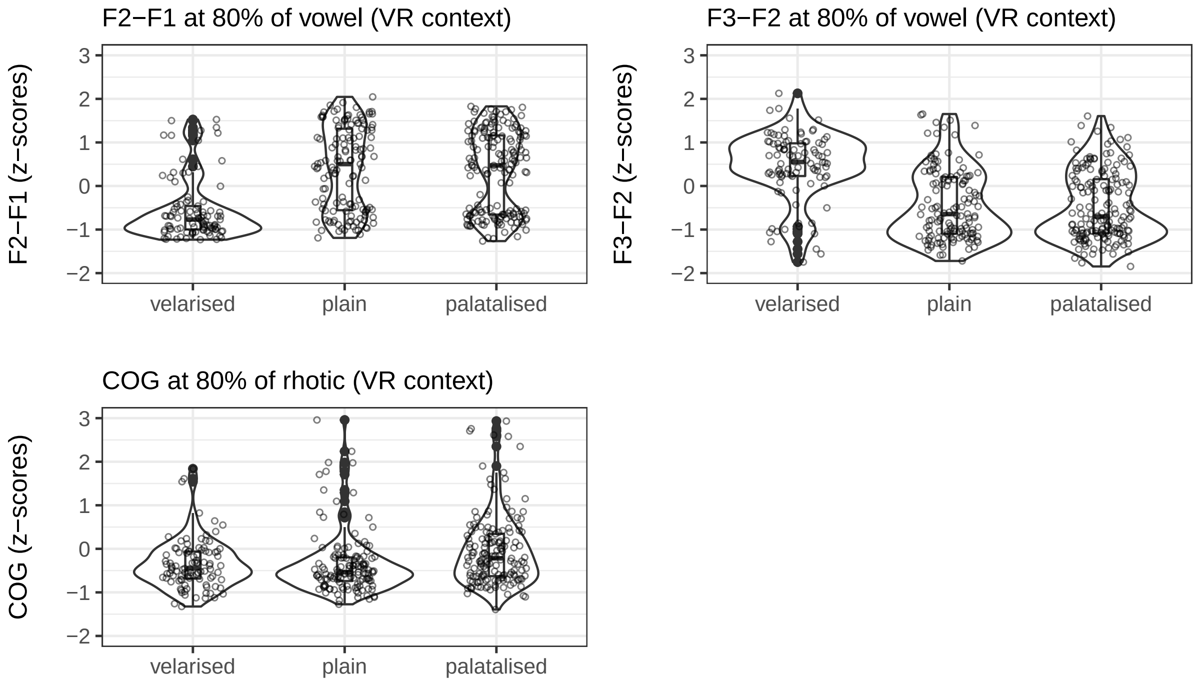

Figure 8: Acoustic measures on word-final rhotics and preceding vowels.

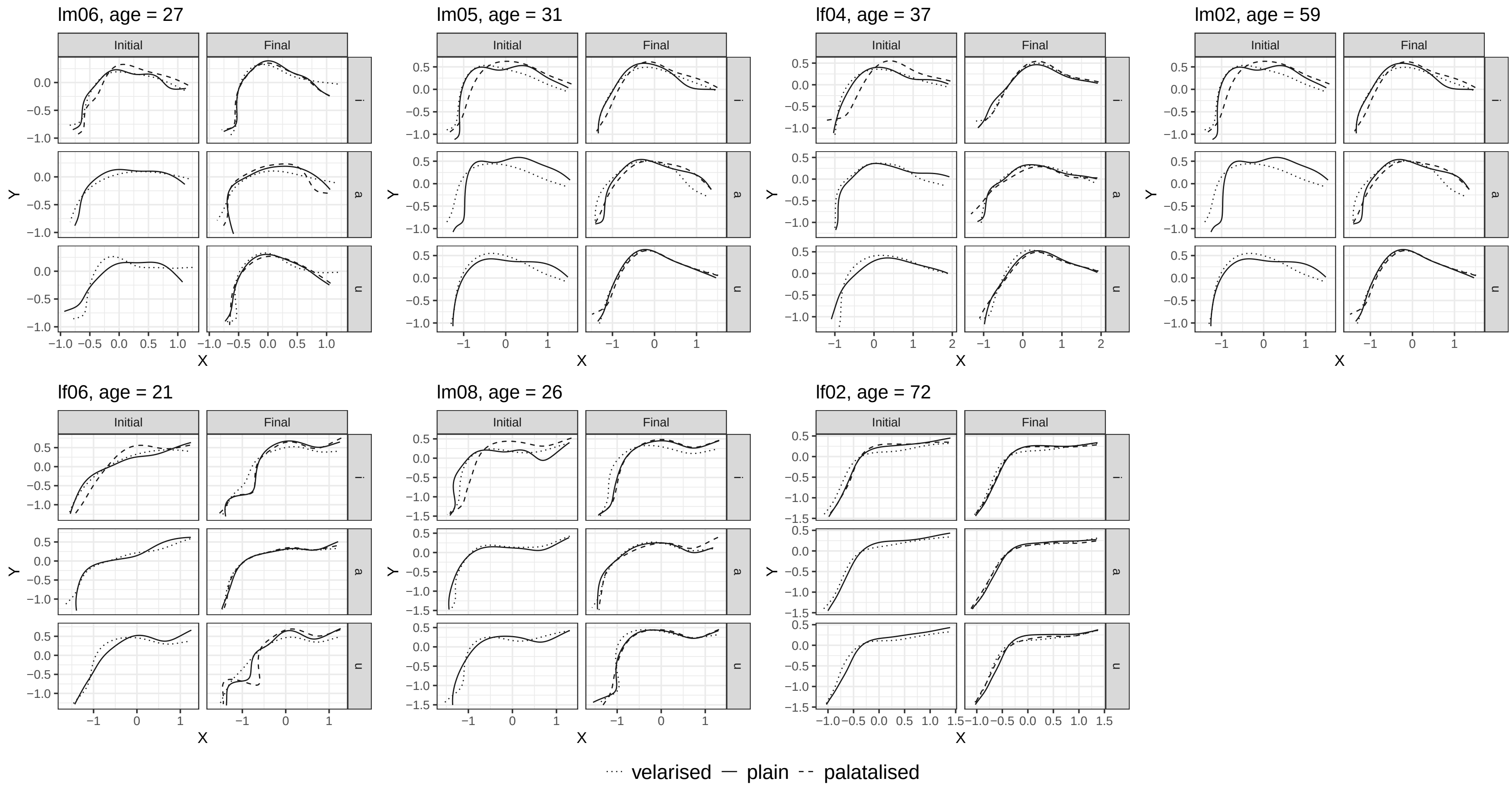

Figure 9: Generalised additive models fitted to midsagittal tongue spline data, split by word position and vowel context. Each panel represents a single speaker. The lines represent the mean estimate for that context. A colour version of this figure is available at https://osf.io/xvfpw/.

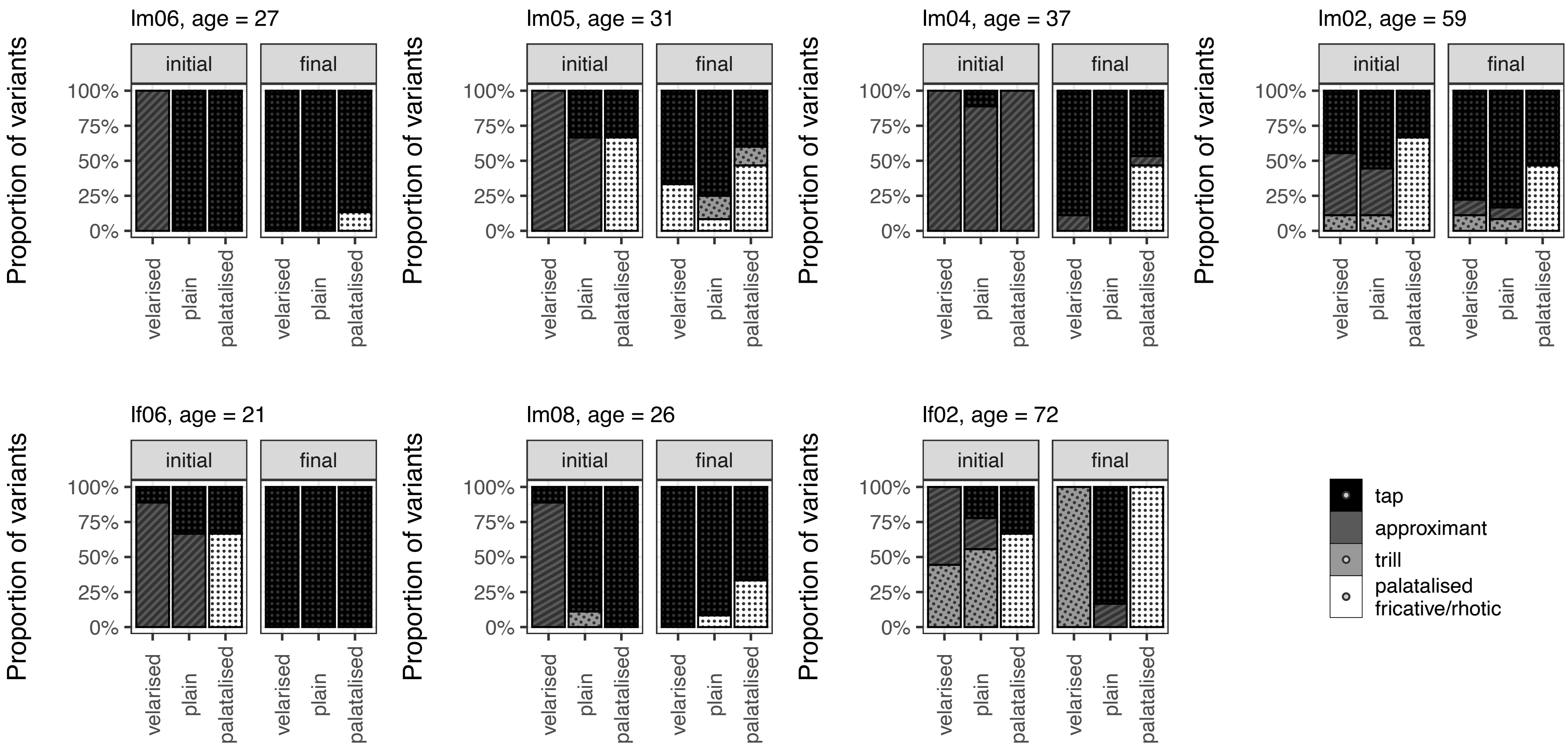

Figure 10: Results of the auditory coding for the individual speakers involved in the ultrasound analysis. Speakers are ordered as in the GAM figure above to show maximum comparability.

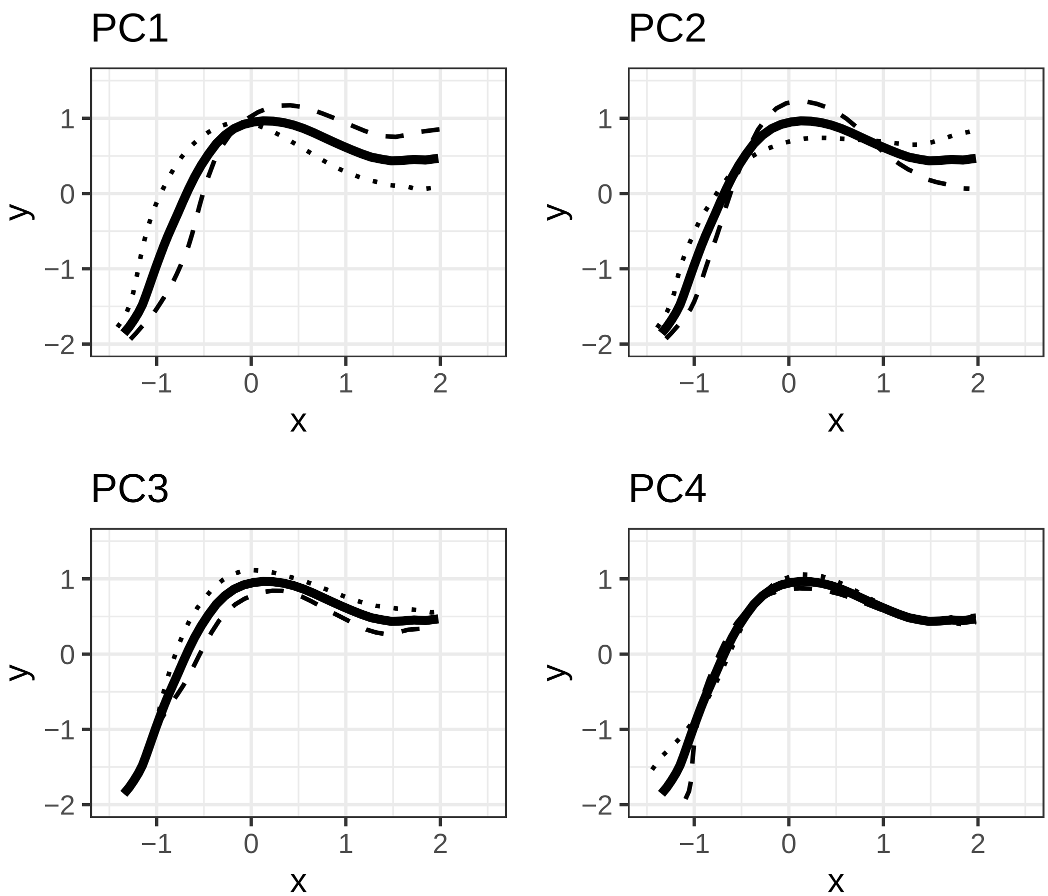

Figure 11: Variation captured by the first four PCs. In each panel, the thick black line shows the mean tongue spline for all the data from all speakers. The dashed dashed line shows mean tongue spline plus the value of each loading multiplied by the standard deviation of PC scores. The dotted line shows mean tongue spline minus the value of each loading multiplied by the standard deviation of PC scores.

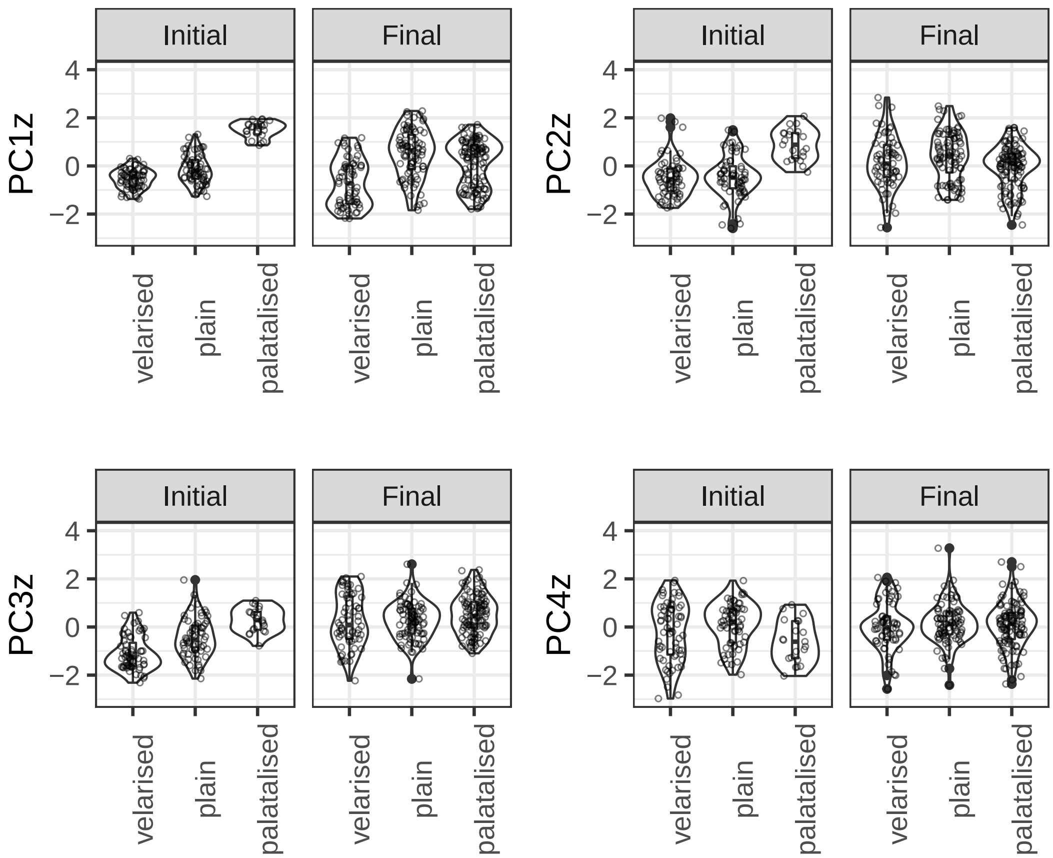

Figure 12: Values of the first four PCs for each phoneme and word position.

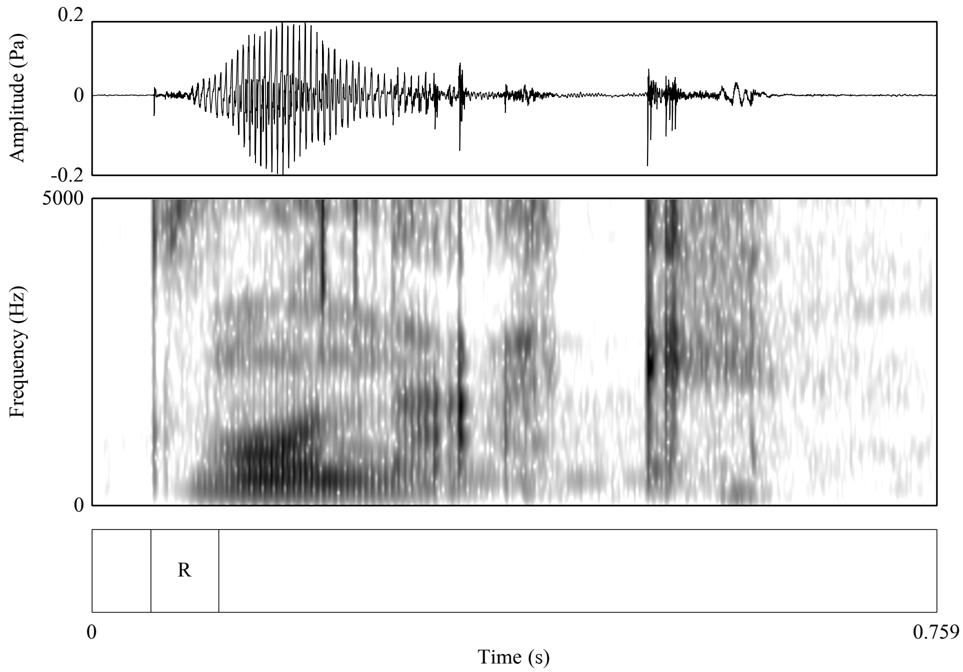

Figure 13: Example spectrogram and waveform from *rionnag* ‘star’, word-initial /rˠ/. Spoken by a female speaker lf04 and realised here as an approximant.

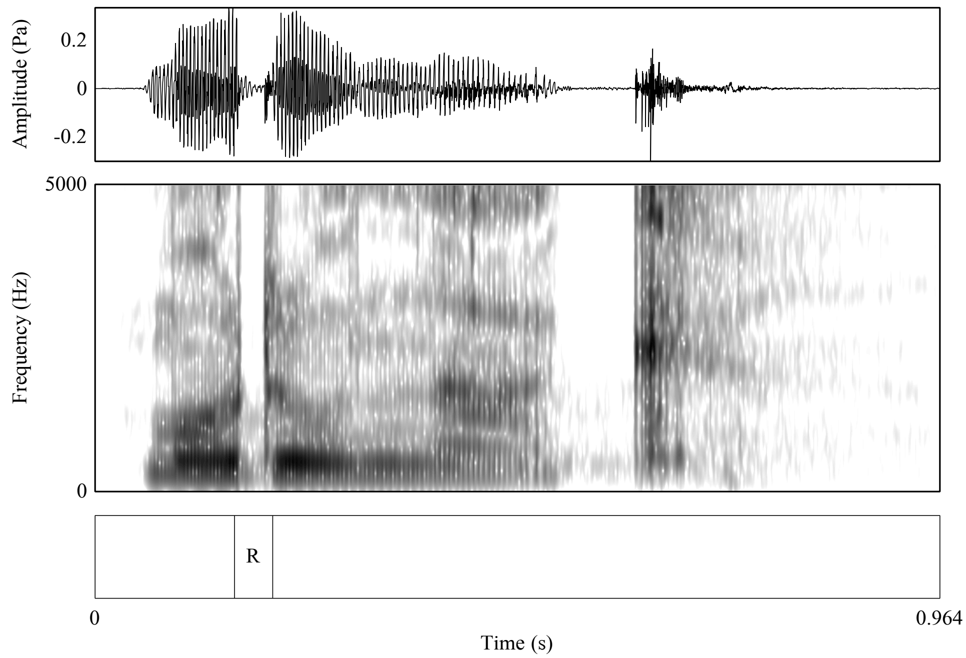

Figure 14: Example spectrogram and waveform from *mo rionnag* ‘my star’, word-initial /r/. Spoken by a female speaker lf04 and realised here as a tap.

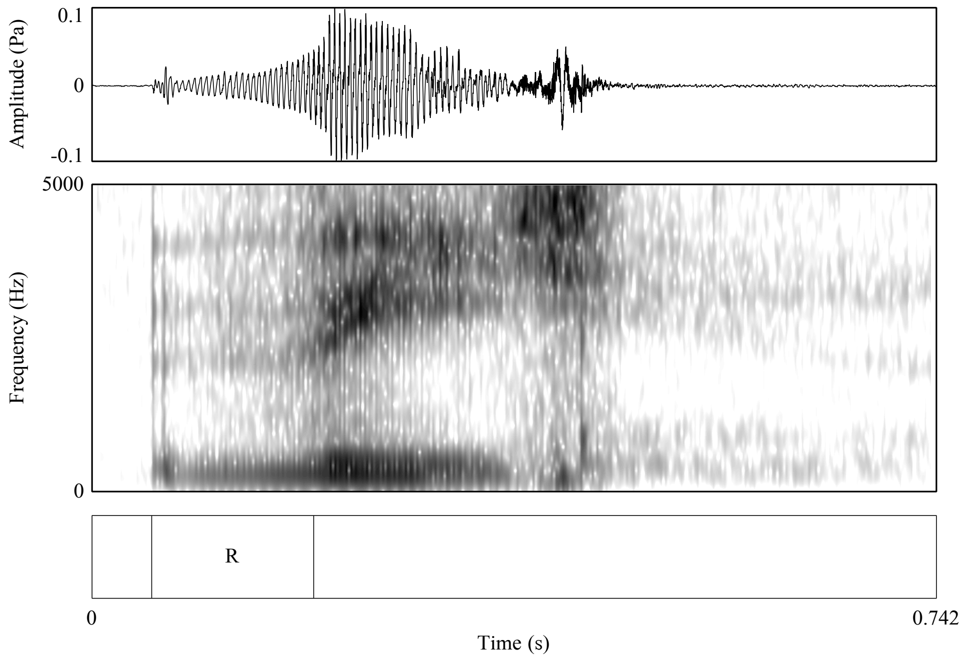

Figure 15: Example spectrogram and waveform from *ri* ‘to’, word-initial /r^{j}/. Spoken by a female speaker lf04 and realised here as a fricative with no audible rhoticity.

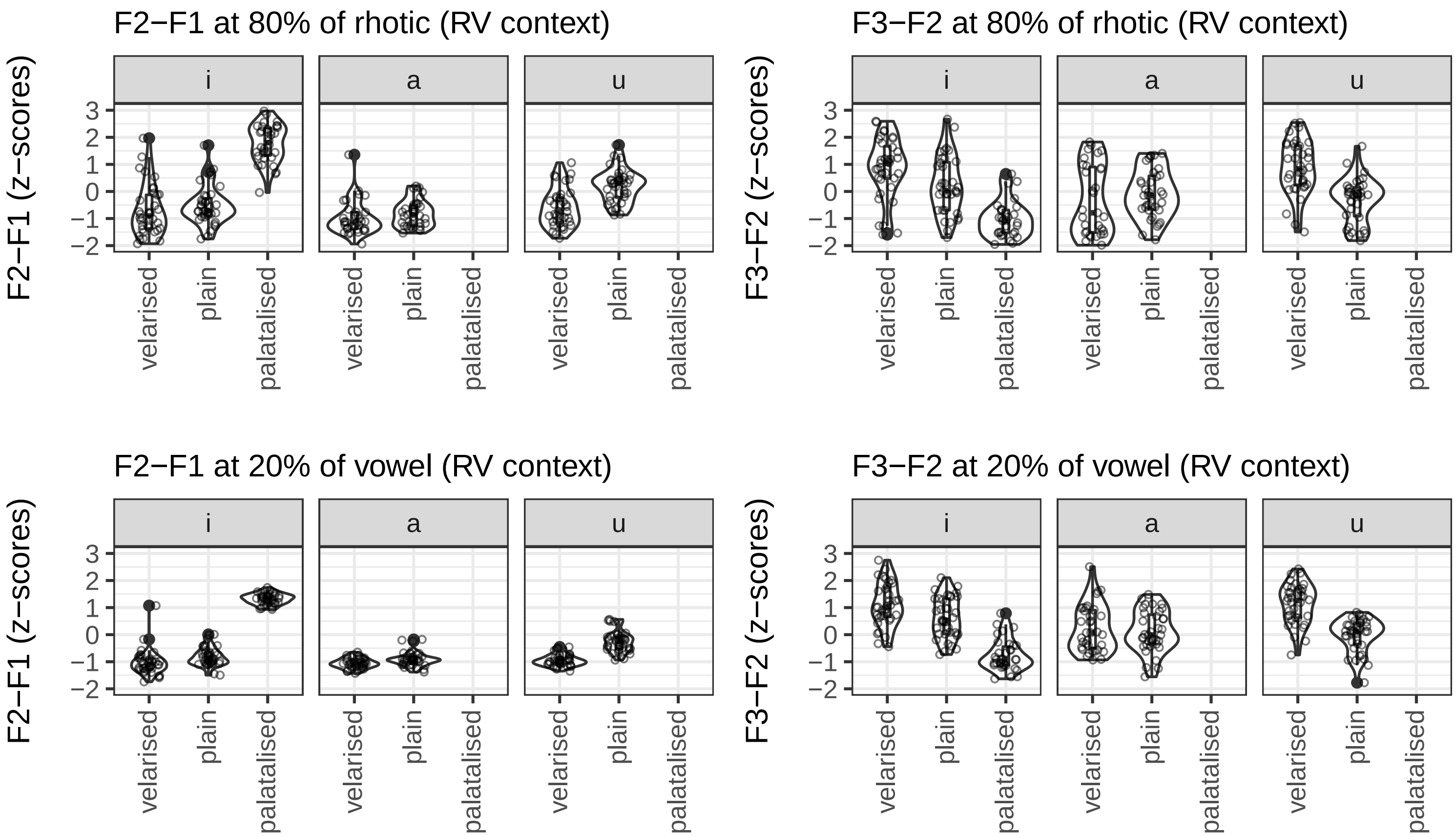

Figure 16: Acoustic measures on word-initial rhotics and following vowels according to vowel context.

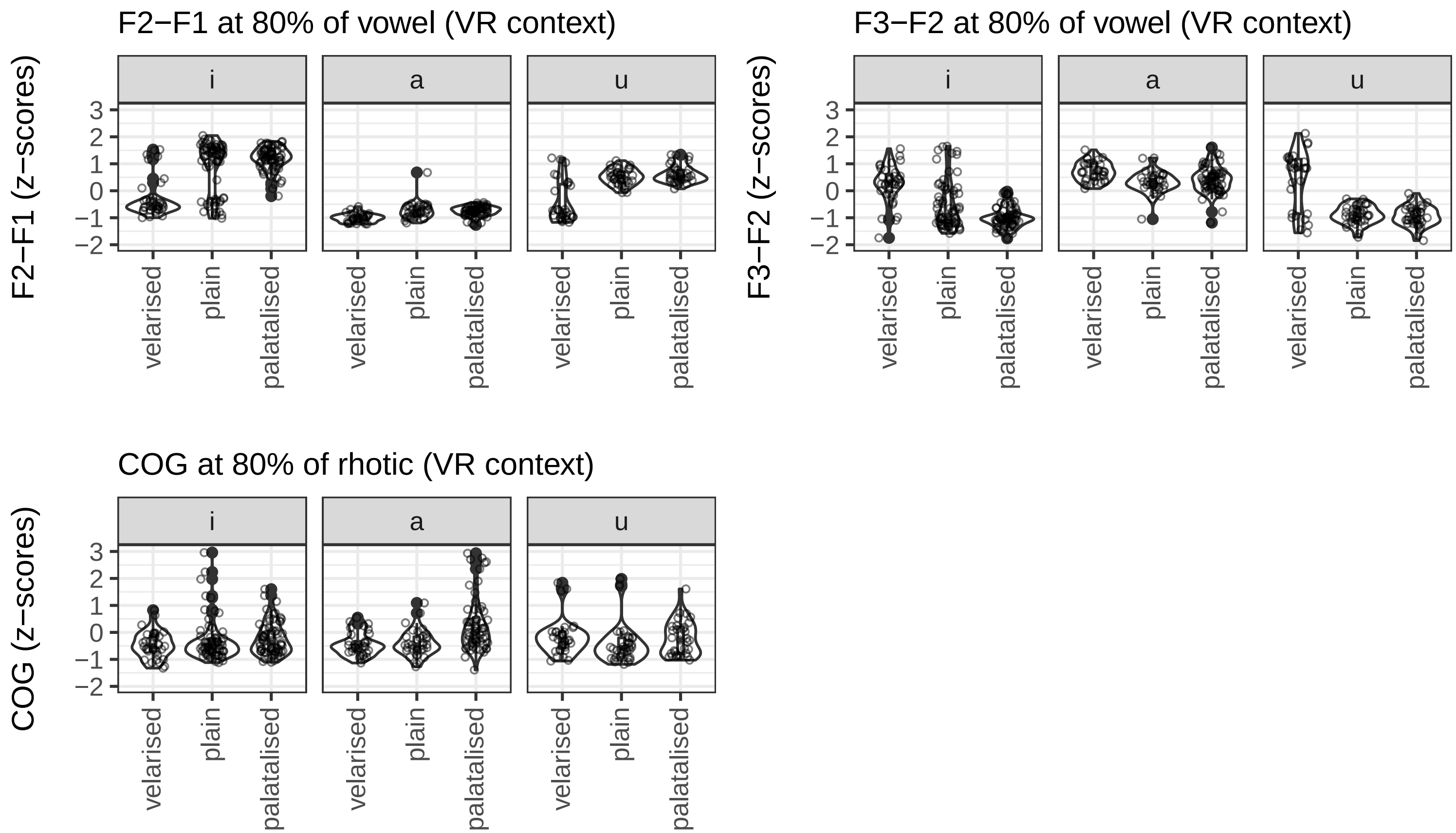

Figure 17: Acoustic measures on word-final rhotics and preceding vowels according to vowel context.

Date (CE)	**Language form**	**Sound change**	**IPA**
400-600	Archaic Irish	Geminate vs. singleton	rr r
600-900	Old Irish	Geminate vs. singleton and also palatalised vs. non palatalised	rr r rr^{j} r^{j}
		Gemination becomes POA contrast and also palatalised vs. non palatalised	r ɽ r^{j} ɽ^{j}
900-1200	Middle Irish	POA contrast lost; palatalised, velarised, plain contrast develops	r$^{\gamma}$ r r^{j}
1100 onwards	Scottish Gaelic	Palatalised, velarised, plain	r$^{\gamma}$ r r^{j}

Table 1: Summary of the development of rhotics in Scottish Gaelic. Dates are approximate and processes which took place over several centuries have been summarised for clarity.

Dialect	Rhotics (phonemic IPA)	Main sources
Lewis Gaelic	$r^{ɣ}$ r r^{j}	Borgstrøm (1940) and Oftedal (1956); P. Ladefoged, J. Ladefoged, et al. (1998)
Applecross Gaelic	$r^{ɣ}$ r	Ternes (2006)
East Sutherland Gaelic	r	Dorian (1978)
Irish	r r^{j}	Ní Chasaide (1999) and Hickey (2014)
Manx	r	Broderick (2009)

Table 2: Summary of the rhotics in descriptive work on the modern Goidelic dialects.

Gaelic	**Phoneme**	**Word position**	**Vowel context**	**English**
ri	r^j	initial	i	to
fir	r^j	final	i	men
sir	r^j	final	i	ask
gàir	r^j	final	a	laugh
bàir	r^j	final	a	goal
muir	r^j	final	u	sea
mo rionnag	r	initial	i	my star
mo rabaid	r	initial	a	my rabbit
riubh	r	initial	u	to you
fìor	r	final	i	really
sìor	r	final	i	eternal
far	r	final	a	where
cur	r	final	u	put
rionnag	$r^ɣ$	initial	i	star
rabaid	$r^ɣ$	initial	a	rabbit
rudan	$r^ɣ$	initial	u	things
piorr	$r^ɣ$	final	i	pierce
as fheàrr	$r^ɣ$	final	a	best
cùrr	$r^ɣ$	final	u	corner

Table 3: Word list used in this study.

Full model	$\hat{\beta}$	SE($\hat{\beta}$)	z	$p(z)$
Intercept	-4.78	0.70	-6.82	$<$.001
Main effects		df	χ^2	$p(\chi^2)$
Rhotic phoneme		16	282.82	$<$ .001
Vowel		16	67.61	$<$ .001
Post-hoc tests	$\hat{\beta}$	SE($\hat{\beta}$)	z	$p(z)$
$\text{r}^{\text{ɣ}}$ - r	0.18	0.58	0.31	.95
$\text{r}^{\text{ɣ}}$ - r^{j}	-4.67	0.66	-7.13	$<$.001
r - r^{j}	-4.85	0.51	-9.59	$<$.001
a - u	-1.20	0.63	-1.76	.18
a - i	1.00	1.02	0.98	.59
u - i	2.10	0.72	2.92	.010

Table 4: Logistic mixed-effects regression model comparisons testing the effect of phoneme and vowel context on the likelihood of a rhotic being produced as a palatalised fricative/rhotic. The likelihood ratio tests for the main effects were conducted with speaker as a random intercept due to random slopes not converging.

	Word-initial rhotics F2−F1					**Word-initial rhotics F3−F2**				
Full model	$\hat{\beta}$	SE($\hat{\beta}$)		t		$\hat{\beta}$	SE($\hat{\beta}$)		t	
Intercept	-1.32	0.13		-10.06		-0.03	0.14		-0.21	
Main effects			df	χ^2	$p(\chi^2)$			df	χ^2	$p(\chi^2)$
Rhotic phoneme			2	26.72	$<.001$			2	75.26	$<.001$
Vowel			2	66.09	$<.001$			2	31.41	$<.001$
Post-hoc tests	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$
$r^{ɣ}$ - r	-0.48	0.09	11.0	-5.32	$<.001$	0.58	0.12	346	4.80	$<.001$
$r^{ɣ}$ - r^{j}	-2.15	0.24	12.4	-8.82	$<.001$	1.93	0.22	346	8.99	$<.001$
r - r^{j}	-1.67	0.24	12.5	-7.06	$<.001$	1.35	0.20	346	6.63	$<.001$
a - u	-0.73	0.10	317	-6.97	$<.001$	-0.64	0.14	346	-4.58	$<.001$
a - i	-0.81	0.10	318	-7.74	$<.001$	-0.74	0.14	346	-5.25	$<.001$
u - i	-0.08	0.10	317	-0.80	.70	-0.10	0.14	346	-0.70	.77

Table 5: Regression models for word-initial rhotics at 80% duration. The F2−F1 models were run with only a random slope of phoneme by speaker. All F3−F2 models run with only a random intercept for speaker.

	Vowel following Word-initial rhotics F2−F1					Vowel following Word-initial rhotics F3−F2				
Full model	$\hat{\beta}$	SE($\hat{\beta}$)		t		$\hat{\beta}$	SE($\hat{\beta}$)		t	
Intercept	-1.35	0.07		-20.34		0.62	0.14		4.39	
Main effects			df	χ^2	$p(\chi^2)$			df	χ^2	$p(\chi^2)$
Rhotic phoneme			11	50.93	$<.001$			2	23.24	$<.001$
Vowel			11	67.91	$<.001$			2	8.47	.01
Post-hoc tests	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$
$r^{ɣ}$ - r	-0.57	0.06	11.3	-8.94	$<.001$	0.74	0.12	5.38	6.45	.002
$r^{ɣ}$ - r^{j}	-2.05	0.11	11.2	-18.30	$<.001$	1.62	0.19	3.62	8.38	.003
r - r^{j}	-1.48	0.11	11.2	-13.96	$<.001$	0.88	0.21	8.69	4.15	.007
a - u	-0.37	0.09	12.2	-4.35	.002	-0.33	0.12	361	-2.82	.01
a - i	-0.62	0.08	11.5	-8.21	$<.001$	-0.20	0.12	361	-1.69	.21
u - i	-0.24	0.10	12.9	-2.52	.06	0.13	0.12	361	1.14	.49

Table 6: Regression models for vowel following word-initial rhotics at 20% duration. Likelihood ratio tests for F2−F1 testing main effect of phoneme and vowel were run with only a random slope for phoneme by speaker. F3−F2 models were run with a random slope for phoneme by speaker.

	Vowel preceding Word-final rhotics F2−F1					Vowel preceding Word-final rhotics F3−F2				
Full model	$\hat{\beta}$	SE($\hat{\beta}$)		t		$\hat{\beta}$	SE($\hat{\beta}$)		t	
Intercept	-1.37	0.10		-13.35		0.97	0.15		6.66	
Main effects			df	χ^2	$p(\chi^2)$			df	χ^2	$p(\chi^2)$
Rhotic phoneme			11	55.17	$<.001$			2	22.92	$<.001$
Vowel			2	47.06	$<.001$			2	26.98	$<.001$
Post-hoc tests	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$
$r^{ɣ}$ - r	-0.62	0.15	13.1	-4.16	.003	0.57	0.19	12.9	3.06	.02
$r^{ɣ}$ - r^{j}	-0.92	0.13	13.0	-7.17	$<.001$	0.90	0.14	12.4	6.59	$<.001$
r - r^{j}	-0.30	0.07	11.7	-4.34	.003	0.32	0.11	12.7	2.91	.03
a - u	-0.97	0.10	12.2	-9.96	$<.001$	0.81	0.10	12.3	7.84	$<.001$
a - i	-1.41	0.08	12.1	-17.34	$<.001$	0.86	0.13	12.8	6.63	$<.001$
u - i	-0.43	0.14	13.0	-3.19	.02	0.05	0.15	13.0	0.34	.94

Table 7: Regression models for vowel preceding word-final rhotics at 80% duration. Likelihood ratio test for F2−F1 testing main effect of phoneme run with only a random slope for phoneme by speaker.

	Word-final rhotics COG				
Full model	$\hat{\beta}$	SE($\hat{\beta}$)		t	
Intercept	-0.22	0.09		-2.45	
Main effects			df	χ^2	$p(\chi^2)$
Rhotic phoneme			7	36.42	<.001
Vowel			2	11.21	.003
Post-hoc tests	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$
$r^{ɣ}$ - r	0.04	0.10	12.0	0.43	.90
$r^{ɣ}$ - r^{j}	-0.33	0.14	13.2	-2.46	.07
r - r^{j}	-0.38	0.08	12.3	-4.53	.002
a - u	0.22	0.08	478	2.78	.02
a - i	0.21	0.07	481	3.03	.007
u - i	-0.005	0.07	478	-0.06	.99

Table 8: Linear mixed-effects regression models testing the effect of phoneme and vowel context on COG in word-final rhotics at 80% duration. The full model was run with only a random intercept of phoneme by speaker. Likelihood ratio test for the main effect of phoneme run with only a random intercept for speaker.

	Word-initial PC1					Word-initial PC2				
Full model	$\hat{\beta}$	SE($\hat{\beta}$)		t		$\hat{\beta}$	SE($\hat{\beta}$)		t	
Intercept	-0.75	0.14		-5.52		-1.00	0.20		-5.10	
Main effects			df	χ^2	$p(\chi^2)$			df	χ^2	$p(\chi^2)$
Rhotic phoneme			11	73.92	$<.001$			16	120.06	$<.001$
Vowel			2	3.93	.14			2	5.35	.07
Post-hoc tests	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$
$r^{ɣ}$ - r	-0.40	0.13	8.13	-3.05	.04	-0.02	0.27	8.14	-0.09	.10
$r^{ɣ}$ - r^{j}	-2.08	0.17	7.79	-11.96	$<.001$	-1.36	0.33	7.85	-4.17	.008
r - r^{j}	-1.67	0.26	8.06	-6.55	$<.001$	-1.33	0.18	6.95	-7.41	$<.001$
a - u	-0.47	0.23	8.15	-2.10	.15	-1.04	0.41	8.15	-2.53	.08
a - i	-0.18	0.12	7.90	-1.57	.31	-0.54	0.21	8.08	-2.51	.08
u - i	0.29	0.14	7.97	2.04	.16	0.50	0.26	8.00	1.95	.19

Table 9: Regression models for word-initial PC1 and PC2. Likelihood ratio test for word-initial PC1 testing main effect of phoneme run with only a random slope for phoneme by speaker. Likelihood ratio test for word-initial PC2 testing main effect of phoneme run with only a random intercept for speaker only.

	Word-initial PC3					Word-initial PC4				
Full model	$\hat{\beta}$	SE($\hat{\beta}$)		t		$\hat{\beta}$	SE($\hat{\beta}$)		t	
Intercept	-0.92	0.15		-7.07		-0.17	0.24		-0.69	
Main effects			df	χ^2	$p(\chi^2)$			df	χ^2	$p(\chi^2)$
Rhotic phoneme			2	20.10	$<$.001			2	3.95	0.14
Vowel			2	10.51	.005			2	0.53	.77
Post-hoc tests	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$
$r^{ɣ}$ - r	-0.65	0.18	8.11	-3.51	.02	-0.36	0.26	8.16	-1.38	.40
$r^{ɣ}$ - r^{j}	-1.71	0.19	6.51	-9.27	$<$.001	0.35	0.44	7.67	0.78	.73
r - r^{j}	-1.07	0.23	7.01	-4.72	.005	0.70	0.39	7.60	1.79	.24
a - u	0.03	0.22	7.86	0.13	.99	0.18	0.26	7.31	0.70	.77
a - i	0.50	0.19	7.30	2.58	.08	0.09	0.31	7.74	0.30	.95
u - i	0.47	0.15	6.61	3.19	.04	-0.09	0.28	7.10	-0.32	.95

Table 10: Regression models for word-initial PC3 and PC4.

	Word-final PC1					Word-final PC2				
Full model	$\hat{\beta}$	SE($\hat{\beta}$)		t		$\hat{\beta}$	SE($\hat{\beta}$)		t	
Intercept	-1.68	0.11		-15.76		-0.67	0.17		-3.82	
Main effects			df	χ^2	$p(\chi^2)$			df	χ^2	$p(\chi^2)$
Rhotic phoneme			16	144.3	$<$.001			2	4.94	.08
Vowel			2	23.82	$<$.001			2	14.99	$<$.001
Post-hoc tests	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$
$r^{ɣ}$ - r	-1.04	0.25	7.99	-4.10	.009	-0.13	0.27	8.14	-0.49	.88
$r^{ɣ}$ - r^{j}	-0.86	0.11	6.87	-8.09	$<$.001	0.14	0.20	7.83	0.72	.76
r - r^{j}	0.18	0.21	7.97	0.82	.70	0.27	0.14	7.16	1.93	.20
a - u	-1.26	0.20	7.92	-6.37	$<$.001	-1.27	0.23	8.10	-5.50	.001
a - i	-1.69	0.13	7.92	-12.83	$<$.001	-1.25	0.19	8.06	-6.68	$<$.001
u - i	-0.43	0.20	7.88	-2.12	.15	0.02	0.15	7.75	0.11	.99

Table 11: Regression models for word-final PC1 and PC2. Likelihood ratio test for word-final PC1 testing main effect of phoneme run with only a random intercept for speaker only.

	Word-final PC3					Word-final PC4				
Full model	$\hat{\beta}$	SE($\hat{\beta}$)		t		$\hat{\beta}$	SE($\hat{\beta}$)		t	
Intercept	0.69	0.26		2.64		-0.06	0.20		-0.32	
Main effects			df	χ^2	$p(\chi^2)$			df	χ^2	$p(\chi^2)$
Rhotic phoneme			2	2.48	.29			2	0.33	.85
Vowel			2	5.54	.06			2	0.93	.63
Post-hoc tests	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$	$\hat{\beta}$	SE($\hat{\beta}$)	df	t	$p(t)$
$r^{\text{ɣ}}$ - r	-0.09	0.20	7.78	-0.44	.90	-0.11	0.22	7.69	-0.52	.86
$r^{\text{ɣ}}$ - r^{j}	-0.23	0.19	7.89	-1.19	.49	-0.05	0.29	8.12	-0.18	.98
r - r^{j}	-0.14	0.11	6.13	-1.30	.45	0.06	0.25	8.02	0.25	.97
a - u	0.59	0.27	8.16	2.15	.14	-0.21	0.24	7.77	-0.86	.68
a - i	0.75	0.28	8.15	2.67	.06	-0.10	0.30	8.14	-0.33	.94
u - i	0.16	0.14	8.12	1.13	.52	0.11	0.22	7.92	0.51	.87

Table 12: Regression models for word-final PC3 and PC4.

Word Position	Measure	$/r^{ɣ}/$ different from /r/	$/r^{ɣ}/$ different from $/r^{j}/$	/r/ different from $/r^{j}/$
Word-initial	rhotic F2−F1	✓	✓	✓
	rhotic F3−F2	✓	✓	✓
	vowel F2−F1	✓	✓	✓
	vowel F3−F2	✓	✓	✓
Word-final	vowel F2−F1	✓	✓	✓
	vowel F3−F2	✓	✓	✓
	rhotic COG	n.s.	n.s.	✓
Word-initial	PC1	✓	✓	✓
	PC2	n.s.	✓	✓
	PC3	✓	✓	✓
	PC4	n.s.	n.s.	n.s.
Word-final	PC1	✓	✓	n.s.
	PC2	n.s.	n.s.	n.s.
	PC3	n.s.	n.s.	n.s.
	PC4	n.s.	n.s.	n.s.

Table 13: Summary of acoustic and articulatory (PCA) results comparing phonemic categories. ✓ indicates a significant difference was found, 'n.s.' indicates that no significant difference was found.

Narrow transcription	Broader category
ɾ	tap
ɾ̥	tap
r	trill
r̥	trill
ɹ	approximant
ɹ̥	approximant
ɻ	approximant
ɻ̊	approximant
ɾð	palatalised fricative/rhotic
ɾθ	palatalised fricative/rhotic
ð	palatalised fricative/rhotic
θ	palatalised fricative/rhotic
ʒ	palatalised fricative/rhotic
ʃ	palatalised fricative/rhotic
dʒ	palatalised fricative/rhotic
tʃ	palatalised fricative/rhotic
ç	palatalised fricative/rhotic
ɾç	palatalised fricative/rhotic
v	palatalised fricative/rhotic
s	palatalised fricative/rhotic
ɚ	weakly-/non-rhotic
ə	weakly-/non-rhotic
Ø	weakly-/non-rhotic

Table 14: Categories for auditory coding.

SGDS transcription	Contemporary IPA	Broader category
r	ɾ	tap
r̥	ɾ̥	tap
r‘	ɾˠ	tap
r̥‘	ɾ̥ˠ	tap
r̥’	ɾ̥ʲ	tap
r’	ɾʲ	tap
ʀ	r	trill
ʀ̥	r̥	trill
ɹ	ɹ	approximant
ɹ̥	ɹ̥	approximant
ɹ̥‘	ɹ̥ˠ	approximant
ɹ̥’	ɹ̥ʲ	approximant
ð	ð	palatalised fricative/rhotic
ð̥	ð̥	palatalised fricative/rhotic
ð’	ðʲ	palatalised fricative/rhotic
ð̥’	ð̥ʲ	palatalised fricative/rhotic
ðh	ðh	palatalised fricative/rhotic

Table 15: SGDS transcriptions.

Position	**Measure**	**Full model formula**	**n (groups)**	**AUC full**	**AUC null**
Combined	Palatalisation	palatalisation $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	871 (speaker: 12)	0.95	0.77
Position	**Measure**	**Full model formula**	**n (groups)**	**AIC full**	**AIC null**
Initial	rhotic F2−F1	F2−F1 $\sim$ phoneme + vowel + (phoneme|speaker)	354 (speaker: 12)	864.84	938.49
	rhotic F3−F2	F3−F2 $\sim$ phoneme + vowel + (1|speaker)	354 (speaker: 12)	1038.24	1122.37
	vowel F2−F1	F2−F1 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	357 (speaker: 12)	606.4	653.63
	vowel F3−F2	F3−F2 $\sim$ phoneme + vowel + (phoneme|speaker)	357 (speaker: 12)	918.8	942.39
Final	vowel F2−F1	F2−F1 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	509 (speaker: 12)	907.4	953.80
	vowel F3−F2	F3−F2 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	509 (speaker: 12)	1016.9	1048.67
	rhotic COG	COG $\sim$ phoneme + vowel + (phoneme|speaker)	503 (speaker: 12)	1049.1	1070.36
Initial	PC1	PC1 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	147 (speaker: 7)	129.95	148.95
	PC2	PC2 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	147 (speaker: 7)	277.98	294.83
	PC3	PC3 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	147 (speaker: 7)	336.52	349.13
	PC4	PC4 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	147 (speaker: 7)	460.05	456.35
Final	PC1	PC1 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	252 (speaker: 7)	472.75	498.31
	PC2	PC2 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	252 (speaker: 7)	604.9	613.43
	PC3	PC3 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	252 (speaker: 7)	616.20	616.66
	PC4	PC4 $\sim$ phoneme + vowel + (vowel + phoneme|speaker)	252 (speaker: 7)	671.51	666.24

Table 16: Further information about the formula and fit of each regression model, following the conventions in Sonderegger (2021). Measures of model fit (AUC or AIC) are included comparing the model we fitted to a model containing only the random effects as a comparison. AUC was calculated using the ModelMetrics package (Hunt 2020).