PHONETIC TYPOLOGY AND ARTICULATORY CONSTRAINTS: THE REALIZATION OF SECONDARY ARTICULATIONS IN SCOTTISH GAELIC RHOTICS

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Much progress has been made in the last 200 years with regard to understanding the origins and mechanisms of sound change. It is hypothesized 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 multidimensional 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 generalizations about crosslinguistic phonetic typology.*

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

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 recategorizing them (Ohala 1981) or patterns of variability in speech production becoming phonologized (Ohala 1989). Such constraints on speech perception and production can be used to explain a wide variety of changes and patterns of sounds crosslinguistically (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 comparable structures being widely lost in a range of other languages? This is the central question of the present study, and we propose that answering it is fundamental to our understanding of crosslinguistic 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, palatalized rhotics appear prone to reduction and loss. Previous studies of Russian have noted the articulatory challenge of producing a trill with secondary articulation, specifically palatalization, explaining why secondary articulations

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are comparatively rarer in rhotics than, for example, 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 disfavored 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 palatalization and velarization. Our aim is to examine the phonetic realization of secondary articulatory contrasts in a context where they appear to be diachronically, perceptually, and articulatorily disfavored: 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 this study, we advance our understanding of the typology of secondary rhotic articulations and examine the realization of an unusual consonant inventory that appears to exist in relative stability despite a diachronic tendency toward 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 (§1.1). We then apply these models to the case of secondary articulations in rhotics (§1.2). Section 1.3 explores how these typological patterns are manifested in the history of Indo-European, focusing on the Goidelic languages, and §1.4 introduces the specific sociolinguistic context of Scottish Gaelic, before our summary in §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 realization of back vowels as front in this context and may fail to perceptually compensate for the coarticulatory effects of a coronal sound, eventually recategorizing 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—for example, 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 that of the original speaker over time (Blevins 2009:32–33).

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

[1] We henceforth generally 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.

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 f0 following aspirated stops compared with lower f0 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 nasalized 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 & Ohala 1993, Warner et al. 2015). These examples point toward biomechanical or aerodynamic factors yielding biases for or against particular phonetic realizations, 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 underarticulation may lead to consistent and perceptually noticeable variation in the speech signal, presenting another potential source of sound change that can be consolidated and may stabilize 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 2001:58). 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 others (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 to potential acoustic change once such articulatory change stabilizes. This explanation has been proposed in recent studies of prelateral 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 toward describing many possible processes and historical developments in sound systems crosslinguistically, 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 toward 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 realization of secondary articulations in rhotics, a typologically unusual phenomenon, which appears crosslinguistically 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 the Maddieson 1984 sample). Most languages have a single rhotic, which is commonly a trill (Ladefoged & Maddieson 1996:217). In Maddieson's (1984) sample, 183 of 317 languages had one rhotic, while fifty-one had two rhotics, eight had three rhotics, and one language had four rhotics. Languages contrasting three or more rhotics constituted just 2.8% of the sample. While not included in Maddieson 1984, it is also worth noting that Toda (Dravidian) has six contrastive rhotics: palatalized and plain trills at three different places of articulation (Spajić et al. 1996). Of the 316 rhotic phonemes analyzed by Maddieson (1984:81), only eleven have a secondary articulation: eight are palatalized, two velarized, and one pharyngealized. Other rhotic secondary articulation contrasts may include labialization, as in Marshallese and Kusaien (Micronesian; Bender 1968, Lee 1975:25).

In view of the small number of languages with rhotics contrasting in secondary articulations in Maddieson's sample and other literature, the Gaelic situation involving three rhotics that contrast in secondary articulations is typologically unusual. The most commonly reported secondary articulation in rhotics is palatalization. Hall (2000) provides an overview of secondary palatalization in rhotics across the world's languages, showing 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 toward losing palatalization in rhotic consonants as a phonemic feature. Note this is not always the case, however; for example, palatalized rhotics are not found in Proto-Dravidian (Krishnamurti 2003:120), but appear to be an innovative feature in Toda (Spajić et al. 1996).

The tendency toward loss of palatalized rhotics in Indo-European may stem from two sources. First, palatalized rhotics may be disfavored due to biases from 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 palatalization (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 in order for the Bernoulli effect to produce vibration. In trill production, the tongue body is retracted and stabilized (McGowan 1992, Recasens 2013). When the tongue body is also raised and fronted for palatalization, this produces additional constraints on the production of vibrations necessary for trilling. In order to overcome this fundamental incompatibility between trilling and palatalization, Stoll (2017) shows that Russian speakers delay the palatalization gesture in palatalized rhotics compared with the same gesture in palatalized laterals (see Kochetov 2005 for a similar finding). This temporal delay may lead to increased gestural overlap, and therefore strengthens the 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 palatalized rhotics in other Slavic languages.

Another potential bias against the production of palatalized rhotics comes from perceptual constraints. Howson and Monahan (2019) show that rhotics occupy a small perceptual space and are acoustically and perceptually more similar to each other than other sound classes are. In their experiment, listeners were worse at distinguishing three different rhotic segments than three different laterals, stops, nasals, or fricatives. Howson and Monahan (2019) suggest that the perceptual similarities across the class of rhotics has led to (i) common occurrences of change from one rhotic to another: for example, /r/ > /ʀ/ in Sorbian (Howson 2017); (ii) allophonic alternations across rhotics:

for example, [ɾ r ɹ ɽ] as allophones in Brazilian Portuguese (Veloso 2015); and (iii) 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 palatalized rhotics, especially in Slavic. In the next section, we consider the realization 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 section above, we explained how biases in production and perception might lead to change in rhotic systems, especially to 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 palatalization, 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 palatalization in Russian and other Slavic languages. Originally present in Proto-Slavic, palatalized 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 Ukrainian, Upper Sorbian, and Bulgarian. An overview table in Iskarous & Kavitskaya 2010:627 shows that palatalized rhotics have been lost in languages such as Belarusian, Slovak, Serbian, Croatian, and Macedonian. Two languages have spirantized palatalized rhotics: a postalveolar fricative /ʒ/ in Polish, and a trill-fricative /r̤/ in Czech (Howson et al. 2014). Finally, palatalized rhotics have changed into a rhotic + /j/ in Slovenian (Stoll 2017). Similarly, palatalized rhotics appear to have been present in Proto-Baltic, but are reduced in the modern Baltic languages. Lithuanian contrasts palatalized and nonpalatalized 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 represented in Celtic studies literature as <L, l, L', l'>. The apostrophe denotes palatalization, and the capitalization a 'fortis/lenis' contrast (Russell 1995, Stifter 2006). In the Archaic Irish period around 400–600 CE, it is thought that the 'fortis/lenis' distinction was one of geminate/singleton; this is shown in orthography by use of a double vs. single grapheme (Hickey 1995:149). 'Lenition' refers to a sound change that happened pre-Old Irish (i.e. pre-600 CE). In lenition sound changes in Goidelic, intervocalic consonants spirantized, voiced, or degeminated, which 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 1995:154), and palatalization gradually became phonemic during the Old Irish period (Greene 1973). Toward the end of the Old Irish period, around 800–900 CE, it is thought that gemination was lost as a contrastive aspect of the language (Hickey 1995:150). Thurneysen (1946:84) 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 (POA) contrast as a contrast between alveolar (advanced) and retroflex (retracted) rhotics, but this is speculative given the differences in terminology.

Around 900 CE, Irish had contrastive palatalization, 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 palatalized versus velarized counterparts and that the sonorants were included in this system of oppositions. Where sonorants occurred in synchronic and diachronic contexts of lenition, the former geminate/singleton ('fortis/lenis') contrast was replaced by a 'depolarization' contrast. By this, Hickey means that palatalized sonorants in lenition contexts become nonpalatalized and velarized sonorants become nonvelarized (Hickey 2014:46). This results in the three-way contrast found in most dialects of Scottish Gaelic between palatalized, 'plain', and velarized 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 summarized in Table 1.

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 palatalized vs. nonpalatalized	rr, r, rrʲ, rʲ
		Gemination becomes POA contrast and also palatalized vs. nonpalatalized	r, ɽ, rʲ, ɽʲ
900–1200	Middle Irish	POA contrast lost; palatalized, velarized, plain contrast develops	rˠ, r, rʲ
1100 onward	Scottish Gaelic	Palatalized, velarized, plain	rˠ, r, rʲ

TABLE 1. Summary of the development of rhotics in Scottish Gaelic. Dates are approximate, and processes that took place over several centuries have been summarized for clarity.

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 (1940:24) describes (i) a velarized rhotic that is trilled, 'strongly hollow' sounding, and retroflex in articulation, (ii) a plain alveolar tap/trill with one to two taps, and (iii) a dental fricative that is not strongly palatal. Oftedal (1956:126–29) also refers to (i) an alveolar trill with a 'hollow timbre', (ii) a plain tap without 'hollow timbre', and (iii) a dental or alveolar fricative, which is sometimes palatalized. In their phonetic study of Gaelic, Ladefoged et al. (1998) report formant differences between the plain and velarized rhotics suggestive of a palatalization contrast, and state that the palatalized phoneme was realized as a dental fricative. In a wide-ranging dialect survey of Gaelic speakers collected in the mid-twentieth century, Ó Dochartaigh 1997 largely confirms these reports above, yet the auditory transcription data have not been systematically analyzed in the phonetic literature. We address this by presenting such a reanalysis in this article. Finally, Nance et al. (2016) conducted an auditory analysis of word-final rhotics in L2 Gaelic speakers. They found that phonemically palatalized rhotics were more likely to be produced with palatalization or spirantization, but that the velarized rhotics were comparatively rare in spontaneous speech and it was therefore difficult to conclusively determine their phonetic realization 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 (2006:25) suggests that the alveolar and palatalized rhotic have merged, leaving a velarized vs. 'unmarked' rhotic. A two-way contrast is similarly described for modern Irish. Ní Chasaide (1999) reports a distinction between palatalized and velarized taps, which is neutralized in word-initial context where the rhotic is produced as an approximant. Similarly, Ní Chiosáin and Padgett (2012) and Bennett et al. (2018) show a contrast between palatalized and velarized trills. Finally, Hickey (2014:93) suggests a contrast between a trill and a palatalized trill, which is neutralized in word-initial context. The most innovative Goidelic dialects in terms of rhotics are East Sutherland Gaelic and Manx. In East Sutherland, Dorian (1978:45) reports one rhotic sound, which is typically realized as a tap or trill. Similarly, there is one rhotic in Manx, though Broderick (2009:310) reports 'traces' of palatalized rhotics in some relic words. Broderick's description is based on Classical Manx (mid-1700s). The information above is summarized in Table 2.

DIALECT	RHOTICS (PHONEMIC IPA)	MAIN SOURCES
Lewis Gaelic	$r^{ɣ}$, r, r^{j}	Borgstrøm 1940 and Oftedal 1956; Ladefoged et al. 1998
Applecross Gaelic East	$r^{ɣ}$, r	Ternes 2006
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.

The discussion above suggests that the three-way phonemic contrast in contemporary Lewis Gaelic rhotics provides the context for a particularly strong case study examining the maintenance of typologically unusual contrasts in the face of considerable biomechanical, perceptual, and sociolinguistic pressures. Lewis Gaelic was chosen for this study since it is a traditional dialect with a relatively large speaker base, among whom 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 (i) whether this distinction does indeed remain intact in present-day Scottish Gaelic; (ii) the nature of complex rhotic contrasts in terms of their auditory, acoustic, and articulatory correlates; and (iii) how such a typologically unusual system persists in the face of diachronic pressures that would predict its loss. Before we describe our method for analyzing this system, we briefly outline the status of contemporary Scottish Gaelic, which helps to further contextualize 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 of Scotland's northwest 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 was used as the language of the Scottish nobility (MacKinnon 1974). Due to political shifts in allegiance toward 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 that time (McLeod 2020). At the same time, a revitalization 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. As part of this linguistic expansion, the language is now used in domains such as technical policy documentation (Lamb 2008, Dunmore 2019).

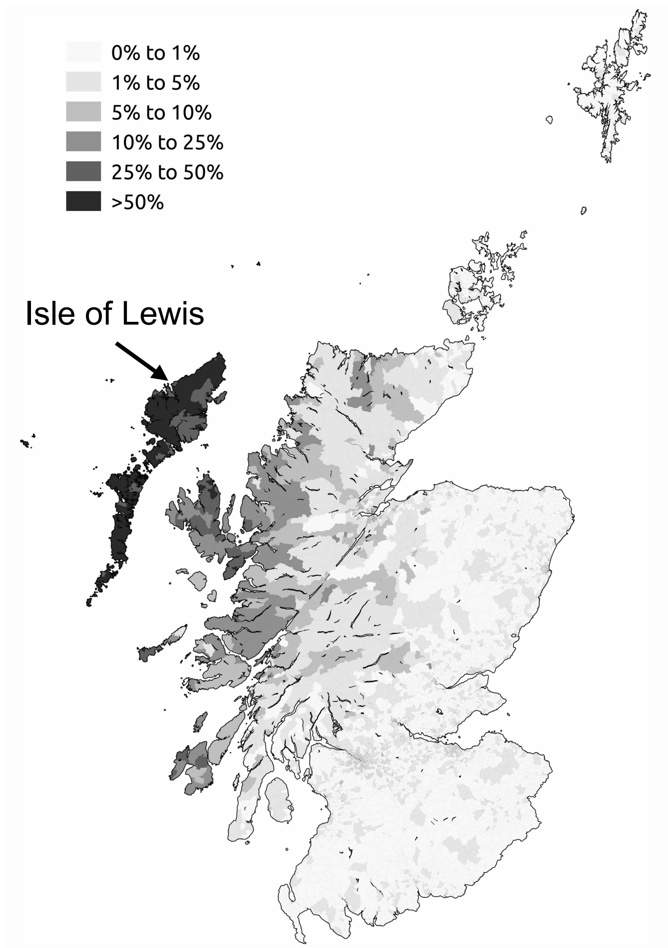

FIGURE 1. Map showing the concentration of Gaelic speakers across Scotland using data from the 2011 UK Census (most recent available results). Attribution: SkateTier, CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0), via Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Scots_Gaelic_speakers_in_the_2011_census.png), converted to grayscale here.

The sociolinguistic context described above points to 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 system with a 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 to the fact that dense contrasts are perceptually vulnerable to misperception. We have highlighted, however, the maintenance of some typologically disfavored sound systems 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 multidimensional analysis of the auditory, acoustic, and articulatory characteristics of the 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 to identify patterns in articulation that may be indicative of pressure toward a future change in progress (Lawson et al. 2013). In order to contextualize our findings in terms of the broader diachronic situation of Gaelic, we compare our data to a dialect survey of 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 of the speakers had spent some time living on the Scottish mainland, but 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 were retired from work involving Gaelic. The speakers in this study are aged twenty-one to eighty, with a mean age of forty. While the sample is age-diverse, the speakers are consistent in identifying as Gaelic-dominant bilinguals. In the minoritized context of Gaelic, this is increasingly rare, and our sample represents 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 and 1922 and recorded in 1961–1963.

2.2. DATA COLLECTION. Data for this study were collected in a community center 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 preamplified and digitized using a Sound Devices USBPre audio interface and then recorded to a laptop computer at 44.1 kHz with 16-bit quantization. The microphone was attached to a headset used to stabilize 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 sixty-four element probe of 20 mm radius. We used a 2 MHz probe frequency, 80 mm depth, 90% field of view, and fifty-seven scan lines, which resulted in a frame rate of ~92 Hz. The probe was stabilized 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 synchronization was carried out 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 synchronization 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-final position. Due to the fatigue that resulted from recording while wearing the ultrasound headset, we were unable to elicit data on the word-medial context. The occurrence of /rʲ/ in word-initial position is limited to a small handful of words. We chose to elicit the word *ri* 'to' as it is reliably produced with /rʲ/, but the extremely limited context for /rʲ/ in word-initial position is further discussed in §4. The 'plain' phonemes in word-initial position are usually triggered by initial consonant mutation, so we elicited them using the possessive *mo* 'my', which triggers mutation. The auditory and acoustic analyses were conducted on 1,088 tokens (from twelve speakers), and the ultrasound analysis was conducted on 399 tokens (from seven speakers).

GAELIC	PHONEME	WORD POSITION	VOWEL CONTEXT	GLOSS
ri	rʲ	initial	i	'to'
fir	rʲ	final	i	'men'
sir	rʲ	final	i	'ask'
gàir	rʲ	final	a	'laugh'
bàir	rʲ	final	a	'goal'
muir	rʲ	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	rˠ	initial	i	'star'
rabaid	rˠ	initial	a	'rabbit'
rudan	rˠ	initial	u	'things'
piorr	rˠ	final	i	'pierce'
as fheàrr	rˠ	final	a	'best'
cùrr	rˠ	final	u	'corner'

TABLE 3. Word list used in this study.

[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 with 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.

2.3. DATA SEGMENTATION. The duration of the rhotic was manually labeled 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 trills 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 based on spectrographic clues. Approximants were segmented as ending where there was a clear change in the second and/or the third formant on the spectrogram, as well as based on 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 similar to voiceless fricatives on the spectrogram. 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 realization of different rhotic phonemes are shown in the spectrograms and waveforms in Appendix A, Figures A1–A3.

2.4. AUDITORY ANALYSIS. Auditory analysis was carried out by means of 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 can vary between transcribers. After this initial transcription, the data were collapsed into broader categories and analyses of interrater reliability carried out. The collapsing of narrow transcriptions into broader categories is detailed in Appendix B, Table A1. Initial interrater reliability between the two sets of transcriptions was conducted using Cohen's kappa (Cohen 1960, Gisev et al. 2013), which 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, $z = 30.6$, $p < 0.001$, suggesting moderate reliability (McHugh 2012). Disagreement occurred most commonly on word-final taps with palatalization, which one transcriber categorized as taps and the other as palatalized fricatives. The first author of the current article then checked all tokens where the transcribers disagreed and made a final decision based on previous experience with working on Gaelic rhotics (Nance et al. 2016). When organizing these data and all of 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 and mapped them into the same broad categories used for our analysis. Details of the exact process used are given in Appendix C, Table A2.

The data from the SGDS can provide 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 realization of these particular sounds. Our transcription scheme therefore focused on potential differences between major manners and places 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 about what he was likely to hear.

2.5. Acoustic analysis. Previous acoustic work on palatalization 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 and Kavitskaya (2018:62), palatalization 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 palatalized and nonpalatalized fricatives in Russian. Our acoustic analysis thus considers the rhotic and the vowel following/preceding it. A final point to consider is that the palatalization gesture in rhotics occurs relatively late (as compared to laterals) in the duration of the segment (Kochetov 2005, Stoll 2017).

Considering this previous research, we included in our analysis 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 25 ms Gaussian window and the linear predictive coding (LPC) Burg method, which was set up to find five formants up to 5500 Hz (female speakers) or 5000 Hz (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. For this reason, we measured spectral center of gravity (COG) instead of extracting formants, following Kochetov (2017). For this analysis, sound files were band-pass filtered at 2000–11,000 Hz and downsampled to 22,050 Hz. COG was obtained from a 40 ms Hamming window centered on 80% of the rhotic duration, and values were then 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 labeling 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 conceptualize 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 to a substantial degree for all speakers. After model fitting, we split the interaction variable back into its component parts, which allows us to examine how tongue shapes differ according to phoneme, position, and vowel context. Visualization 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 2008, 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 forty-two fanlines, this leads to a data frame with eighty-four possible axes of variation (*x* and *y* values for each fanline). The PCA reduces these eighty-four potential areas of variation into a smaller number of components that characterize each tongue shape. Before the PCA was run, data from each speaker were *z*-scored to better facilitate interspeaker comparison. The PCA was calculated using the princomp() function in R. The first four components accounted for 88% of the variation in the data set, with PC4 accounting for only 7% of the variation. Following Baayen (2008:130) and Turton (2017), we report principal components (PCs) that capture more than 5% of the data. PC5 explains 4% of the variation in the data so is not included, and subsequent PCs explain less and less of the variation. In order to interpret the aspects of tongue splines that 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 data set, 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 data set ± the standard deviation of each PC times the loading. For more details see Johnson 2008:95–102.

2.7. Statistical testing. This section outlines our overall approach to statistical testing, with more specific details provided in the relevant results sections. Our modeling uses mixed-effects regression analysis via the lme4 R package (Bates et al. 2015). After listening to the data and conducting some initial visualizations, we found that the word-initial and word-final data behaved quite differently, so we have modeled the two word positions separately (except in the auditory analysis; see below). Phoneme (velarized, plain, palatalized) and vowel context (/i/, /a/, /u/) were included as independent variables. We use the IPA symbols to refer to the three phonemic categories (/rˠ/, /r/, /rʲ/) in order to clearly distinguish between them and the phonetic auditory perception of palatalization and velarization. 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 optimizer to the bobyqa method using the optimx package (Nash & Varadhan 2011, Nash 2014). If this model also would not converge, we included only a by-speaker random slope for phoneme, and, if even this model would not converge, we included only 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 of detecting such interactions (Harrell 2015), which was not possible to meet in all aspects of our data set. Instead, we discuss the results of possible interaction between factors via data visualization.

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 modeling whether a particular variable significantly improves model fit, and thus significantly predicts variation in the data (Winter 2020:260). 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 emmeans R package (Lenth 2021). Full model formulae and measures of model fit are given in Appendix D, Table A3. All data and code used in our analysis are available as online supplementary materials at http://muse.jhu.edu/resolve/158, as well as at https://osf.io/jsa7k/.

3. RESULTS. Our aim here is to examine how palatalization and velarization contrasts are produced in Gaelic, in light of current models of sound change predicting pressures toward reduction in the system. We first present results of the auditory analysis in order to identify the distinguishing perceptual characteristics of rhotics. We then analyze the acoustic correlates of phonological contrast, before examining the tongue shapes used in speech production. All data visualization 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 labeling are shown in Figure 2. The figure shows clear differences according to word position, especially for the velarized /rˠ/: in word-initial position these are usually realized as approximants, but in word-final position a tap is the most common realization. There are also more approximants for the plain /r/ in word-initial than word-final position. In word-initial position, taps represent about half of the tokens of /r/ and the palatalized /rʲ/, but there are also a large number of palatalized fricative/rhotic realizations in the /rʲ/ category. In word-final position, most /rˠ/ and /r/ tokens are taps, but /rʲ/ is frequently realized as a palatalized fricative/rhotic.

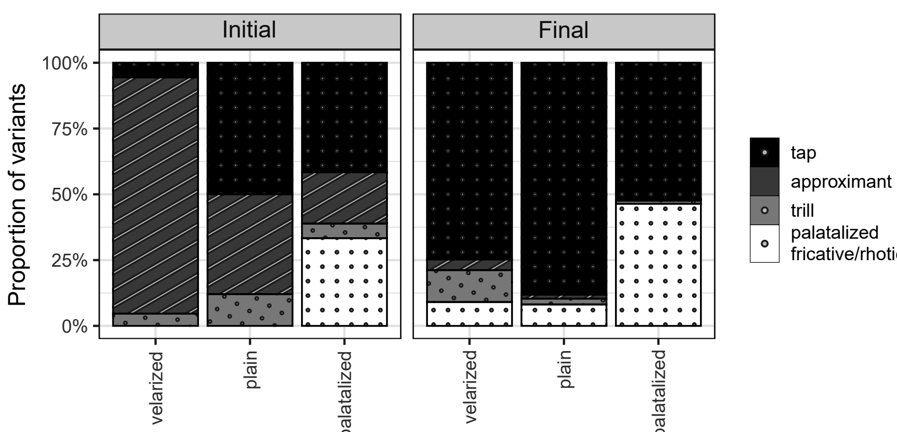

FIGURE 2. Auditory transcription of rhotic phonemes.

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

FULL MODEL	$\hat{\beta}$	$SE(\hat{\beta})$	z	$p(z)$
(intercept)	−4.78	0.70	−6.82	< 0.001
MAIN EFFECTS		df	χ^2	$p(\chi^2)$
Rhotic phoneme		16	282.82	< 0.001
Vowel		16	67.61	< 0.001
POST-HOC TESTS	$\hat{\beta}$	$SE(\hat{\beta})$	z	$p(z)$
rˠ - r	0.18	0.58	0.31	0.95
rˠ - rʲ	−4.67	0.66	−7.13	< 0.001
r - rʲ	−4.85	0.51	−9.59	< 0.001
a - u	−1.20	0.63	−1.76	0.18
a - i	1.00	1.02	0.98	0.59
u - i	2.10	0.72	2.92	0.01

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 palatalized fricative/rhotic. The likelihood ratio tests for the main effects were conducted with speaker as a random intercept due to random slopes not converging.

In order to further investigate the realization of /rʲ/, we listened to these sounds again to analyze them in more detail. We wished to ascertain which ones were produced with audible rhoticity and which ones were produced with some kind of nonrhotic fricative. Previous literature suggests that the phonemic /rʲ/ is produced as a dental fricative (Borgstrøm 1940, Ladefoged 1998). We found, however, that a large number of tokens (fifty-two of 204) were produced with audible rhoticity, which usually took the form of a rhotic off-glide to the vowel, followed by voiceless frication. These are the tokens we consider to be phonetically palatalized rhotics in the data set. A breakdown of this labeling by word containing a phonemic /rʲ/ is in Figure 3. Words with the vowel /i/ (*fir* and *sir*) seem more likely than others to be produced with a phonetically palatalized rhotic, but we have not tested this statistically due to small token counts.

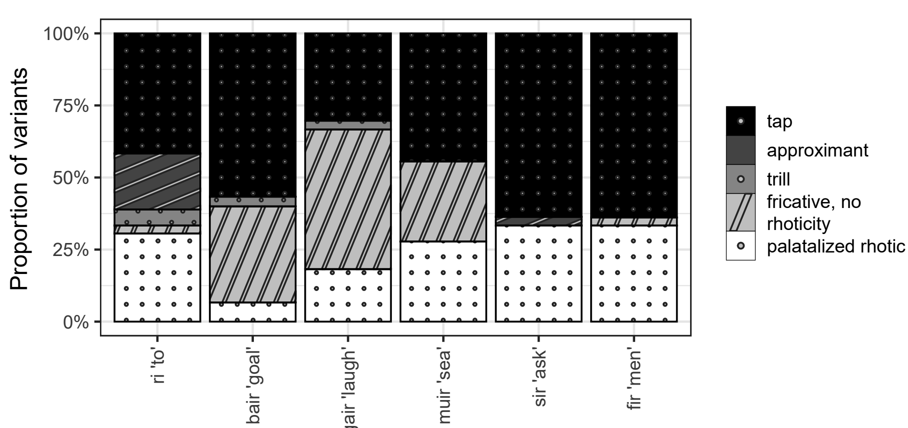

FIGURE 3. More detailed auditory labeling of /rʲ/ tokens only, word by word.

Tokens in Fig. 3 coded as ‘fricative, no rhoticity’ were generally dental or alveolar fricatives, but this represented only thirty-eight of the 204 /rʲ/ tokens. With regard to the fifty-two tokens we heard as phonetically palatalized rhotics, these were realized 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 palatalized rhotic word *ri*, tokens we heard as phonetically palatalized rhotics were also usually realized as a tap and palato-alveolar frication, that is, [ɾɕ]. A sample waveform and spectrogram of a word-final token in the word *fir* /firʲ/ 'men' are given in Figure 4. In this token, the word is produced as [fiʳɕ].

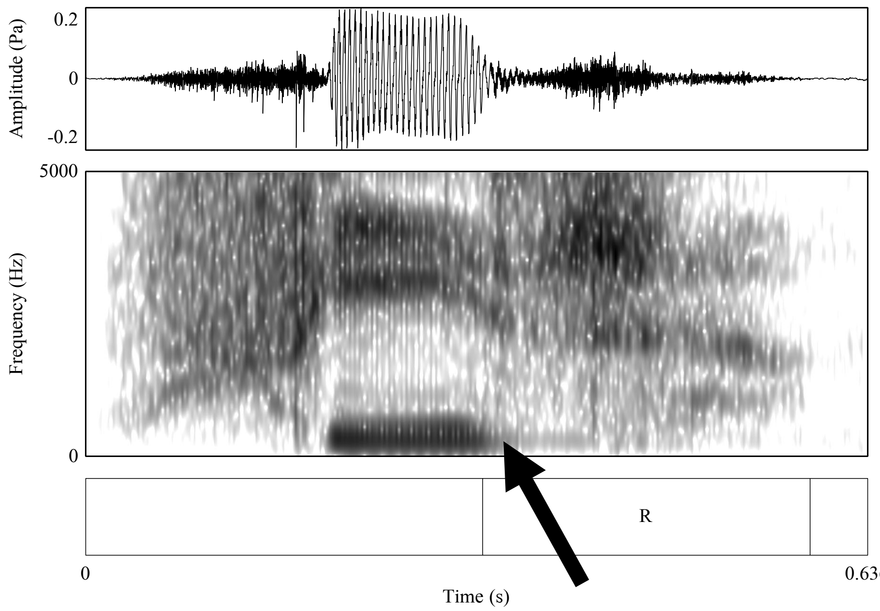

FIGURE 4. Example waveform and spectrogram of a word-final /rʲ/ in the word *fir* 'men' spoken by a female speaker (lf03). The arrow shows the location of a tap-like transition between the vowel and voiceless fricative [ɕ], which is audibly rhotic.

A breakdown of /rʲ/ realization by speaker is provided in Figure 5. The figure shows that every speaker except lf04 produced some instances of phonetically palatalized rhotics; speaker lf04 consistently produced dental fricatives, approximants, or nonpalatalized taps. The speakers have been ordered by age, with the youngest speakers on the left in Fig. 5. There is a trend toward more audible palatalization and more phonetically palatalized rhotics among older speakers. We have not tested this statistically due to the small token counts, but this would be an interesting area to investigate in the future.

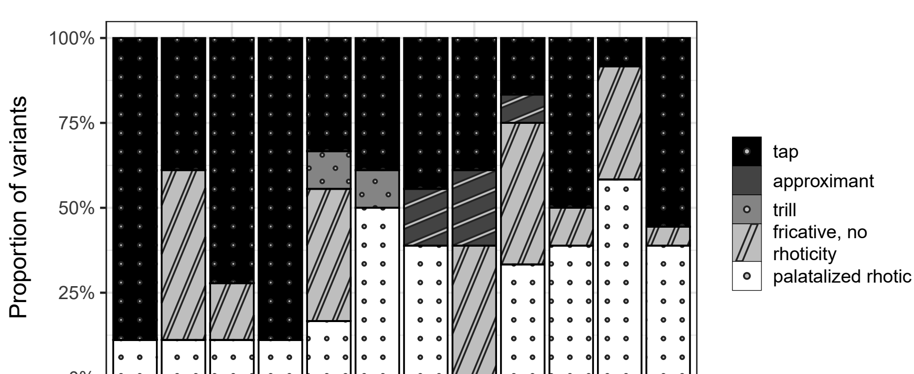

FIGURE 5. More detailed auditory labeling of just /rʲ/ according to speaker. Speakers are ordered by age (youngest on the left, oldest on the right).

The results of our comparison to the Lewis data points in the SGDS are shown in Figure 6. Note that these data consider word-final rhotics only. The SGDS data show a very clear three-way split, with the /rˠ/ realized as trills, the /r/ as taps, and the /rʲ/ as palatalized fricatives/rhotics. We have not attempted to break down the palatalized 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.

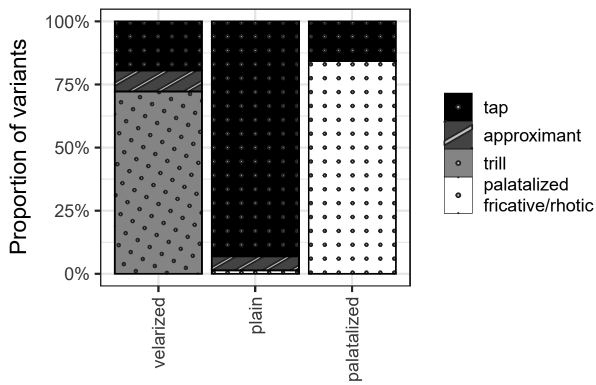

FIGURE 6. Word-final rhotics in the Survey of the Gaelic Dialects of Scotland.

To summarize: our auditory analysis reveals differences in realization of the three phonemic categories, with /rʲ/ demonstrating audible palatalization, and /rˠ/ 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 appear to show less clear-cut distinctions between phonemic categories. We return to this finding in §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 report on the acoustic differences between the three rhotic phonemes. As described above, in word-initial position we measured (i) F2 − F1 at 80% of rhotic duration, (ii) F3 − F2 at 80% of rhotic duration, (iii) F2 − F1 at 20% of vowel duration, and (iv) F3 − F2 at 20% of vowel duration. In word-final position, we measured (i) F2 − F1 at 80% of vowel duration, (ii) F3 − F2 at 80% of vowel duration, and (iii) COG centered on 80% of rhotic duration. These results are shown in Figure 7 for word-initial and Figure 8 for word-final tokens. A breakdown of results according to the three vowel contexts is given in Appendix E, Figures A4 and A5.

Statistical testing as detailed in §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 via post-hoc testing. The results of these models are shown in Tables 5–8.

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

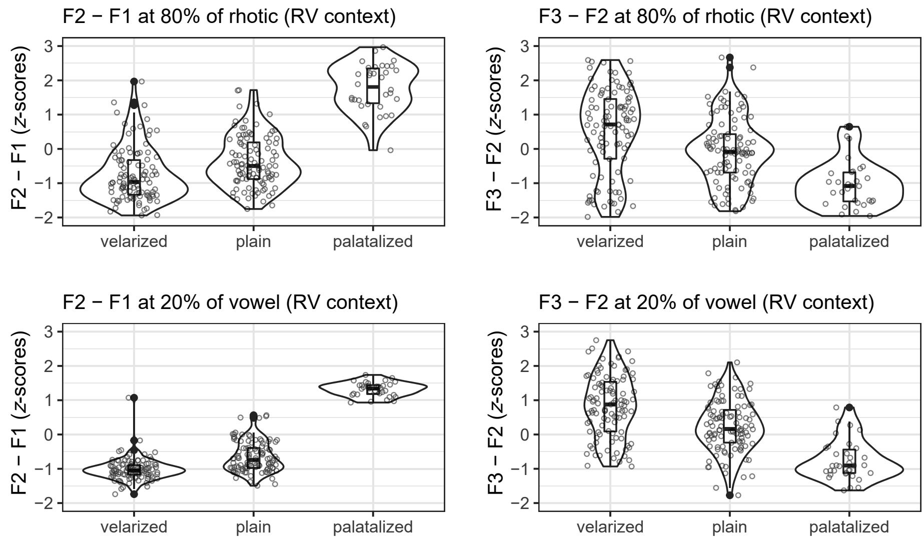

FIGURE 7. Acoustic measures of word-initial rhotics and following vowels.

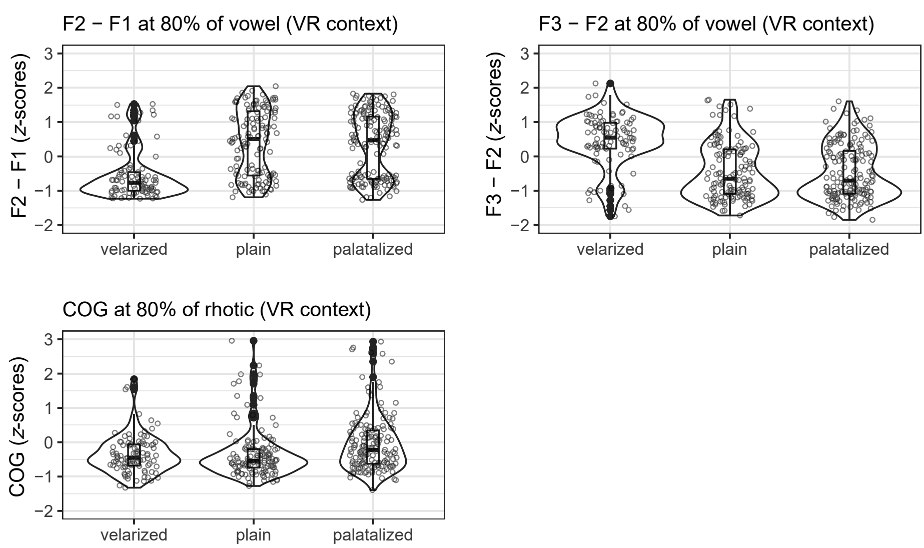

FIGURE 8. Acoustic measures of word-final rhotics and preceding vowels.

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 above shows that vowels pre-

	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	< 0.001			2	75.26	< 0.001
Vowel			2	66.09	< 0.001			2	31.41	< 0.001
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	< 0.001	0.58	0.12	346	4.80	< 0.001
$r^ɣ$ - r^j	−2.15	0.24	12.4	−8.82	< 0.001	1.93	0.22	346	8.99	< 0.001
r - r^j	−1.67	0.24	12.5	−7.06	< 0.001	1.35	0.20	346	6.63	< 0.001
a - u	−0.73	0.10	317	−6.97	< 0.001	−0.64	0.14	346	−4.58	< 0.001
a - i	−0.81	0.10	318	−7.74	< 0.001	−0.74	0.14	346	−5.25	< 0.001
u - i	−0.08	0.10	317	−0.80	0.70	−0.10	0.14	346	−0.70	0.77

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 were 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	< 0.001			2	23.24	< 0.001
Vowel			11	67.91	< 0.001			2	8.47	0.01
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	< 0.001	0.74	0.12	5.38	6.45	0.002
$r^ɣ$ - r^j	−2.05	0.11	11.2	−18.30	< 0.001	1.62	0.19	3.62	8.38	0.003
r - r^j	−1.48	0.11	11.2	−13.96	< 0.001	0.88	0.21	8.69	4.15	0.007
a - u	−0.37	0.09	12.2	−4.35	0.002	−0.33	0.12	361	−2.82	0.01
a - i	−0.62	0.08	11.5	−8.21	< 0.001	−0.20	0.12	361	−1.69	0.21
u - i	−0.24	0.10	12.9	−2.52	0.06	0.13	0.12	361	1.14	0.49

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	< 0.001			2	22.92	< 0.001
Vowel			2	47.06	< 0.001			2	26.98	< 0.001
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	0.003	0.57	0.19	12.9	3.06	0.02
$r^ɣ$ - r^j	−0.92	0.13	13.0	−7.17	< 0.001	0.90	0.14	12.4	6.59	< 0.001
r - r^j	−0.30	0.07	11.7	−4.34	0.003	0.32	0.11	12.7	2.91	0.03
a - u	−0.97	0.10	12.2	−9.96	< 0.001	0.81	0.10	12.3	7.84	< 0.001
a - i	−1.41	0.08	12.1	−17.34	< 0.001	0.86	0.13	12.8	6.63	< 0.001
u - i	−0.43	0.14	13.0	−3.19	0.02	0.05	0.15	13.0	0.34	0.94

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

ceding /$r^ɣ$/ 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.

			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	< 0.001
Vowel			2	11.21	0.003
POST-HOC TESTS	$\hat{\beta}$	$SE(\hat{\beta})$	df	t	$p(t)$
$r^ɣ$ - r	0.04	0.10	12.0	0.43	0.90
$r^ɣ$ - r^j	−0.33	0.14	13.2	−2.46	0.07
r - r^j	−0.38	0.08	12.3	−4.53	0.002
a - u	0.22	0.08	478	2.78	0.02
a - i	0.21	0.07	481	3.03	0.007
u - i	−0.005	0.07	478	−0.06	0.99

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 was run with only a random intercept for speaker.

Table 8 considers COG measures at 80% of word-final rhotic duration. There is a significant effect of phoneme, and /r^j/ has a significantly different COG from /r/. Vowel phoneme is significant for predicting COG, but not for differentiating /u/ and /i/.

To summarize: 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 /$r^ɣ$/, and F3 − F2 significantly higher. /r^j/ has the highest F2 − F1 and lowest F3 − F2. COG is significantly different in /r^j/ compared to /r/. We now consider how these contrasts are realized in articulation via examination of midsagittal tongue shape.

3.3. Ultrasound analysis. So far, the acoustic analysis has shown significant differences in formant and COG values between phonemic categories, both in the rhotic itself and 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 in order to explore individual variation in tongue shapes used. We then report a PCA that aims to summarize the most salient dimensions of tongue-shape variation between speakers, which helps us form generalizations 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 in the top row, and tip-up speakers are in 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 include 'f' for female and 'm' for male), but we note that our small sample size makes such generalizations difficult to make. Accordingly, we propose that this likely represents speaker-specific variation, as reported for rhotics in other languages (Mielke et al. 2016). In Figure 10 we have plotted the audi-

[3] This figure is presented in color in the electronic versions of this article, but in grayscale in the print version. The color version is also available at https://osf.io/xvfpw/.

tory 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 imperceptible, perhaps representing motor-equivalent strategies for producing an audibly similar output. We consider this possibility in much greater detail in the discussion (§4).

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

Our second ultrasound analysis employs PCA in order to summarize 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 PCs together explain 88% of the data. The respective proportions were: PC1 49%, PC2 21%, PC3 11%, PC4 7%. The loadings of the first four PCs 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.

The values of the first four PCs were tested via linear mixed-effects regression modeling, as described in §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.

In word-initial position, there is a significant effect of rhotic phoneme on PC1, PC2, and PC3. For PC1, /rˠ/ has the lowest value and /rʲ/ significantly the highest. For PC2, /rʲ/ has the highest values, but /rˠ/ and /r/ rhotics are not significantly different. For PC3, /rˠ/ rhotics again have the lowest value and /rʲ/ the highest. The 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 /rʲ/ have significantly higher values than /rˠ/. 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 Fig. 11, we can make the following generalizations. In word-initial position, /rˠ/ has a backer tongue shape, /rʲ/ is more fronted, and /r/ lies somewhere in the middle. /rʲ/ has a higher tongue middle, and /r/ and /rˠ/ are similar. /rˠ/ has the lowest overall tongue shape, /rʲ/ the highest, and /r/ somewhere in between. In word-final position, /rˠ/ has a backer tongue shape, but /rʲ/ and /r/ are generally similar. In summary, our ultrasound analysis shows some individual differences in tongue-shape strategy to achieve the Gaelic phonemic contrast. Across the data set though, there is a general tendency to produce /rʲ/ with a fronting gesture and /rˠ/ with tongue lowering and backing. The phonemic differences are greatest in word-initial position.

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

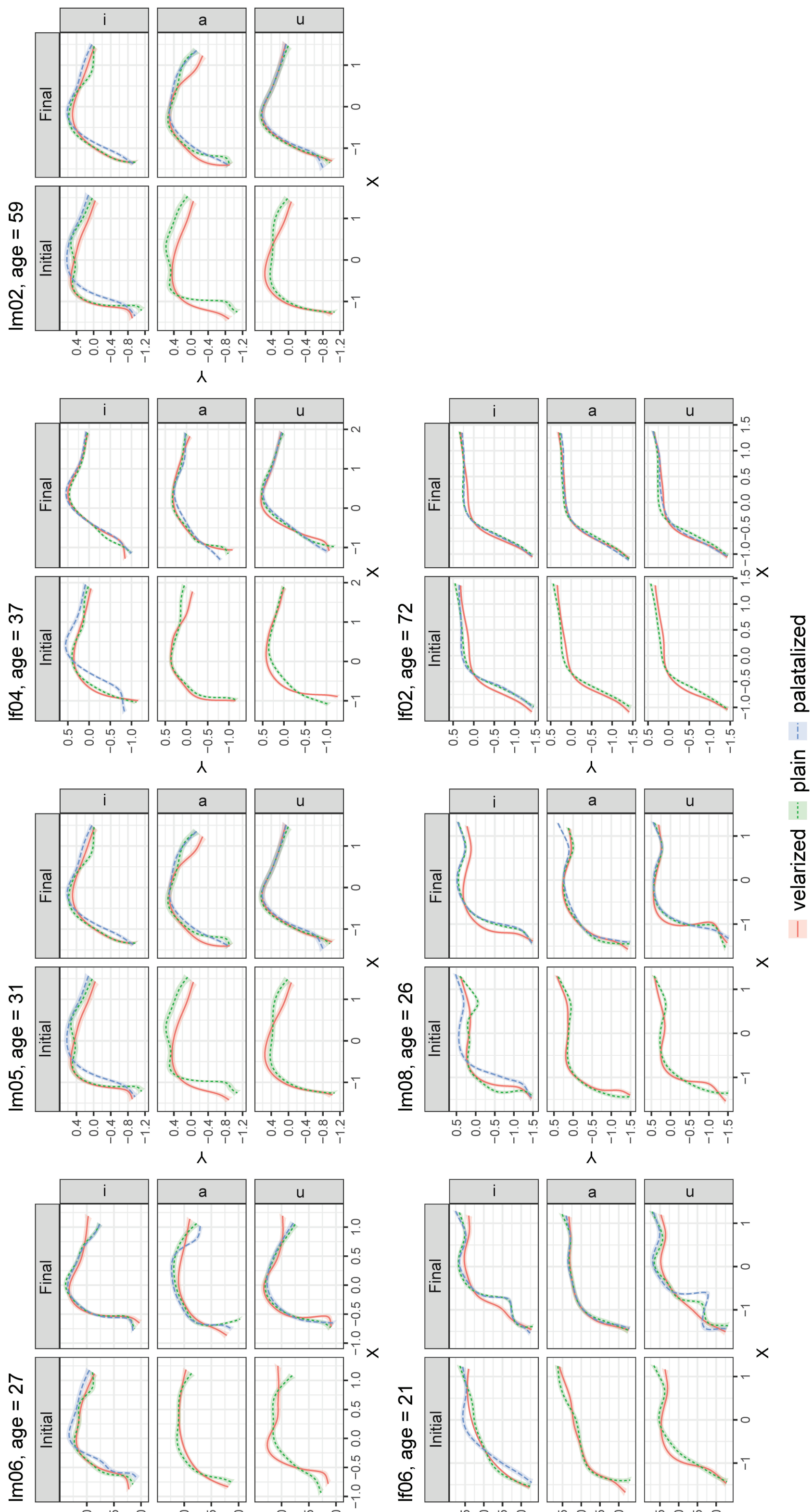

FIGURE 9. Generalized additive models fitted to midsagittal tongue spline data, split by word position and vowel context. Each panel represents a single speaker. The lines represent the mean estimate for that context.

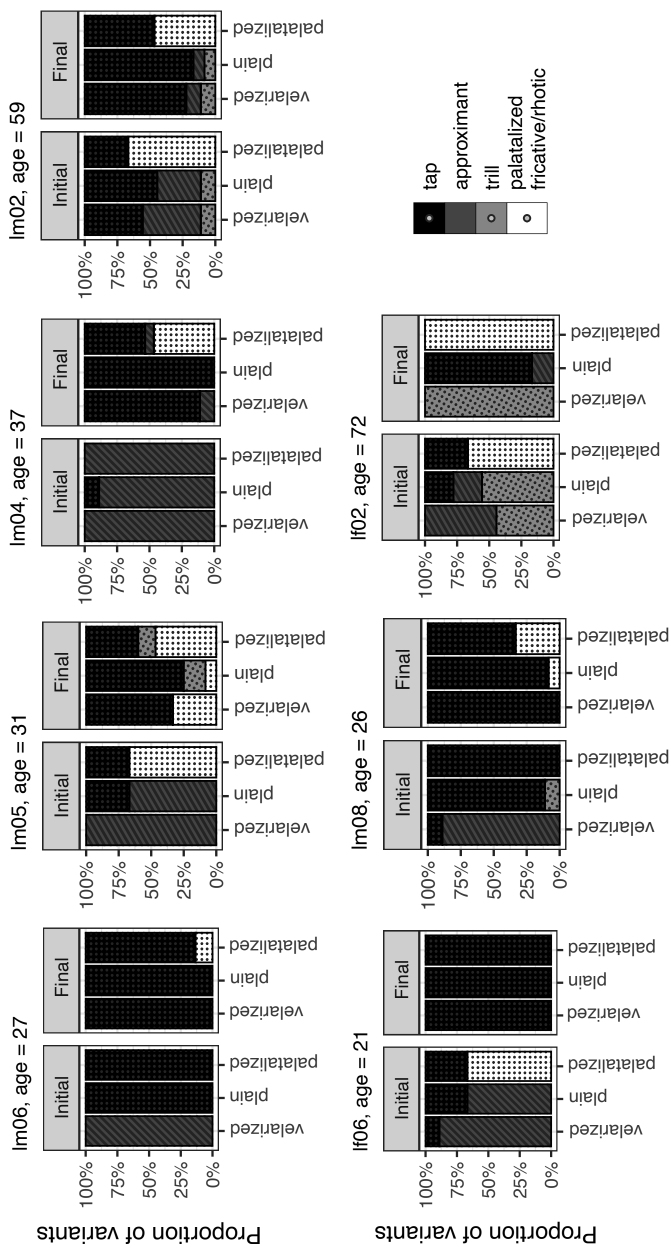

FIGURE 10. Results of the auditory coding for the individual speakers involved in the ultrasound analysis. Speakers are ordered as in Fig. 9 above to show maximum comparability.

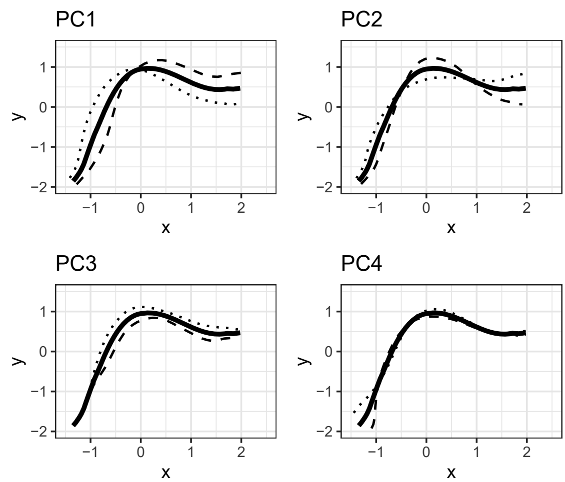

FIGURE 11. Variation captured by the first four PCs. In each panel, the thick black line shows the mean tongue spline for all of the data from all speakers. The dashed line shows mean tongue spline plus the value of each loading multiplied by the standard deviation of PC scores. The dotted line shows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

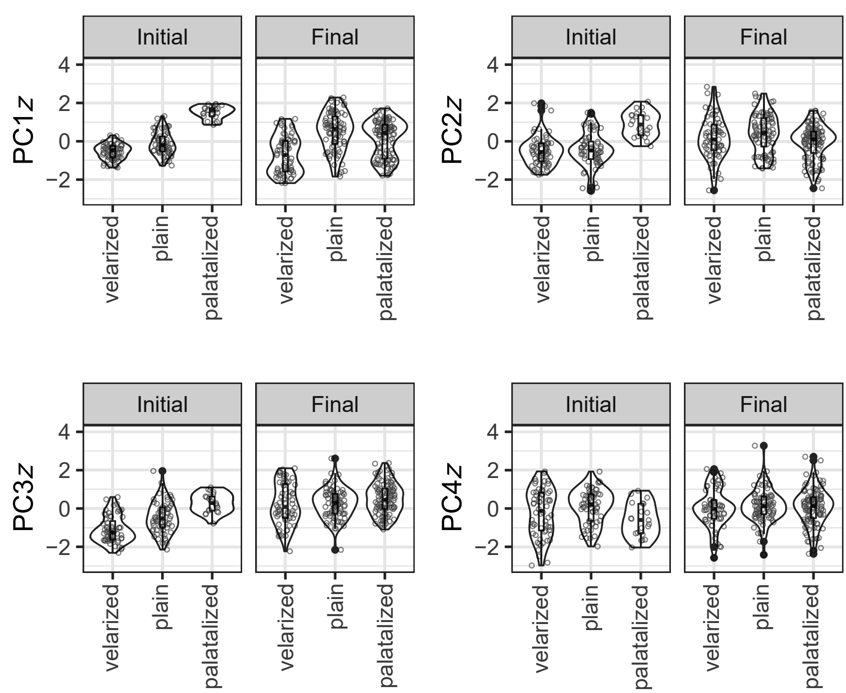

FIGURE 12. Values of the first four PCs for each phoneme and word position.

we summarize 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.

	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	< 0.001			16	120.06	< 0.001
Vowel			2	3.93	0.14			2	5.35	0.07
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	0.04	−0.02	0.27	8.14	−0.09	0.10
$r^{ɣ}$ - r^{j}	−2.08	0.17	7.79	−11.96	< 0.001	−1.36	0.33	7.85	−4.17	0.008
r - r^{j}	−1.67	0.26	8.06	−6.55	< 0.001	−1.33	0.18	6.95	−7.41	< 0.001
a - u	−0.47	0.23	8.15	−2.10	0.15	−1.04	0.41	8.15	−2.53	0.08
a - i	−0.18	0.12	7.90	−1.57	0.31	−0.54	0.21	8.08	−2.51	0.08
u - i	0.29	0.14	8.13	−3.05	0.04	−0.02	0.27	8.14	−0.09	0.10

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

	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	< 0.001			2	3.95	0.14
Vowel			2	10.51	0.005			2	0.53	0.77
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	0.02	−0.36	0.26	8.16	−1.38	0.40
$r^{ɣ}$ - r^{j}	−1.71	0.19	6.51	−9.27	< 0.001	0.35	0.44	7.67	0.78	0.73
r - r^{j}	−1.07	0.23	7.01	−4.72	0.005	0.70	0.39	7.60	1.79	0.24
a - u	0.03	0.22	7.86	0.13	0.99	0.18	0.26	7.31	0.70	0.77
a - i	0.50	0.19	7.30	2.58	0.08	0.09	0.31	7.74	0.30	0.95
u - i	0.47	0.15	6.61	3.19	0.04	−0.09	0.28	7.10	−0.32	0.95

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	144.30	< 0.001			2	4.94	0.08
Vowel			2	23.82	< 0.001			2	14.99	< 0.001
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	0.009	−0.13	0.27	8.14	−0.49	0.88
$r^{ɣ}$ - r^{j}	−0.86	0.11	6.87	−8.09	< 0.001	0.14	0.20	7.83	0.72	0.76
r - r^{j}	0.18	0.21	7.97	0.82	0.70	0.27	0.14	7.16	1.93	0.20
a - u	−1.26	0.20	7.92	−6.37	< 0.001	−1.27	0.23	8.10	−5.50	0.001
a - i	−1.69	0.13	7.92	−12.83	< 0.001	−1.25	0.19	8.06	−6.68	< 0.001
u - i	−0.43	0.20	7.88	−2.12	0.15	0.02	0.15	7.75	0.11	0.99

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

4.1. SUMMARY OF RESULTS: SECONDARY ARTICULATIONS IN GAELIC RHOTICS. Our results provide evidence for different realizations of phonemic rhotics in both word-initial and word-final contexts. The auditory analysis (Fig. 2) suggests that word-initial /$r^{ɣ}$/ is most frequently an approximant, /r/ is an approximant or tap, and /r^{j}/ is mainly a tap or a palatalized fricative/rhotic. In word-final position, taps are the most common realiza-

	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	0.29			2	0.33	0.85
Vowel			2	5.54	0.06			2	0.93	0.63
POST-HOC TESTS	$\hat{\beta}$	$SE(\hat{\beta})$	df	t	$p(t)$	$\hat{\beta}$	$SE(\hat{\beta})$	df	t	$p(t)$
r^{γ} - r	−0.09	0.20	7.78	−0.44	0.90	−0.11	0.22	7.69	−0.52	0.86
r^{γ} - r^{j}	−0.23	0.19	7.89	−1.19	0.49	−0.05	0.29	8.12	−0.18	0.98
r - r^{j}	−0.14	0.11	6.13	−1.30	0.45	0.06	0.25	8.02	0.25	0.97
a - u	0.59	0.27	8.16	2.15	0.14	−0.21	0.24	7.77	−0.86	0.68
a - i	0.75	0.28	8.15	2.67	0.06	−0.10	0.30	8.14	−0.33	0.94
u - i	0.16	0.14	8.12	1.13	0.52	0.11	0.22	7.92	0.51	0.87

TABLE 12. Regression models for word-final PC3 and PC4.

tion for /r^{γ}/ and /r/. /r^{j}/ tokens are either taps, palatalized rhotics, or a fricative with some kind of palatalization. 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 fully trilled productions are noted to be rare, especially in palatalized contexts (Lindau 1985, Spajić et al. 1996, Iskarous & Kavitskaya 2010, Stoll 2017).

A summary of the results from the acoustic and articulatory (PCA) analyses is shown in Table 13, focusing on the significant differences between phonemic categories. In word-initial position, there were 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 a significant difference only between /r^{j}/ compared to /r/ and /r^{γ}/ together. These results pattern closely with other studies of palatalization across rhotics and other segments, indicating that the acoustic signature for palatalization extends substantially into the surrounding vowels (Kochetov 2017, Howson 2018, Iskarous & Kavitskaya 2018).

WORD POSITION	MEASURE	/r^{γ}/ DIFFERENT FROM /r/	/r^{γ}/ 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 that a significant difference was found, 'n.s.' that no significant difference was found.

In general, our ultrasound analysis shows that /r^{j}/ is produced with fronted and raised tongue shapes, and /r^{γ}/ 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 produce rhotics either with a tongue-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 these two strategies to be correlated with sociolinguistic variation in our sample, and they do not appear to have consistently different auditory realizations. 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).

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 than in the PCA analysis. Also, as can be seen by comparing Fig. 9 and Fig. 10, the auditory impressions do not always align perfectly with differences in tongue shape. In other respects, however, there are strong correspondences between the different sources of data, in that generally there were more differences between phoneme categories in word-initial than word-final position (discussed in detail in §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 §4.3.

4.2. EVIDENCE FOR THE THREE-WAY CONTRAST IN GAELIC. The auditory, acoustic, and articulatory evidence we present here largely supports proposals of 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 nonconjugated form, with a high front vowel following the rhotic and thus perhaps making it susceptible to being produced with a high, front, palatalized tongue shape. Classic accounts of Gaelic phonology, such as Borgstrøm 1940 and Oftedal 1956, see the word-initial palatalized rhotic as a separate phoneme, despite its highly limited context. Our analysis demonstrates that there is a separate phonetic realization 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, Ladefoged et al. 1998). Our account further supports the view that evidence from less prototypical and minority languages such as Gaelic is important for understanding the full nature of phonological typology, as well as the structure of the world's languages.

We observed in Fig. 5 that there might be a pattern according to speaker age, whereby younger speakers produce fewer phonetically palatalized fricatives/rhotics and especially fewer palatalized rhotics. This may possibly indicate change in the future, but we cannot say conclusively due to the size of the current data set, despite the fact that our data represents a sizeable sample of the very small community under study. The inclusion of data from the SGDS does, however, allow some comparison to speakers born at the turn of the twentieth century. The youngest participant in the SGDS sample was twenty years older than our oldest participant. Word-final rhotics in the SGDS sample show a clear picture of place and manner of articulation distinguishing the three categories, which was less clear in our data. The SGDS sample was collected mainly by Magnus Oftedal a few years after he wrote his monograph on Lewis Gaelic (Oftedal 1956), and 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 unattested in the SGDS, such as a high number of approximants in word-final position. We suggest that the differences between the two data sets probably do not represent sound change, but rather a transcriber bias in the SGDS toward what rhotics are 'supposed to be' in Oftedal's analysis of the phonemic structure of Gaelic. The elicitation methods in the SGDS also included several repetitions and explicit instruction toward a canonical production, after which the fieldworkers selected a 'representative' variant. We do not criticize the SGDS in this respect, but instead suggest that the different methodology employed in our study is more likely to be responsible for the differences in results in this case, rather than sound change. 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 around 1100 CE.

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, 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 palatalization, including some dental fricatives, or as a (phonetically) palatalized rhotic. We also found some approximants and trills, and we therefore propose that the palatalized category should be considered 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 palatalized rhotic is a common realization of this phonemic category in Lewis.

Analysis of 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 proposed that, unlike taps, trills are characterized by a current of air passing over a narrow aperture and producing a vibration via the Bernoulli effect (McGowan 1992, Ladefoged & Maddieson 1996:217). Taps, by contrast, are characterized by one muscular movement of the tongue tip/blade, which is not extended to include multiple vibrations. As stated by Recasens and 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's (1985) crosslinguistic analysis and in Spajić et al. 1996, as well as some detailed studies of Russian trills (Iskarous & Kavitskaya 2010, Stoll 2017). In Russian, the palatalized rhotics in particular are less likely than nonpalatalized rhotics to be realized as full trills (Iskarous & Kavitskaya 2010:630). Our data do contain some trilled realizations across contexts and across phonemes. The evidence above suggests that these are unlikely to be underlying taps that surface as trills. We therefore propose that a suitable representation for Gaelic rhotics would be trills with secondary articulations, that is, /$r^ɣ$, r, r^j/.

4.3. Sound change and phonetic typology. Classic models of sound change, such as Ohala 1981, 1989, and 2012, and more recent developments, such as Blevins 2009, suggest that there are perceptual and articulatory explanations for how and why features such as palatalized rhotics are lost. Specifically, perceptually ambiguous sounds may be misperceived, while articulatorily challenging segments are disfavored over time. Indeed, the research summarized in §1 suggests that large rhotic systems are typologically unusual and that palatalized rhotics are particularly subject to loss in Indo-European and in other Goidelic varieties. In Slavic, palatalized rhotics are maintained in all positions in Russian and Lower Sorbian, maintained to some extent in Ukrainian, Upper Sorbian, and Bulgarian, spirantized 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 crosslinguistic tendency toward 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, the Gaelic rhotics are rarely realized as full trills and are more commonly realized as an approximant, tap, or tap plus voiceless frication. In particular, we were interested in how speakers might resolve the articulatory conflict between palatalization and trilling in order to distinguish the phonemically palatalized rhotic. It appears that one strategy for resolving this conflict is simply not to produce a full trill with several vibration cycles. This is not uncommon in languages that maintain palatalized rhotics, and even in those described as having palatalized trills, such as Toda and Russian (Lindau 1985, Spajić et al. 1996, Iskarous & Kavitskaya 2010). For example, Iskarous and Kavitskaya (2010:630) report for Russian that 26% of the plain rhotics were fully trilled, but only 1% of the phonemically palatalized rhotics. It appears, therefore, that speakers of Scottish Gaelic use adaptation of articulatory strategies to preserve palatalization, reducing the incompatibility between primary and secondary articulations. That said, this strategy alone does not eliminate the challenges posed by simultaneous rhoticity and palatalization, which we now address further.

A second mechanism behind how 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 Fig. 9, which lead to substantial acoustic differences between the phonemic categories. This may represent motor-equivalent ways of addressing the articulatory challenges posed by simultaneous rhoticity and palatalization. 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 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 similarity 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 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 vs. word-final positions. 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). Crosslinguistically, it is very common for rhotics to behave quite differently in syllable onset and coda positions. For example, Standard German rhotics are frequently vocalized in coda position, but not 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 1993:29). Gaelic is described as a VC language, though, so it 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-final tokens to 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 productions 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 understanding why these strategies are deployed by speakers. Accordingly, a fourth and final factor is the production aims of the speakers themselves. As discussed in §1, 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 revitalization. Speakers such as those recorded for our study are well aware of their role in the revitalization movement. Additionally, they all were working or had worked in occupations requiring the use of Gaelic. Gaelic's status as a revitalizing 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 et al. 2016. Here, fluent L2 users of Gaelic showed that individual accent aims 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 'foregone 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. Authors agree that the Middle Irish three-way rhotic contrast has been reduced in modern Irish dialects to a two-way distinction between palatalized and nonpalatalized (Ní Chasaide 1999, Ní Chiosáin & Padgett 2012, Hickey 2014). Hickey (2014:95–96) suggests that the contrast in Modern Irish is neutralized in word-initial position, with an approximant being the most common variant. In word-final position, spirantization and devoicing of the palatalized phoneme to [ʐ] or [ʂ] is very common, especially in western Irish dialects. Hickey's (2014:97) 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 nonpalatalized word-final rhotics are produced as [ɻ] due to influence from Irish English (Hickey 2014:97).

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 distinguishes /rʲ/ in a small subset of words. Second, in word-final position, all Gaelic rhotics are devoiced, rather than just /rʲ/. 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 palatalization or nonpalatalization. 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 palatalization 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 realizations 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 they 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 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 maximize 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 crosslinguistic 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.

Appendix A: Example spectrograms and waveforms

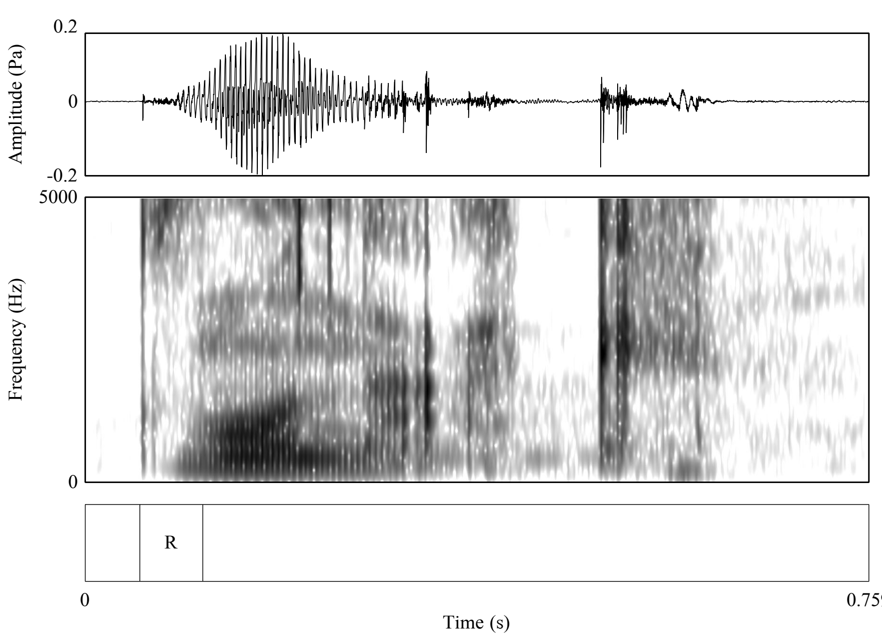

Figure A1. Example spectrogram and waveform of word-initial /rˠ/, from *rionnag* ‘star’. Spoken by female speaker lf04 and realized here as an approximant.

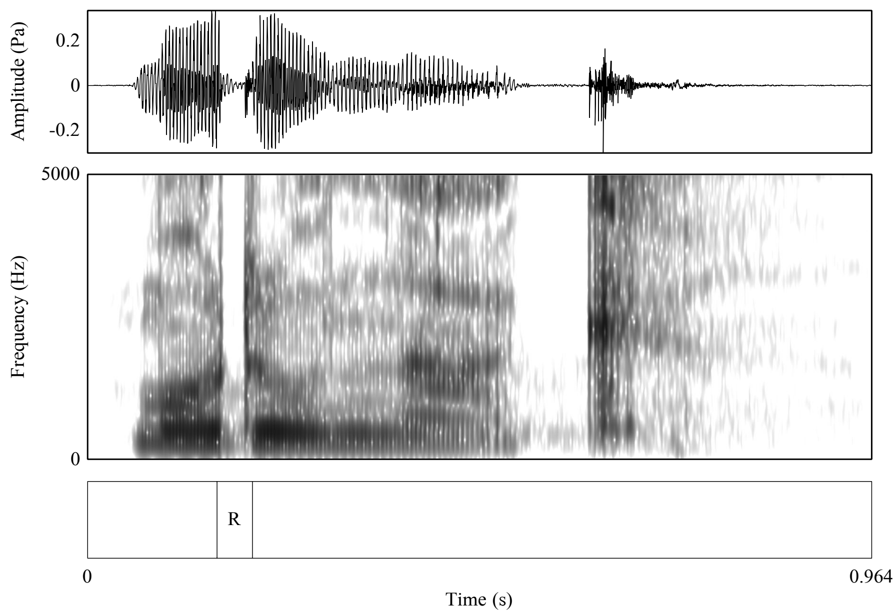

FIGURE A2. Example spectrogram and waveform of word-initial /r/, from *mo rionnag* 'my star'. Spoken by female speaker lf04 and realized here as a tap.

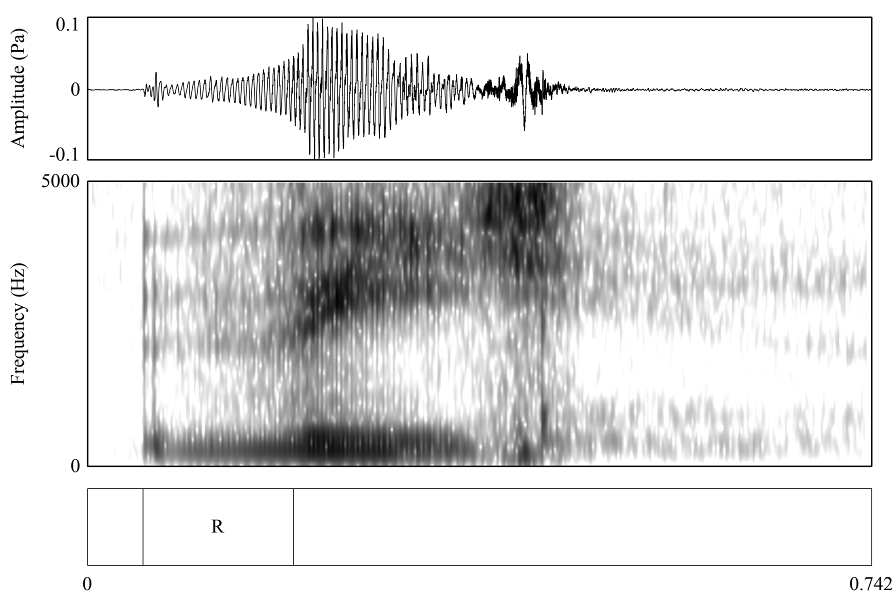

FIGURE A3. Example spectrogram and waveform of word-initial /rʲ/, from *ri* 'to'. Spoken by female speaker lf04 and realized here as a fricative with no audible rhoticity.

Appendix B: Auditory coding categories

narrow transcription	broader category
ɾ	tap
ɾ̥	tap
r	trill
r̥	trill
ɹ	approximant
ɹ̥	approximant
ɻ	approximant
ɻ̊	approximant
ɾð	palatalized fricative/rhotic
ɾθ	palatalized fricative/rhotic
ð	palatalized fricative/rhotic
θ	palatalized fricative/rhotic
ʒ	palatalized fricative/rhotic
ʃ	palatalized fricative/rhotic
dʒ	palatalized fricative/rhotic
tʃ	palatalized fricative/rhotic
ɕ	palatalized fricative/rhotic
ɾɕ	palatalized fricative/rhotic
v	palatalized fricative/rhotic
s	palatalized fricative/rhotic
ɚ	weakly rhotic/nonrhotic
ə	weakly rhotic/nonrhotic
ø	weakly rhotic/nonrhotic

Table A1. Categories for auditory coding.

Appendix C: Interpreting the SGDS transcriptions

Table A2 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, pp. 130–34. We have focused 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’.

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	palatalized fricative/rhotic
ð̥	ð̥	palatalized fricative/rhotic
ð’	ðʲ	palatalized fricative/rhotic
ð̥’	ð̥ʲ	palatalized fricative/rhotic
ðh	ðh	palatalized fricative/rhotic

Table A2. SGDS transcriptions and our interpretation.

APPENDIX D: EXTRA INFORMATION ON REGRESSION MODELS

POSITION	MEASURE	FULL MODEL FORMULA	*N* (GROUPS)	AUC FULL	AUC NULL
Combined	palatalization	palatalization ~ phoneme + vowel + (vowel + phoneme|speaker)	871 (spkr: 12)	0.95	0.77

POSITION	MEASURE	FULL MODEL FORMULA	*N* (GROUPS)	AIC FULL	AIC NULL
Initial	rhotic F2 − F1	F2−F1 ~ phoneme + vowel + (phoneme|speaker)	354 (spkr: 12)	864.84	938.49
	rhotic F3 − F2	F3−F2 ~ phoneme + vowel + (1|speaker)	354 (spkr: 12)	1038.24	1122.37
	vowel F2 − F1	F2−F1 ~ phoneme + vowel + (vowel + phoneme|speaker)	357 (spkr: 12)	606.40	653.63
	vowel F3 − F2	F3−F2 ~ phoneme + vowel + (phoneme|speaker)	357 (spkr: 12)	918.80	942.39
Final	vowel F2 − F1	F2−F1 ~ phoneme + vowel + (vowel + phoneme|speaker)	509 (spkr: 12)	907.40	953.80
	vowel F3 − F2	F3−F2 ~ phoneme + vowel + (vowel + phoneme|speaker)	509 (spkr: 12)	1016.90	1048.67
	rhotic COG	COG ~ phoneme + vowel + (phoneme|speaker)	503 (spkr: 12)	1049.10	1070.36
Initial	PC1	PC1 ~ phoneme + vowel + (vowel + phoneme|speaker)	147 (spkr: 7)	129.95	148.95
	PC2	PC2 ~ phoneme + vowel + (vowel + phoneme|speaker)	147 (spkr: 7)	277.98	294.83
	PC3	PC3 ~ phoneme + vowel + (vowel + phoneme|speaker)	147 (spkr: 7)	336.52	349.13
	PC4	PC4 ~ phoneme + vowel + (vowel + phoneme|speaker)	147 (spkr: 7)	460.05	456.35
Final	PC1	PC1 ~ phoneme + vowel + (vowel + phoneme|speaker)	252 (spkr: 7)	472.75	498.31
	PC2	PC2 ~ phoneme + vowel + (vowel + phoneme|speaker)	252 (spkr: 7)	604.90	613.43
	PC3	PC3 ~ phoneme + vowel + (vowel + phoneme|speaker)	252 (spkr: 7)	616.20	616.66
	PC4	PC4 ~ phoneme + vowel + (vowel + phoneme|speaker)	252 (spkr: 7)	671.51	666.24

TABLE A3. 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. AUC was calculated using the ModelMetrics package (Hunt 2020).

Appendix E: Acoustic measures according to vowel context

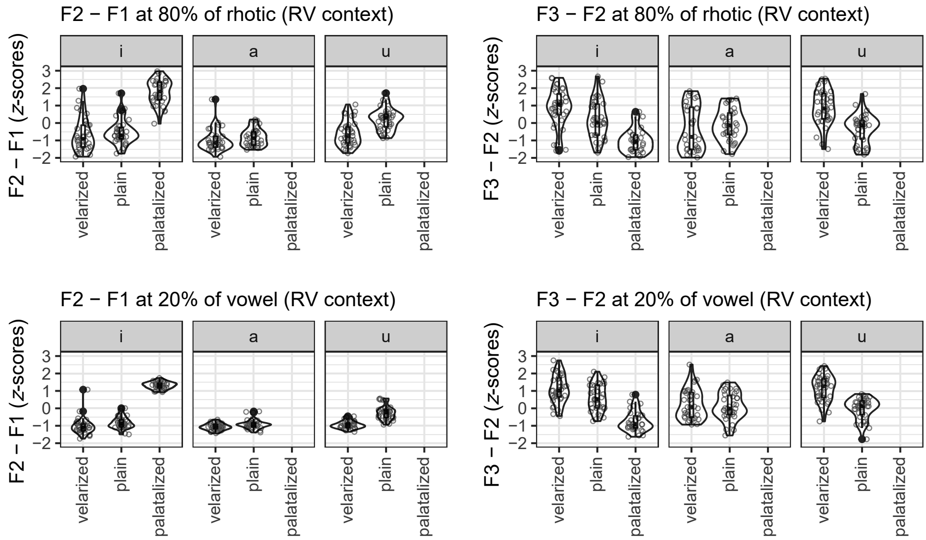

Figure A4. Acoustic measures of word-initial rhotics and following vowels according to vowel context.

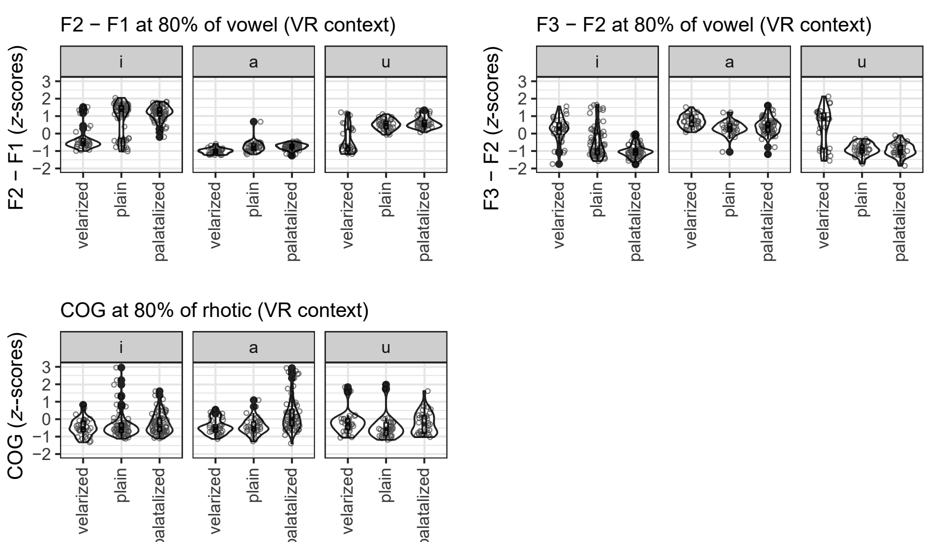

Figure A5. Acoustic measures of word-final rhotics and preceding vowels according to vowel context.

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