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The acoustics of three-way lateral and nasal palatalisation contrasts in Scottish Gaelic

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ABSTRACT:
This paper presents an acoustic description of laterals and nasals in an endangered minority language, Scottish Gaelic (known as "Gaelic"). Gaelic sonorants are reported to take part in a typologically unusual three-way palatalisation contrast. Here, the acoustic evidence for this contrast is considered, comparing lateral and nasal consonants in both word-initial and word-final position. Previous acoustic work has considered lateral consonants, but nasals are much less well-described. An acoustic analysis of twelve Gaelic-dominant speakers resident in a traditionally Gaelic-speaking community is reported. Sonorant quality is quantified via measurements of F2–F1 and F3–F2 and observation of the whole spectrum. Additionally, we quantify extensive devoicing in word-final laterals that has not been previously reported. Mixed-effects regression modelling suggests robust three-way acoustic differences in lateral consonants in all relevant vowel contexts. Nasal consonants, however, display lesser evidence of the three-way contrast in formant values and across the spectrum. Potential reasons for lesser evidence of contrast in the nasal system are discussed, including the nature of nasal acoustics, evidence from historical changes, and comparison to other Goidelic dialects. In doing so, contributions are made to accounts of the acoustics of the Celtic languages, and to typologies of contrastive palatalisation in the world's languages.
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I. INTRODUCTION

This paper provides an acoustic description of a typologically unusual three-way contrast in Gaelic[1] sonorants. In Gaelic, along with the other Goidelic Celtic languages, most consonants are members of either a palatalised or non-palatalised series. This system of contrastive palatalisation as a secondary articulation across the consonant system is well-described for Celtic and Slavic (Kochetov, 2002; Spinu *et al*., 2012). Cross-linguistically, secondary palatalisation was found to occur in 27% of a sample of 117 languages [Bateman (2007), p. 50]. In sonorant consonants, instead of the palatalised vs non-palatalised contrast, Gaelic (and some dialects of Irish) is reported to have a three-way contrast between palatalised, alveolar, and velarised counterparts (Nance and Ó Maolalaigh, 2019; Ní Chasaide, 1999). While this system has been the subject of some previous work (Ladefoged *et al*., 1998; Nance, 2014), we here extend and build upon earlier work and present a detailed comparison of word-initial and word-final laterals and nasals in three vowel contexts. Word-final laterals, and nasal consonants in any position, have not previously been the subject of systematic acoustic analysis in Gaelic. In presenting our analysis, we give an up-to-date acoustic description of this unusual contrast in the context of Gaelic as an endangered, minority language, which may be subject to rapid change (Dorian, 1981; Nance, 2015). Our participants are twelve L1, Gaelic-dominant adults who were born and raised in a Gaelic heartland community, the Isle of Lewis. In the context of Gaelic as a minoritised language, our sample represents an important proportion of the Gaelic-dominant community in a traditional Gaelic-speaking area.

A. Context of Gaelic

Gaelic is a Celtic language, closely related to Irish. In 2011, when the last census was conducted, there were around 58 000 Gaelic speakers in Scotland (1.1% of the population) (Scottish Government, 2015). While Gaelic was widely spoken in early medieval Scotland, speaker numbers have declined since census records began. The densest Gaelic-speaking communities are now in the north-west Highland and Island areas, especially the Outer Hebrides. On the Isle of Lewis, where the data for this study were collected, approximately 60% of the population can speak Gaelic, making the island one of the highest concentrations of Gaelic speakers in the world (Scottish Government, 2015). A map showing the location of Lewis within the United Kingdom is shown in Fig. 1. Since the later twentieth century, Gaelic has been undergoing a programme of revitalisation (McLeod, 2006). One of the important components of this programme has been the Gaelic Language Act (Scotland), which affords the language the same legal status as English in Scotland (Scottish Parliament, 2005).

As part of revitalisation measures, parents across Scotland can now request that their child be educated

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FIG. 1. A map of the United Kingdom showing the location of the Isle of Lewis.

through the medium of Gaelic. Gaelic Medium Education is currently available in 14 out of 32 council areas in Scotland (Education Scotland, 2019), and nearly 6800 children received their education through Gaelic in 2018–2019 (Bòrd na Gàidhlig, 2019). The revitalisation programme has also led to the development of many other Gaelic language initiatives such as BBC Alba, the Gaelic TV channel, and BBC Radio nan Gàidheal, the Gaelic radio channel (Cormack, 2006). As such, there has been an increase in the number of graduate-level jobs requiring command of Gaelic. These opportunities are available in cities such as Glasgow and Edinburgh, but also in Highland and Island communities such as Stornoway on Lewis, where these data were collected.

The most recent detailed survey study of language use in a community on the Isle of Lewis suggested that although over 60% of residents reported fluent ability in Gaelic, this ability is concentrated in the 50+ age bracket and tails off heavily among younger age groups (Munro *et al.*, 2011). This finding is echoed in analysis of the 2011 National Census, which shows that age-related ability is similar across Scotland (Scottish Government, 2015). In terms of family usage, Gaelic in Lewis is most used in households of one or two people where people are aged 50 or older [Munro *et al.* (2011), p. 9]. The report also refers to intergenerational transmission as "broken" in this community, although it remains one of the most heavily Gaelic-speaking communities [Munro *et al.* (2011), p. 10]. The research in the report of Munro *et al.* (2011) confirms Nance (2013, 2015), who found that it is now very rare for a young person to grow up in an exclusively Gaelic-speaking household. On leaving the school system, it is also now rare for young people to continue using Gaelic as part of their adult lives (Dunmore, 2019). All of this research demonstrates the highly minoritised status of Gaelic and some of the social barriers that can impede its usage.

B. Sonorants in the Goidelic languages

Contrastive palatalisation is one of the major features that distinguishes Goidelic Celtic languages (Irish, Gaelic, Manx) from Brythonic Celtic languages (Welsh, Breton, Cornish) (Russell, 1995). Similar to Russian, almost all consonants in the Goidelic languages are subject to a system of contrastive secondary palatalisation. Typically, this manifests as a contrast between a palatalised and a non-palatalised counterpart across the consonant system. For example *caill* /kʰail̪ʲ/ "lose" vs *càl* /kʰaːl̪ˠ/ "cabbage." This system arose historically due to assimilation, with front vowels leading to palatalised consonants, which eventually became phonemic (Greene, 1973).

As well as a contrast between palatalised and non-palatalised counterparts, Early Gaelic (Old Irish) phonology had a contrast between what is referred to in the Celtic literature as "tense" vs "lax," or "fortis" vs "lenis" sonorants [Russell (1995), p. 38]. As suggested by Ladefoged *et al.* (1998), we interpret the "fortis/lenis" terminology as a contrast between laminal dental and apical alveolar sounds. As such, the Early Gaelic lateral system would have been as follows: /l̪ l l̪ʲ lʲ/, with a corresponding four-way contrast in the nasals. Rhotic consonants also took part in this four-way contrast [Ternes (2006), p. 19], but are not considered in this paper. The historical four-way system evolved into a series of three-way contrasts in modern Gaelic, which is shown in Fig. 2 [adapted from Ternes (2006), p. 19]. As such, in addition to a contrast between *càl* /kʰːl̪ˠ/ "cabbage" vs *caill* /kʰail̪ʲ/ "lose" as described above, a third contrast is also possible, e.g., *càil* /kʰaːl/ "anything." For more information on the historical development of these contrasts, see supplementary materials.[2]

Previous auditory studies of modern Gaelic have specifically mentioned a three-way contrast in sonorants. Early dialect descriptions of Lewis Gaelic from the twentieth century aimed to record the most conservative forms possible and, as such, refer to conservative Gaelic from speakers

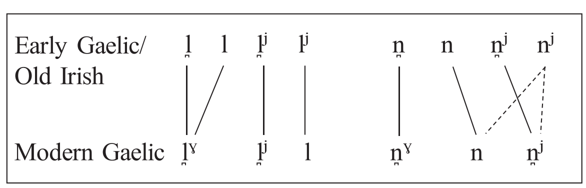

FIG. 2. Historical development of the Gaelic lateral and nasal system. Adapted from Ternes (2006), p. 19.

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born in the late nineteenth century (Borgstrøm, 1940; Oftedal, 1956). The laterals and nasals are as described above: a three-way contrast between velarised dental, alveolar, and palatalised dental; i.e., /l̪ˠ l l̪ʲ/ and /n̪ˠ n n̪ʲ/, respectively. The contrast between /n̪ˠ/ and /n/ is not reported to be very distinct, especially in word-initial position [Borgstrøm (1940), p. 65 and Oftedal (1956), p. 121]. Sample spectrograms of the three laterals and three nasals from the dataset in the present study are presented in the supplementary materials.[2] In the closely related Irish language, Ní Chasaide (1999) reports that the laterals and nasals maintain a three-way contrast between velarised dentals, alveolar, and palatalised alveolopalatal variants; i.e., /l̪ˠ l l̠ʲ/ and /n̪ˠ n n̠ʲ/. However, Ní Chiosáin and Padgett (2012) state that a three-way contrast is characteristic of very conservative older speakers in certain areas and suggest that two-way contrasts are more widespread in contemporary Irish.

Instrumental studies have largely confirmed the auditory dialect descriptions of Gaelic above. For example, Shuken (1980); Ladefoged *et al*. (1998), and Nance (2014) all used acoustic methods to consider the lateral contrast and found three distinct productions. Nance (2014) compared word-initial and word-medial laterals in Gaelic speakers from Lewis and Glasgow. The study focussed on the realisation of contrast in different forms of Gaelic, especially new varieties developing as a result of Gaelic Medium Education in areas such as Glasgow. This study found three distinct productions in traditional Gaelic as spoken by older speakers in Lewis. However, this system is subject to some variation, especially among younger speakers in Glasgow, some of whom produce only one acoustically distinct lateral. In terms of the nasals, Ladefoged *et al*. (1998) suggest a two-way contrast between palatalised and other nasals. Static palatography has confirmed that the distinction concerns *dental* velarised/palatalised and alveolar sounds. When edible charcoal was painted on the tongue and upper palates of their participants, Ladefoged *et al*. (1998) and Shuken (1980) found that the tongue wiped off the charcoal in the dental region when they asked speakers to produce dental velarised and dental palatalised laterals. An initial analysis of Gaelic palatalisation in Sung *et al*. (2015) suggests that palatalised laterals and nasals are produced with different tongue shapes from alveolar laterals and nasals, but this is a small-scale analysis of two words per speaker and velarised phonemes are not considered.

C. Acoustics of palatalisation and velarisation

Palatalisation contrasts are well described in languages such as Russian, which has the most extensive Slavic palatalisation system, and Romanian [e.g., Kochetov (2017) and Spinu *et al*. (2012)]. Typically, the contrast is considered one of secondary palatalisation, with optional velarisation in the other member of the pair [Kochetov (2002), p. 58]. Secondary palatalisation, as found in Slavic and Goidelic, involves a primary constriction and also a secondary constriction in the palatal region, which may be delayed in time with respect to the primary articulation [Ladefoged and Maddieson (1996), p. 364].

The palatalisation gesture involves tongue body fronting and raising, which reduces front cavity length. As such, the acoustic correlates of palatalisation in voiced segments are a raised F2 (associated with shorter front cavity) and a lowered F1 (associated with longer back cavity). Conversely, velarisation involves tongue body backing and so is associated with raised F1 and lowered F2 (Fant, 1960; Kochetov, 2002; Sproat and Fujimura, 1993).

Previous acoustic studies of secondary palatalisation have made use of these tendencies in selecting measures for distinguishing pairs of consonants. In considering the palatalisation contrast in Russian, Iskarous and Kavitskaya (2010) used F2–F1 as a measure of tongue backing, Kochetov (2017) found that the main difference between palatalised and non-palatalised Russian consonants was the difference between F2 and F1, and Ní Chiosáin and Padgett (2012) found higher F2 in palatalised segments. Previous acoustic studies of Gaelic sonorants have noted substantial differences in F2, as well as lesser differences in F1 (Ladefoged *et al*., 1998). Nance (2014, 2019) used F2–F1 as a measure of tongue fronting/backing, similar to Iskarous and Kavitskaya (2010) and Kochetov (2017). Variation in F3 may also be a correlate of palatalisation. For instance, Ladefoged *et al*. (1998) (p. 14) suggest that lower F3 may be a perceptual cue to palatalisation in Gaelic, and Kochetov (2017) also finds some differences between palatalised and non-palatalised Russian consonants in F3.

While the differences in secondary articulation in laterals are well captured by measures of F2–F1 and F3–F2 (Iskarous and Kavitskaya, 2010; Kochetov, 2017; Nance, 2014; Sproat and Fujimura, 1993), the relationship between formant values and nasal articulations is less clear. In the acoustics of nasal stops, the oral cavity can be modelled as a closed tube, while the nasal cavity resonates as an open tube [Fant (1960), p. 145 and Stevens (1998), p. 489]. The result of this articulatory configuration is that the formant structure of nasal consonants represents the combined resonances of the nasal cavity and oral side branches. As such, Fant (1960) (pp. 142–145) suggests that the values of F2 and F3 in particular will correspond primarily to resonances of the nasal cavity. The side branch of the oral cavity results in anti-formants in the spectrum, which may correspond to the place of articulation of the nasal consonant in the oral cavity (Johnson, 2012).[2] 3 Experimental studies have shown that measures of the first anti-formant can correlate with nasal place of articulation differences (Fant, 1960; Recasens, 1983; Tabain, 1994), but, as anti-formants are not well modelled in spectral transformations such as Linear Predictive Coding, their measurement can be challenging. For instance, Tabain *et al*. (2016) report formant measures for different nasal places of articulation in three Australian languages. The authors also show the whole spectrum of these sounds to illustrate spectral differences that could imply the presence of different anti-formants. Similarly, Iskarous and Kavitskaya (2018) present an analysis of the whole spectrum of the segment in question, including nasals, from which the presence of differing anti-formants can be inferred.

D. Research questions

This paper builds on the initial work conducted in Nance (2014) in considering the realisation of the three-way lateral contrast in Gaelic. We extend this work in three primary ways: (1) we analyse word-initial and word-final position, whereas previous studies have only considered initial/medial phonemes; (2) we consider the realisation of the reported three-way nasal contrast; (3) we consider a greater number of vowel contexts and a larger set of words than previous studies. The nasal system in particular has not previously been subjected to detailed acoustic analysis. A brief outline on nasals in Gaelic by Ladefoged *et al*. (1998) suggests a possible reduction to a two-way distinction, so we use these data to test this claim in a more robust manner. In summary, our study investigates whether Gaelic-dominant L1 adults in the Isle of Lewis produce (1) three acoustically distinct laterals in word-initial and word-final position, and (2) three acoustically distinct nasals in word-initial and word-final position.

II. METHODS

A. Participants

This study considers data from twelve native speakers of Lewis Gaelic. All participants were born and raised in Gaelic-speaking families on the Isle of Lewis, Outer Hebrides. As is extremely common among the inhabitants of Lewis, they had all spent some time on the Scottish mainland or abroad for work or study, but had returned to the island to continue their careers. All reported using more Gaelic than English in their daily lives, including in personal and professional spheres. Ten of the participants worked in Gaelic-essential employment in the Council's Gaelic service, Gaelic television, or Gaelic radio. The oldest two participants were a married couple who had retired and use Gaelic with each other and in the community. As explored above in Sec. I A, Gaelic does enjoy some legal status and protection in Scotland, but is now highly minoritised and ability is concentrated in the age brackets over 50. While almost every Gaelic-speaker is bilingual in English, it is now rare to use more Gaelic than English in professional and personal life. In the context of Gaelic then, our sample represents a substantial proportion of the Gaelic-dominant population in a Gaelic-heartland community.

The participants were aged 21–80, with a mean age of 40. The speakers are equally distributed across three generational groups: Generation Z born 1991–1997 (n = 4; 2F, 2M), Millennials born 1990–1981 (n = 4; 3F, 1M), and Generation X and Baby Boomers born 1973–1938 (n = 4; 1F, 3M). We do not analyse generational differences here due to the small numbers of speakers in each group. To provide an indication of possible age variation in the dataset, or lack thereof, we also present formant values from individual speakers ordered by age in the supplementary materials.[2] While our speakers are age-diverse, they are consistent in using Gaelic as their dominant language in their island community, which is increasingly rare in contemporary Scotland.

B. Recordings and stimuli

All recordings were carried out in a community centre or in a quiet office at the speaker's place of work. Acoustic data were recorded using a Beyerdynamic Opus 55 headset microphone, which was preamplified and digitized using a Sound Devices USBPre2 audio interface at 44.1 kHz with 16-bit quantization. Simultaneous high-speed ultrasound tongue imaging data were also recorded, but we only focus on the acoustic data in this study, with an ultrasound analysis forming the subject of future research on the Gaelic sonorant system. Data presentation and recording was handled using the Articulate Assistant Advanced software (Articulate Instruments, 2018). As we were also collecting ultrasound data, the participants wore a headset to stabilise the ultrasound probe (Articulate Instruments, 2008). The microphone was affixed to this headset.

The word list for this study is included in Table I. Each word was presented three times in random order without a carrier phrase. Some examples of words containing Gaelic rhotics and English rhotics and laterals were also collected but are not considered for analysis here. The word list aimed to elicit palatalised, alveolar and velarised laterals and nasals in the context of /i/, /a/, and /u/ across word-initial and word-final positions. Due to lexical gaps in Gaelic, there were no examples of velarised laterals or nasals in the /i/ vowel context. This is due to how the palatalisation contrast developed historically (see above), so it is extremely unusual to find velarised sounds associated with high front vowels. We included vowel context as a factor in order to extend previous work such as Ladefoged *et al*. (1998), which allows us to describe the sonorant system in greater detail. As the contrastive palatalisation system developed through coarticulation with vowels, it is interesting to see whether the system is produced in all vowel contexts. In word initial position, /l/ and /n/ occur as the result of initial mutations, a system of morphophonological alternations in the Celtic languages (Ball and Müller, 2009). As such, words for initial /l/ and /n/ were preceded by the word *mo* "my," *ann an* "in," or *air* "on," which trigger initial mutation. A total of 216 words (three repetitions of 72 individual words) were read by each participant, which took around 25 min.

C. Data processing

All tokens were initially auditorily screened. Previous work has shown that in some young speakers, palatalised laterals can be realised without laterality as palatal glides (Nance, 2014, 2019). Our screening revealed that no such tokens were present in these data. Note also that word-final lateral vocalisation is not a feature of Gaelic.

TABLE I. Word list used in this study.

Gaelic	Phoneme	Word position	Vowel context	English
latha	l̪ˠ	initial	a	day
lùib	l̪ˠ	initial	u	bend
càl	l̪ˠ	final	a	cabbage
cùl	l̪ˠ	final	u	back
mo litir	l	initial	i	my letter
mo leannan	l	initial	a	my darling
air an latha	l	initial	a	on the day
ann an Liurbost	l	initial	u	in Leurbost
mil	l	final	i	honey
dil	l	final	i	gravel
fuil	l	final	u	blood
càil	l	final	a	anything
dàil	l	final	a	delay
sùil	l	final	a	eye
litir	l̪ʲ	initial	i	letter
linnean	l̪ʲ	initial	i	centuries
leabaidh	l̪ʲ	initial	a	bed
Liurbost	l̪ʲ	initial	u	Leurbost
till	l̪ʲ	final	i	return (verb)
caill	l̪ʲ	final	a	lose (verb)
saill	l̪ʲ	final	a	salt (verb)
puill	l̪ʲ	final	u	ponds
ùill	l̪ʲ	final	u	oil (verb)
nathair	n̪ˠ	initial	a	snake
nuadh	n̪ˠ	initial	u	new
ceann	n̪ˠ	final	a	head
sunn	n̪ˠ	final	u	blast
mo nighean	n	initial	i	my daughter
mo nathair	n	initial	a	my snake
mo nupair	n	initial	u	my spanner
fion	n	final	i	wine
glan	n	final	a	clean (verb)
dùn	n	final	u	fort
nighean	n̪ʲ	inital	i	daughter
neach	n̪ʲ	initial	a	person
niucleasach	n̪ʲ	initial	u	nuclear
cinn	n̪ʲ	final	i	heads
tàin	n̪ʲ	final	i	cattle
guin	n̪ʲ	final	i	arrow

After this initial analysis, acoustic landmarks were labelled manually in PRAAT using information from the spectrogram (Boersma and Weenink, 2019), especially focusing on change in F2. In the case of laterals, we labelled the lateral steady-state where tokens were voiced, which was defined as a duration where F2 was steady or as close as possible during the lateral production (Carter and Local, 2007; Kirkham *et al.*, 2019). In word-final voiceless laterals we labelled the portion of voiceless frication until the offset of the lateral. For more information on specific examples and detailed labelling criteria see Nance (2014) and Kirkham (2017).

Our initial screening and subsequent labelling revealed that almost all word-final laterals are systematically devoiced. This often occurs only a short time into the duration of audible laterality. Typically, modal voicing swiftly turns to breathy voicing and then complete voicelessness by the end of the lateral. An example waveform of lateral devoicing is shown in Fig. 3. The waveform shows the interval we labelled as containing the lateral. Also shown are the voicing pulses we used to automatically quantify voicing. This descriptive analysis is detailed in Appendix A. Gaelic typically has many voiceless segments including pre-aspirated stops, no voicing during stop closures (Nance and Stuart-Smith, 2013), and a wide variety of voiceless fricatives. However, such widespread and systematic voicelessness in word-final laterals has not been reported previously to the best of our knowledge. Word-final nasals were not devoiced in the same way.

D. Acoustic measures

Our analysis focuses on formant measures, as well as qualitative comparisons of sonorant spectra. For the formant analysis, we measured word-initial laterals and nasals at the mid-point of a steady-state period of F2, which aimed to capture the lateral target as far as possible from surrounding vowels (Carter and Local, 2007; Kirkham, 2017; Kirkham *et al.*, 2019; Nance, 2014). As discussed above, the word-final laterals were mostly devoiced across much of their duration. As such, we measured formant values at a time-point 10% into the duration of the lateral. This allows comparison with word-final nasals in a way which would not be possible if we used a measure of voiceless frication such as Centre of Gravity or cepstral coefficients (Spinu *et al.*, 2018). Our results therefore come from midpoint measurements for word-initial laterals and nasals, and measurements at 10% of the sonorant duration for word-final laterals and nasals. The measures of the first three formants were estimated using PRAAT from a 25 ms Gaussian window. The LPC Burg method in PRAAT was used for formant estimation, which was set to find five formants up to 5500 Hz (female speakers) or 5000 Hz (male speakers). The measurements were validated by overlaying the formant values with the relevant settings on wide-band spectrograms.

In order to quantify sonorant quality, we report the difference between F2 and F1 (F2–F1), and also the difference between F3 and F2 (F3–F2). As discussed above, the difference between formants is known to appropriately characterise the palatalisation contrast. We *z*-scored all measurements within speaker and sonorant type (laterals versus nasals), which better facilitates speaker comparison as each speaker's data lies on the same scale. Similar

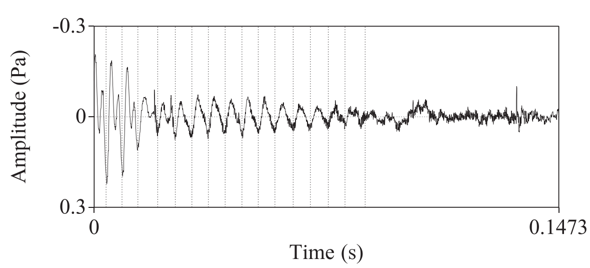

FIG. 3. Waveform and pulses of a word-final lateral.

techniques are commonly used in the analysis of vowels (Flynn and Foulkes, 2011; Lobanov, 1971). The final number of tokens analysed was 1317. Token counts in each word position and vowel context are in Table II. Due to the length of the experiment and repetitive nature of reading a word list, some of the token counts per cell of the dataset are necessarily small. Our results must be interpreted bearing these token counts in mind.

In addition to our formant analysis, we also present data on consonant spectra for laterals and nasals in each vowel context in each word position. This allows us to capture potential differences in broader spectral shape. This is important due to the effect of anti-formants on nasal spectra, so some aspects of spectral shape may provide clues to oral place of articulation in nasals (Fant, 1960; Recasens, 1983; Stevens, 1998). While the LPC analysis does not explicitly model anti-formants, the anti-formants will contribute to differing amplitudes of the formants. For example, an anti-formant near F3 would lower the amplitude of F3. As such, our spectral analysis better accounts for potential effects of anti-formants on the acoustic output (Iskarous and Kavitskaya, 2018; Tabain *et al.*, 2016). We follow the method outlined in Iskarous and Kavitskaya (2018) for deriving the spectra for comparison. Specifically, we estimated LPC spectra from a 40 ms window centered on the sonorant midpoint (initial tokens) or a 40 ms window left-aligned with the sonorant onset (final tokens). This was carried out using Praat's Burg method using a 22 pole filter up to 22 kHz, with a minimum frequency resolution of 100 Hz.

E. Statistics

In order to test the effect of phonemic identity and vowel context on formant values, we fitted linear mixed-effects regression models to z-scored F2–F1 and F3–F2 measurements of the laterals and nasals using the lme4 package in R (Bates *et al.*, 2015). Mixed-effects models allow us to better model the underlying structure of the data, such as modelling the non-independence of tokens produced by the same speaker, while also taking advantage of partial pooling to reduce the effect of extreme values, thereby avoiding overfitting and improving model estimates (Baayen, 2008). Separate models were fitted to each lateral/nasal and position combination (i.e., word-initial laterals, word-initial nasals, etc.). In all cases, we fitted a model with phoneme (alveolar/velarised/palatalised) and vowel context (i/a/u) as the predictor variables, plus random intercepts of speaker and word. However, in the case of some nasal contexts, we found that including the word random intercept resulted in overfitting, so we only include speaker random intercepts for the nasals. We additionally found that a by-speaker random slope for the effect of phoneme consistently resulted in model overfitting, so we used the more parsimonious models that only include random intercepts. We did not test for interactions between phoneme and vowel context given the significantly greater demands on statistical power for detecting significant interactions (Harrell, 2015). Testing such an interaction is also hindered by the fact that /i/ vowels do not co-occur with velarised sonorants in Gaelic, meaning that a balanced set of phoneme*vowel combinations is not possible. Instead, we test the significance of each predictor separately and then interpret these results further via data visualisation.

For significance testing, we use likelihood ratio tests that compare a model containing the phoneme and vowel context variables to nested models that exclude the predictor being tested. If we find a significant difference between these models then it must be due to the presence/absence of the relevant predictor variable, thereby suggesting a significant effect on formant values.

TABLE II. Number of tokens for each phoneme-position-vowel context combination.

	/l̪ˠ/	/l/	/l̪ʲ/	/n̪ˠ/	/n/	/n̪ʲ/
Word-initial						
/i/	0	38	72	0	36	35
/a/	34	75	36	34	36	35
/u/	31	36	35	34	35	36
Word-final						
/i/	0	67	33	0	32	33
/a/	31	63	72	34	25	30
/u/	30	64	67	35	32	31

III. RESULTS

Table III shows the model comparisons for word-initial and word-final laterals. We find a significant effect of phoneme and vowel context in all models. This suggests there is evidence of phonemic contrast in initial and final laterals across both F2–F1 and F3–F2, and that vowel context also has an effect on formant values in laterals. The following paragraphs explore the details of these results in greater depth.

Figure 4 shows F2–F1 values for each lateral phoneme, split by word position and vowel context. For the initial laterals, there is strong evidence of three-way contrast in /a u/ vowel contexts, with /l̪ˠ/ showing the lowest values and /l̪ʲ/ the highest values. The alveolar lateral /l/ falls in between

TABLE III. Linear mixed-effects regression model comparisons testing the effect of phoneme and vowel context on F2–F1 and F3–F2 in laterals.

Model	Measurement (z scores)	χ^2	df	$p(\chi^2)$
Phoneme				
Initial	F2–F1	20.86	2	<0.0001
	F3–F2	15.98	2	0.0003
Final	F2–F1	27.30	2	<0.0001
	F3–F2	25.03	2	<0.0001
Vowel context				
Initial	F2–F1	10.46	2	0.0053
	F3–F2	10.19	2	0.0061
Final	F2–F1	15.92	2	0.0003
	F3–F2	20.37	2	<0.0001

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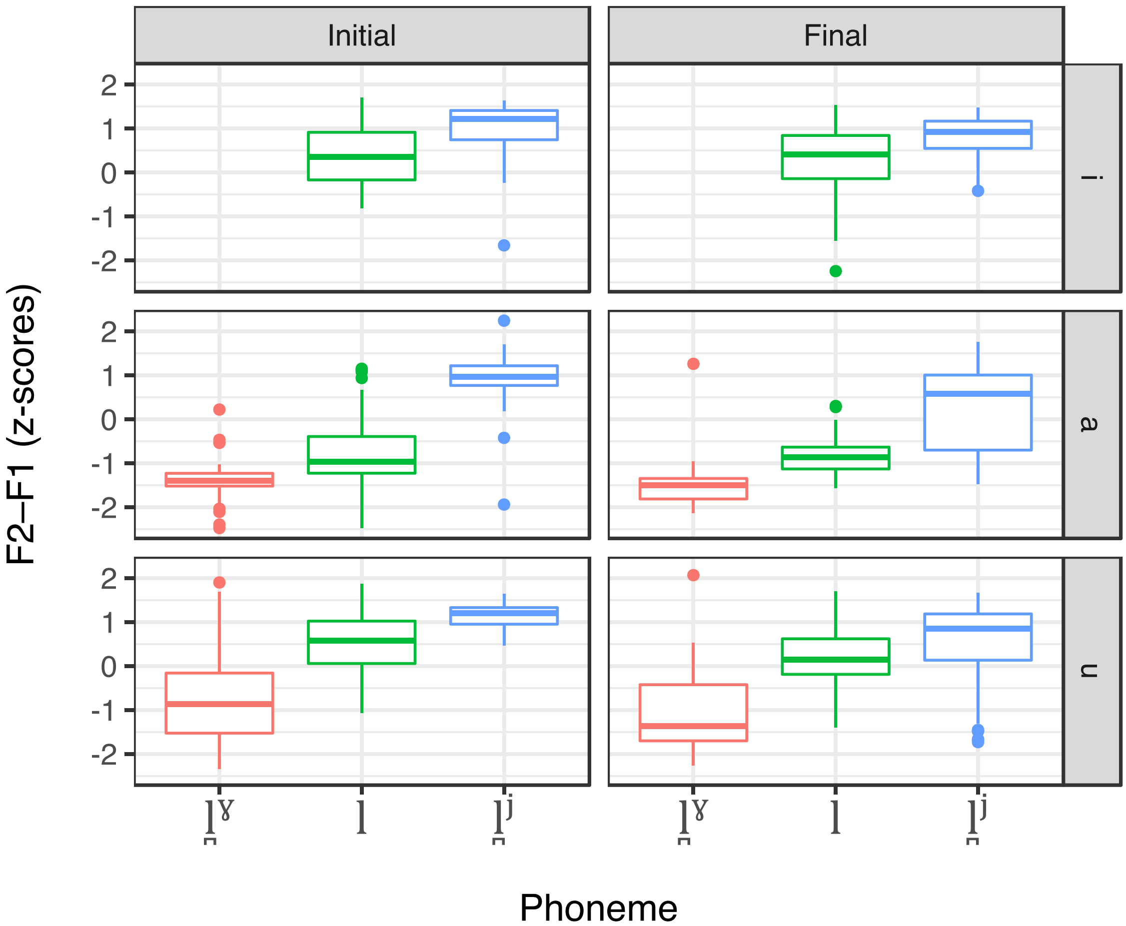

FIG. 4. (Color online) F2–F1 values (z-scored) in laterals by word position and vowel context.

the velarised and palatalised contexts, but remains distinct from both of them. In the /i/ vowel context there is a difference in the distributions of /l/ and /l̪ʲ/, but this is smaller than in the other contexts (recall that the velarised variant does not occur in the /i/ context in Gaelic). Final laterals show a similar pattern, although the magnitude of the differences between phonemes is slightly smaller. Overall, this suggests a three-way phonetic contrast in both initial and final laterals for /a u/ vowel contexts, while the /i/ vowel context shows much smaller differences between the two phonemes that are possible in this context. Formant values from individual speakers ordered by age are presented in the supplementary materials.[2]

The F3–F2 data are shown in Fig. 5. This plot shows a broadly similar pattern to F2–F1, but there are some differences. For initial laterals, there is lesser evidence of /l l̪ʲ/ contrast in the /i/ context, but a clear three-way contrast in the /a/ context. In the /u/ context, /l/ and /l̪ʲ/ are both different from /l̪ˠ/, but appear to be minimally different from one another. For final laterals, we also see no substantial evidence of contrast in the /i/ context, a three-way contrast in the /a/ context, and fairly similar productions for /l/ and /l̪ʲ/ in the /u/ context. Overall, this suggests a more complicated picture in F3–F2, whereby all three phonemes are distinct across both positions in the /a/ vowel context, and potentially less distinct for both positions in the /u/ context.

Table IV shows the model comparisons for initial and final nasals. Word-initial nasals show a significant effect of phoneme in F3–F2 only, and word-final nasals show a significant effect of phoneme in both F2–F1 and F3–F2. There are few significant effects of vowel context on nasal formant values, except for a small effect on F3–F2 in word-initial nasals.

Figures 6 shows boxplots of F2–F1 for each nasal phoneme, split by word position and vowel context. The plot shows that the word-final nasals in /a/ and /u/ contexts each show a two-way contrast. /n̪ˠ/ and /n/ pattern together in being distinct from /n̪ʲ/ in the /a/ context, whereas /n/ and /n̪ʲ/ pattern together in being distinct from /n̪ˠ/ in the /u/ context. This largely appears to be an effect of variation in /n/, which is produced with comparably higher F2–F1 in the /u/ context. There is little evidence of contrast in final nasals in the /i/ vowel context. There was no significant effect of phoneme for initial nasals, which is largely evident from the plots, except for slightly higher values for /n̪ˠ/ in the /a/ vowel context. Overall, this suggests that there is evidence for a two-way contrast in word-final nasals in /a u/ contexts.

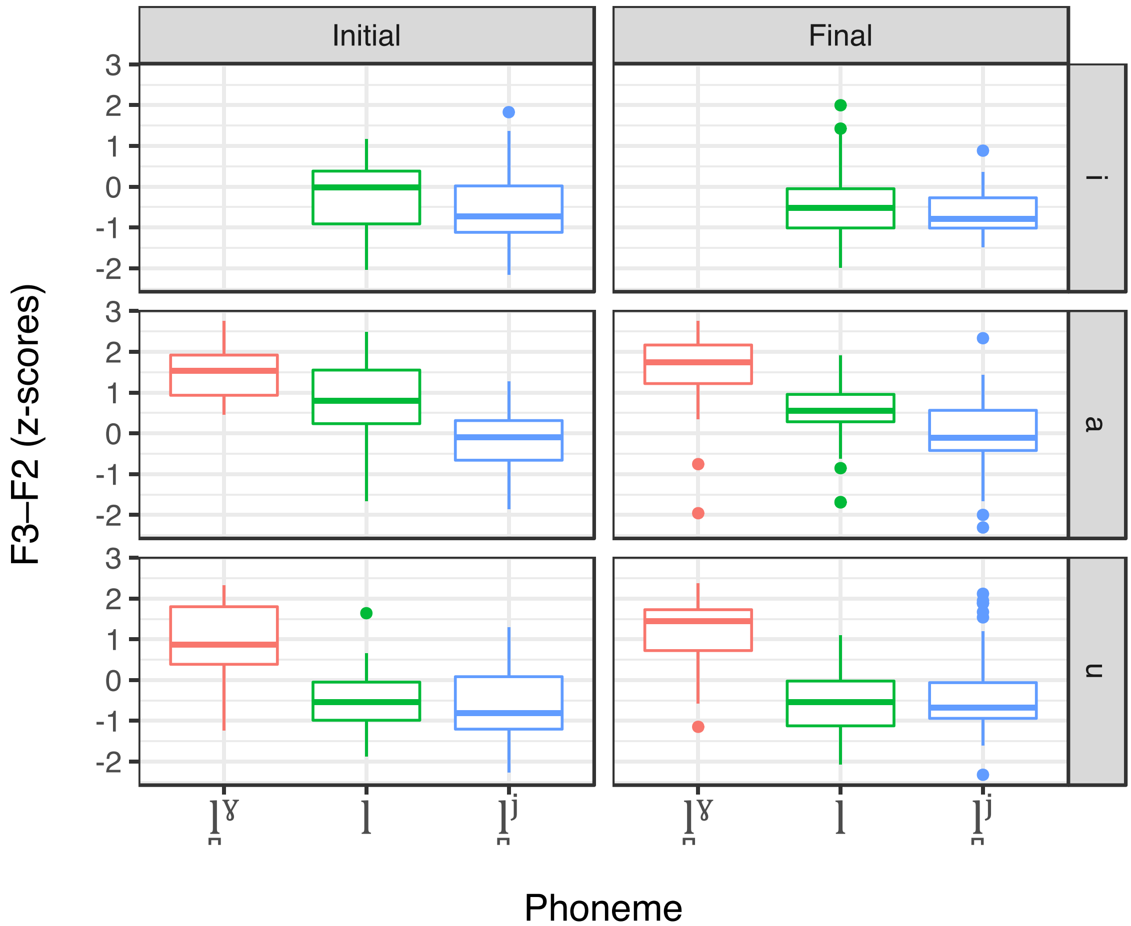

FIG. 5. (Color online) F3–F2 values (z-scored) in laterals by word position and vowel context.

The F3–F2 data are shown in Fig. 7. The statistical model showed a significant effect of phoneme on F3–F2 in initial and final nasals. This effect in final position is evident in the plot with /n̪ˠ/ being produced with slightly higher F3–F2 values than /n/ and /n̪ʲ/ in /a u/ context, while /n/ and /n̪ʲ/ are also produced similarly in the /i/ context. This suggests that there is evidence of two-way contrast in F3–F2 in final nasals. Initial nasals follow a different pattern, however, whereby the /a/ context shows higher F3–F2 values for /n̪ʲ/. This is the reverse pattern of what we see in final position. In comparison to the lateral data, which show robust three-way distinctions with highest F3–F2 in velarised segments, the nasal finding is somewhat unexpected. The plots show the word-initial nasal contrast exists only in one vowel context and is not large in magnitude. For this reason, we highlight the most consistent result: a distinction in multiple vowel contexts for word-final nasals.

TABLE IV. Linear mixed-effects regression model comparisons testing the effect of phoneme and vowel context on F2–F1 and F3–F2 in nasals.

Model	Measurement (z scores)	χ^2	df	$p(\chi^2)$
Phoneme				
Initial	F2–F1	1.61	2	0.4468
	F3–F2	8.19	2	0.0167
Final	F2–F1	10.61	2	0.0050
	F3–F2	13.35	2	0.0013
Vowel context				
Initial	F2–F1	4.09	2	0.1293
	F3–F2	10.96	2	0.0042
Final	F2–F1	2.09	2	0.3523
	F3–F2	0.39	2	0.8217

A. Whole spectrum analysis

In order to observe more holistic spectral patterns between sonorant phonemes, which is especially relevant for the nasals (Recasens, 1983; Tabain *et al.*, 2016), we estimated LPC spectra from a 40 ms window centered on the sonorant midpoint (initial tokens) or a 40 ms window left-aligned with the sonorant onset (final tokens). These time points were chosen to be comparable to the time points chosen for the acoustic analysis. The plots show smoothed spectra that are averaged across all speakers for each phoneme and vowel context combination using generalised additive modelling.

Figure 8 shows the same overall patterns as the formant analysis, with contrast between phonemes in all lateral spectra below 6 kHz. Figure 9 shows similar average spectra for different nasal phonemes below 6 KHz, although there are

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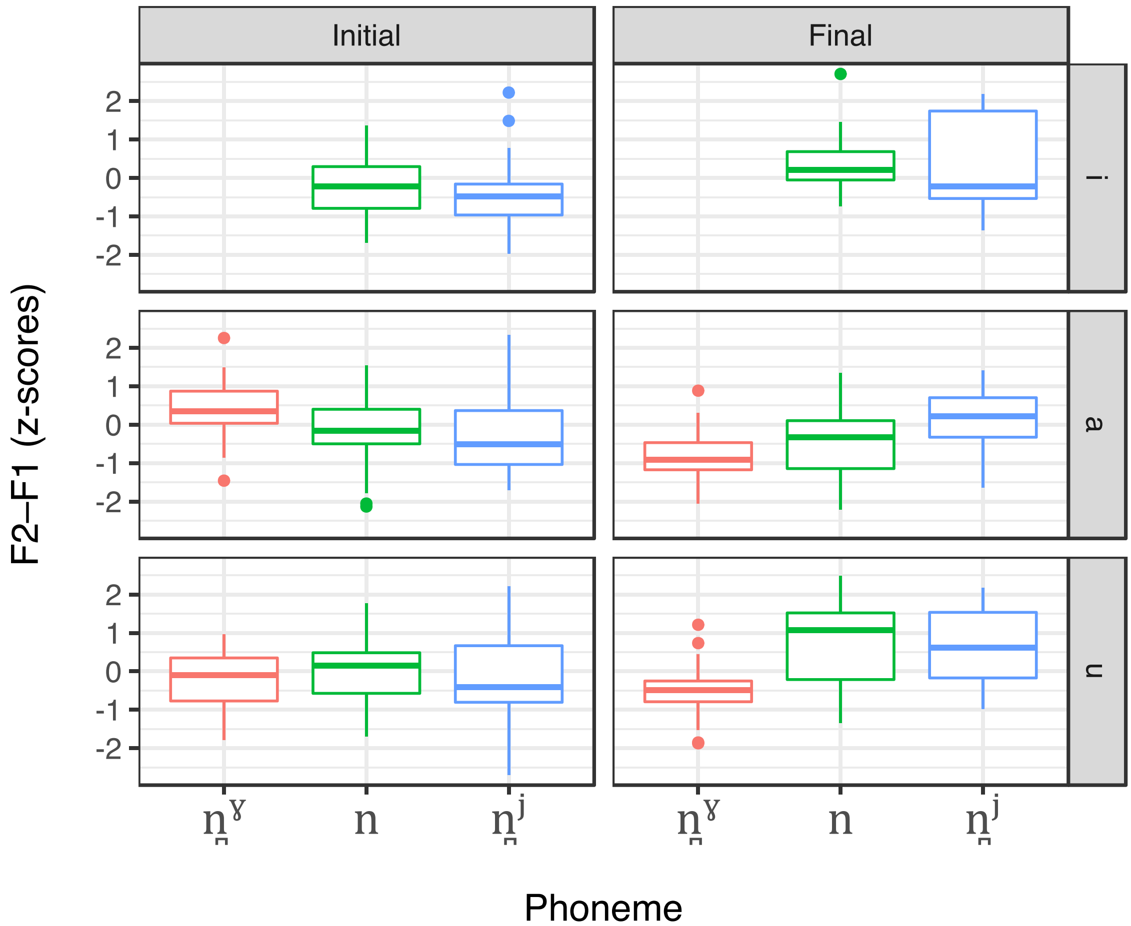

FIG. 6. (Color online) F2–F1 values (z-scored) in nasals by word position and vowel context.

some differences in the word-final /a/ and /u/ contexts, with peaks for the velarised phonemes around 4 kHz. There is a tendency for the palatalised nasals to show distinct spectra above 7 kHz. In summary, this largely confirms our formant analysis, but suggests that there may be some differences between nasal phonemes around 4 kHz and above 7 KHz.

IV. DISCUSSION

The results above show acoustic evidence for the majority of the previously described system in laterals, but lesser evidence for the contrast in nasals. To summarise, we found evidence of a three-way distinction in word-initial laterals in F2–F1 for each possible vowel context. F3–F2 yielded slightly fewer significant results but still shows a three-way contrast in /a/ contexts. In contrast to the laterals, there was lesser acoustic evidence of the phonemic contrast in word-initial nasals for either formant measure. The word-final results show differences in /a/ and /u/ contexts only. We also analysed the whole spectrum for both laterals and nasals. The lateral phonemes are clearly acoustically distinct, and again there is lesser evidence of the contrast in the nasal phonemes. Our discussion first considers the lateral results in comparison to previous work, before then discussing the nasal results and the acoustic nature of nasal consonants.

As stated above, our results suggest a three-way distinction in laterals in both word-initial position and word-final position. We were unable to test the contrast in /i/ vowel contexts fully due to the absence of /l̪ˠ/ + /i/ sequences, but a three-way distinction was significant elsewhere. By taking into account the role of F3, we expand here on previous acoustic studies of Gaelic laterals that have considered F2 and F1 only. A larger F3–F2 value is present in velarised segments compared to alveolar and palatalised phonemes. These data from Gaelic pattern similarly to the data of Kochetov (2017) from Russian, indicating that F3 is involved in the phonetics of palatalisation contrasts. The whole spectrum analysis also suggests three acoustically distinct productions in the laterals. Overall, these data suggest robust maintenance of the traditional three-way distinction reported for Gaelic in classic dialect descriptions such as Borgstrøm (1940) and Oftedal (1956). We also noted substantial durations of voicelessness in word-final laterals, a tendency which was widespread across all speakers and contexts (for full analysis see Appendix A). To the best of our knowledge this has not been reported before, given that previous work has considered word-initial and/or word-medial

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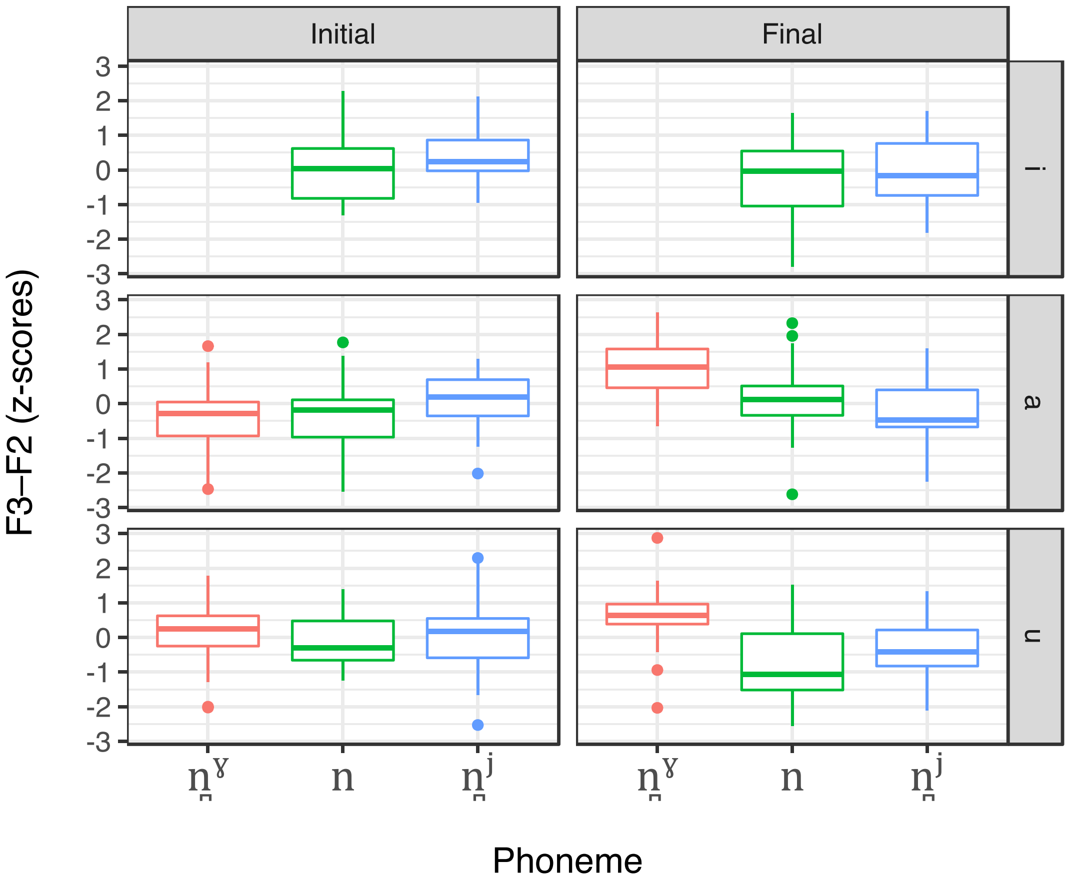

FIG. 7. (Color online) F3–F2 values (z-scored) in nasals by word position and vowel context.

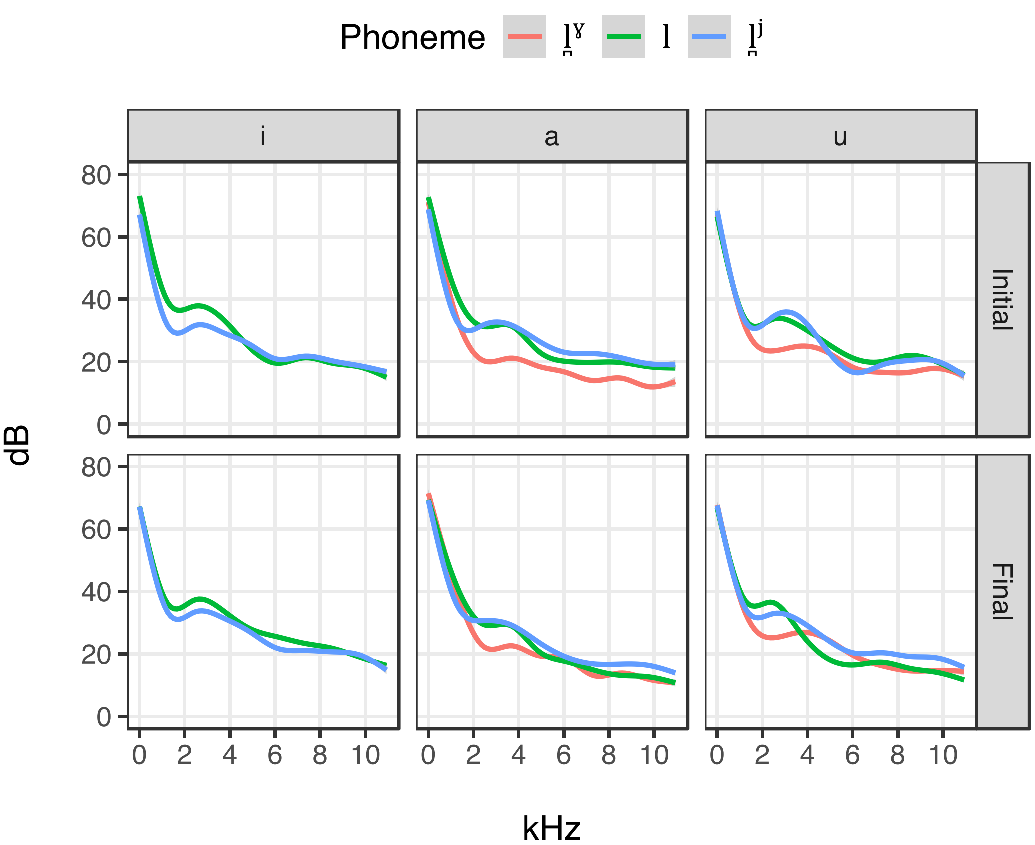

FIG. 8. (Color online) Average smoothed spectra for laterals by vowel context and word position.

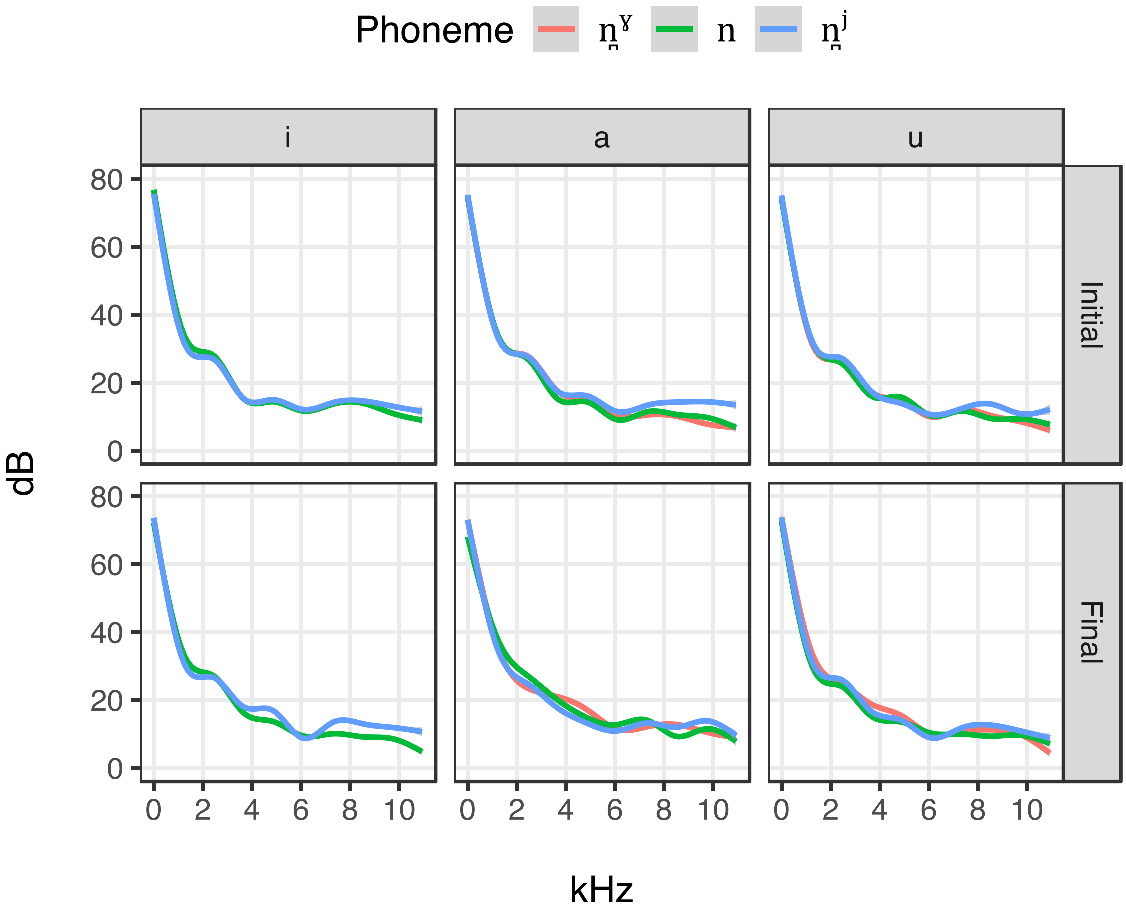

FIG. 9. (Color online) Average smoothed spectra for nasals by vowel context and word position.

laterals only. Based on these findings, we propose that word-final laterals in Gaelic are variably—and often substantially—devoiced.

Our results for nasals represent the first detailed acoustic treatment of nasals in Gaelic. The results for nasals are quite different from the laterals. There is some evidence for a two-way distinction in the formant measures, especially in word-final position. In word-final position, F2–F1 in /a/ contexts suggests that /n̪ʲ/ is distinct from /n/ and /n̪ˠ/. But three analyses indicate that velarised /n̪ˠ/ is distinct from /n/ and /n̪ʲ/ (F2–F1 in /u/ contexts and F3–F2 in /a/ and /u/ contexts). Overall, these findings provide acoustic evidence of two distinct nasals in word-final position, and that alveolar and palatalised nasals have similar formant values. All three reported phonemes are distinct at some points of the whole spectral analysis: the velarised nasals showed a peak around 4 kHz, and palatalised nasals showed higher amplitudes above 7 kHz. In summary, the acoustics of nasals show lesser evidence of a three-way contrast in comparison to the laterals.

As discussed above in Sec. I C, nasal formant values reflect the combined resonances of the nasal cavity and the oral cavity, which is often modelled as a side branch of the nasal resonator. As such, few differences in place of articulation may be present in formant values (Fant, 1960; Johnson, 2012; Stevens, 1998). Previous experimental work has demonstrated that small differences are present in formant values at different places of articulation, presumably due to the formants representing resonances of the two cavities combined (Recasens, 1983; Tabain, 1994; Tabain *et al.*, 2016). These findings are mirrored in our data where we found some small differences. The fact that we did not find greater differences does not necessarily suggest that no articulatory differences are present, but rather that this is not necessarily measurable in formant values. Iskarous and Kavitskaya (2018) find some differences at various points in the spectrum between palatalised and non-palatalised consonants in Russian. However, similar to our data, they find bigger spectral contrasts in laterals when compared with nasals. Again, that we report fewer significant acoustic differences in nasals does not necessarily mean that there is a lack of articulatory differences, but may instead reflect the fact that acoustic correlates of these articulatory configurations are difficult to measure.

A second possibility is that our acoustic measure of word-final nasals may have been taken too early in the timing of the nasal to fully capture the palatalisation gestures and that palatalisation unfolds in a more dynamic fashion. Due to the extensive devoicing in laterals, we extracted formant measurements in word-final segments at 10% of the temporal duration. It may be the case that palatalisation gestures in nasals occur later in the duration of the segment and we would find differences at, for example, 90% into the nasal. Similarly, Spinu *et al.* (2019) found few differences in place of articulation among their palatalised fricatives at consonant midpoint. Ongoing dynamic analysis of our ultrasound data may shed light on these two issues.

A third interpretation of our nasal data may suggest that there is a tendency to reduce the three-way system to a smaller system of contrasts, especially in word-initial position. This finding would not be entirely unexpected based on the previous literature. For example, Ladefoged *et al.* (1998) suggest a two-way contrast, and traditional dialect descriptions state that the contrast is marginal in word-initial position (Borgstrøm, 1940; Oftedal, 1956). Comparison to related contexts reveals similar findings. For example, in the study of Dorian (1978) of obsolescent East Sutherland Gaelic, she describes only two distinctive nasals. A two-way contrast is also reported for the closely related language of contemporary Irish (Ní Chiosáin and Padgett, 2012). Cross-linguistically, it is possible that contrasts between nasals may be perceptually marginal. For example, Tabain *et al.* (2016) (p. 891) suggest that due to wide formant bandwidths and low intensity formants, nasals are perceptually difficult to distinguish.

The tendency to merge nasals specifically in Gaelic may stem from several additional sources. First, as shown in Fig. 2, the historically lenis palatalised nasals were split between alveolar and palatalised categories, instead of straightforwardly mapping onto contemporary categories (Ternes, 2006, 19). This has led to some ambiguity in orthography: non-initial orthographic "n" surrounded by "i" or "e" can be produced as either alveolar or palatalised depending on the word involved. It is possible that this orthographic and historical ambiguity has led to merger in contemporary Gaelic. Second, it is also possible that our word list contained words that were not the most frequently used and familiar, which could render our participants uncertain as to whether a word belonged to palatalised or alveolar categories. When writing the word list, it was relatively easy to find commonly used words containing the laterals of interest. The nasal list was more difficult to construct, suggesting that combinations of these particular nasal and vowel sequences are more rare. It must also be noted that our final word list contained a relatively small number of tokens, and a relatively small number of words compared to the entire Gaelic lexicon. Future work could expand our study to other words and contexts. A final potential explanation is that laterals may somehow be more sociolinguistically salient than nasals. Anecdotally, "correct" lateral production is often commented on in the Gaelic-speaking community, but explicit comment about nasal consonants is extremely rare. The potential salience of laterals compared to nasals in terms of perception and sociolinguistics could be tested further in future work.

With the current analysis it is not possible to conclusively say whether or not the nasal system in Gaelic has reduced to a two-way contrast. As discussed above, lesser acoustic evidence for a three-way contrast cannot straightforwardly imply lack of articulatory differences in production due to the acoustic complexity of nasals. Also, a broader theoretical question concerns whether acoustically distinct productions may or may not represent evidence for a phonemic contrast at all. A typical approach to establish contrast would include eliciting minimal pairs involving the potential sounds of interest, in addition to perceptual tests. It has been remarked that Gaelic has very few minimal pairs, let alone minimal triplets (Ladefoged *et al.*, 1998; Shuken, 1980). This incidence is due in particular to the sound changes that led to contrastive palatalisation. Palatalisation contrasts often mean that certain sounds occur in certain environments, meaning that identical environments are very unlikely to occur. As such, Gaelic often presents a challenge to the conventional minimal pair test, which makes establishing evidence for contrast particularly problematic. This is compounded by Gaelic's status as an endangered language, with the accompanying narrowing of the lexicon that this brings.

The acoustic data from the nasals, especially the formant measures, show greater differences between nasal phonemes in word-final position than in word-initial position. This is perhaps unexpected, given that previous research has shown that codas are less likely to demonstrate acoustic cues for consonants (Ohala, 1990; Wright, 2004), especially secondary palatalisation (Kochetov, 2002). We suggest that this finding is due to the nature of how the three-way contrast is realised in Gaelic specifically: in word-final position, we chose words which were palatalised, velarised, or alveolar as a result of historical sound change. In word-initial position, the alveolar consonants are present due to a synchronic process of initial consonant mutations. In other words, for a speaker to produce the three-way contrast in word-initial position they had to correctly apply a morphophonological process, whereas producing the contrast in word-final position could occur without application of this process. Our study therefore unavoidably tested more than just phonemic production in word-initial position: it may be the case that speakers no longer mutate nasal consonants in word-initial position. Mutation of nasal (and lateral) consonants, unlike other consonants which undergo mutation, is not represented in orthography, so may be more susceptible to change. For examples of mutations in Gaelic and accompanying sound files see Nance and Ó Maolalaigh (2019).

Taking into account all of the discussion above, we suggest that our results at least show evidence of a two-way system in nasals. Further investigation of the ultrasound data recorded as part of this project will allow us to better determine whether there is articulatory evidence for a two-way or three-way contrast in Gaelic nasals.

Finally, there were some differences in the lateral phoneme formants due to vocalic context, which is unsurprising given the effects of coarticulation. However, we found fewer effects of vowel phoneme in the nasal data (vowel context was only significant in F3–F2 in word-initial nasals). Our results mirror those of Tabain (1994) and Tabain *et al.* (2016), who comment that there are few differences in nasal stop acoustics according to vocalic context. We suggest that the lack of vowel effects in nasals in comparison to laterals may also be linked to the relatively long formant transitions into and out of lateral segments, especially velarised ones. This is exemplified in Carter and Local (2007) and modelled with SS-ANOVAs in Nance (2014) and Kirkham (2017) and GAMMs in Kirkham *et al.* (2019). The extensive transitions for liquids have led some authors to suggest studying them as a property of the syllable containing a vowel and liquid sequence (Plug and Ogden, 2003). Such transitions suggest that the effects of vowel environment may persist long into the lateral. No such suggestions are made for nasals, which are not reported to have as extensive formant transitions. These properties may lead to the comparative lack of coarticulatory effects from vowels in our nasal data as compared to the lateral data. Another possibility is that there is simply much greater variation in the phonetic realisation of nasals in our data. This would potentially make finding robust vowel context effects on nasals more difficult, given that the nasals are produced in such variable ways by different speakers to begin with.

V. CONCLUSION

Our analysis has considered the productions of Gaelic-dominant, L1 speakers who were born and raised in a Gaelic heartland community and use Gaelic very extensively in every aspect of their lives. As such, these data can be considered typical of Gaelic as spoken in traditional communities today. We find evidence in support of previous reports of the typologically unusual three-way palatalisation contrast in word-initial and word-final laterals in all vowel contexts. Previous (mainly auditory) work has also described a three-way contrast in nasals. Our data suggest evidence for a two-way contrast in the nasal acoustics, but articulatory analysis is required in order to better understand the dynamics of this contrast in nasals given their complex acoustic signature. Future research will aim to unpack the dynamics of the Gaelic sonorant system further, such as the use of ultrasound data to help establish the extent of articulatory palatalisation and velarisation in these sounds.

VI. ACKNOWLEDGMENTS

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APPENDIX A: WORD-FINAL LATERAL DEVOICING

In order to investigate the nature of word-final lateral devoicing, we calculated the extent to which word-final

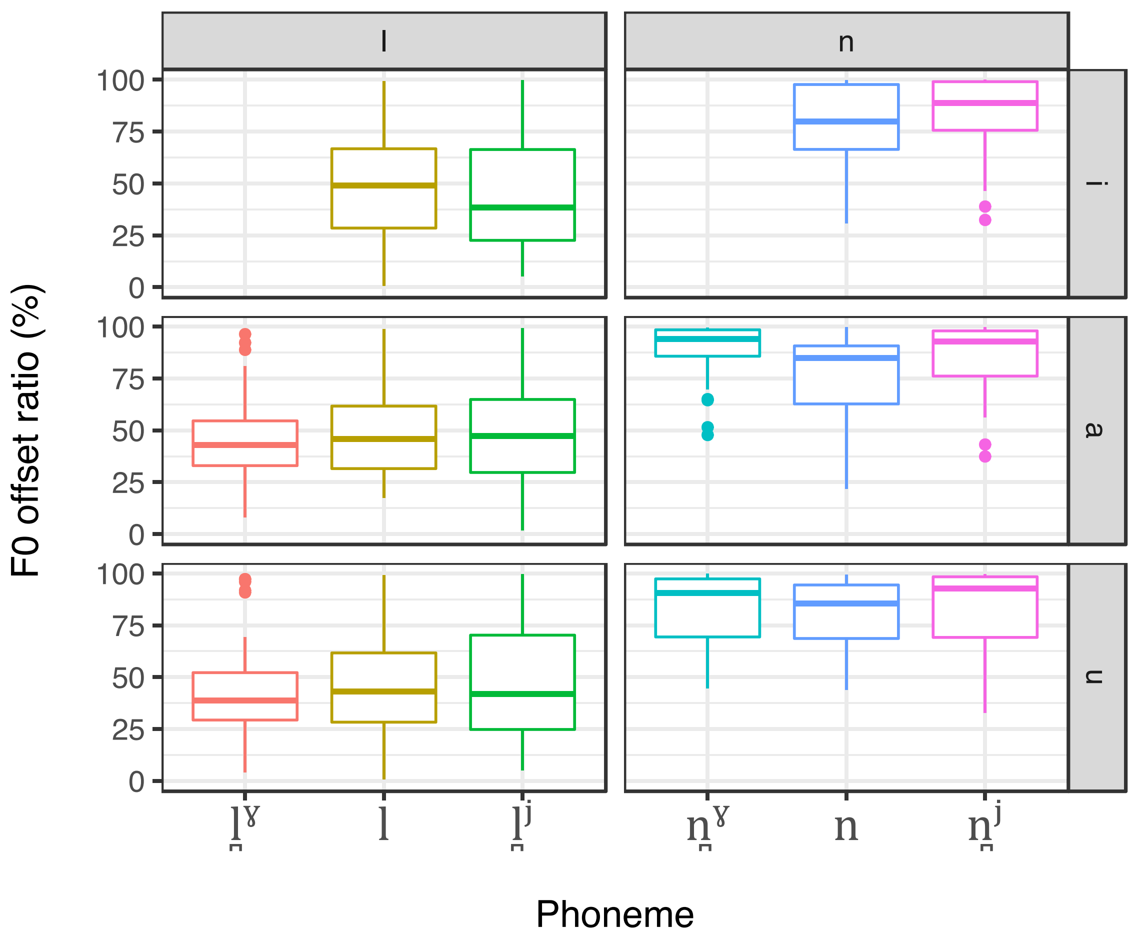

FIG. 10. (Color online) F0 offset ratio in word-final segments by sonorant type and vowel context.

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sonorants were voiced as a percentage of the segment duration. This allows time-normalised comparison of devoicing in word-final laterals and nasals. Voicing was calculated using the PointProcess algorithm in PRAAT, which detects voicing via cross correlation analysis (Boersma and Weenink, 2019). We extracted the time point at which voicing ends and express this as a percentage of the segment's duration giving an F0 offset ratio. The minimum F0 was set at 60 Hz and maximum at 500 Hz for all voicing analyses.

As discussed above, voicing offset occurred some time before the end of the lateral in the majority of cases. Figure 10 shows the F0 offset ratio in word-final laterals and nasals in each vowel context, with higher values indicating that voicing ceases closer to the end of the segment and lower values indicating that voicing ceases closer to the beginning of the segment. The plots show clearly that voicing usually offsets around 25%–60% of the way through laterals, and almost always very close to the end of the segment in nasals. This suggests a strong tendency for variably devoiced phonetic realisations of word-final laterals in Gaelic, but that nasals are typically voiced across most of their duration.

[1]We refer to the language under study here as "Gaelic" /galɪk/, as is customary in the Gaelic-speaking community. The language family which is made up of Gaelic, Irish, and Manx is referred to as "Goidelic" in order to avoid potential ambiguity.

[2]See supplemental material at https://doi.org/10.1121/10.0000998 for discussion of the historical development of the three-way contrasts, example spectrograms and waveforms from the dataset, and acoustic results for individual speakers.

[3]Clearly, the lateral channels involved in the articulation of lateral consonants also introduce an anti-formant structure to lateral acoustic output. However, in the case of laterals the *oral cavity* is the main resonator and the lateral channels are modelled as side branches. In contrast, for nasal stops the *nasal cavity* is the main resonator and the oral cavity is modelled as a side branch. As such, formant measures appear to adequately model place of articulation in laterals (Sproat and Fujimura, 1993).

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