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Acquiring tongue shape complexity in consonants with multiple articulations

Claire Nance[1], *Sam Kirkham*[1]

[1]Lancaster University Phonetics Lab, United Kingdom

c.nance@lancaster.ac.uk

Abstract

This paper reports preliminary findings from a small-scale pilot study. Our aim is to understand the interaction of differing bilingual acquisition modes and the development of articulation in children. Specifically, we investigate differences between Scottish Gaelic-English bilingual children from different backgrounds: sequential bilinguals (Gaelic L1), simultaneous bilinguals, and sequential bilinguals (English L1). Ultrasound and acoustic data were collected from sixteen children in Gaelic immersion education in Lewis, Scotland, and eight adults who are professional Gaelic users. Analysis of tongue shapes using Modified Curvature Index and Number of Inflections indicates that children are less able to differentiate multiple lingual gestures. Children from Gaelic-only homes produced more adult-like tongue shapes. These preliminary results indicate that production differences observed between groups of bilinguals may have an origin in the early acquisition of motor control skills.

Index Terms: ultrasound tongue imaging, tongue complexity, speech articulation, palatalisation, child speech

1. Introduction

1.1. Acquiring tongue shapes

This paper reports the findings of a pilot study comparing the midsagittal tongue shapes used by adult and child speakers in a context of minority language bilingualism. When children learn to speak, they have to learn to precise positioning and timing for the different articulators as well as the abstract structures of their language(s) [1]. Children and adults differ in the size and proportion of the skull and vocal anatomy [2], with non-linear development of vocal tract proportions. In particular, around 18 months there is a change in proportion for tongue length, larynx height, and pharynx length meaning that children and adult proportions become similar. The hard palate develops slower, achieving adult-like proportions around age 24 months [2]. Size and proportion of the vocal anatomy compared to adults continues to develop until late adolescence [3]. Throughout this period of growth, children can produce intelligible speech, but must constantly adjust to their changing anatomy. Through this process, they develop motor equivalent strategies for adapting their speech production techniques as they grow [4, 5].

In child speech acquisition, it is usually reported that sounds requiring very precise motor control or precise timing are acquired later on. For example, fricatives such as /s ð θ/ and sounds requiring multiple gestures such as /ʎ r ɹ/ are often acquired in the 4th or 5th year of life [6]. During this process, children need to learn 'lingual differentiation' i.e. control and coordination of multiple parts of the tongue [7, 8]. In speech with lesser lingual differentiation it is reported that there is a high degree of palatal contact [7], and a palatal quality, implying increased palatal contact, is also characteristic of child speech in general [9]. This lesser lingual differentiation in child speech is due to the immaturity of the superior longitudinal muscle, which runs the length of the tongue surface and allows speakers to manipulate multiple lingual gestures simultaneously or very closely in time [5].

When children acquire languages bilingually or multilingually, it has been demonstrated that this can occur at a faster rate compared to monolingual children, but may also occur at the same or slower rates. This development is modelled through the PRIMIR model of bilingual infant development [10]. In minority language contexts, research on Welsh- and Gaelic-speaking children indicates that development of complex grammatical and phonological structures can be protracted [11, 12, 13]. When acquiring languages bilingually, learning can occur right across the lifespan [14] but speech production outcomes usually differ between early and later bilinguals [15, 16]. In minority language settings, sometimes the peer group in adolescence appears to be more important than differences in early bilingual experience [17, 18]. The process by which adolescent peer group varieties develop in childhood minority language education is, however, unknown. Differences in speech articulation strategy are a possible source of these varying production outcomes. It is reported that advanced adult bilinguals can develop language-specific articulation strategies [19, 20], but it is not yet known whether there are language-specific or bilingual-specific differences in child articulation.

1.2. This study

In this study, we aim to investigate the link between knowledge about child speech articulation strategies, and knowledge about phonological acquisition outcomes in multilingual speakers. Specifically, we investigate the interaction between child motor equivalent strategies for speech, and also the outcomes of different kinds of bilingual acquisition. In an applied context, we aim to contribute to the literature on bilingual speech acquisition since bilingual children are either under-referred or over-referred to speech and language services [21]. This is due to inadequate information about multilingual development in a range of languages and forms of bilingualism.

We investigate children acquiring Scottish Gaelic as well as English. Gaelic is a Celtic language spoken by ~70,000 people in Scotland, around 1% of the Scottish population [22]. Gaelic is an endangered language and family transmission is limited [23, 24]. In the Outer Hebrides, a chain of islands off the northwest of Scotland where the data for this study were collected, Gaelic is spoken by ~50% of the population. This is the densest concentration of Gaelic speakers worldwide. On these islands, children are now automatically enrolled in Gaelic Medium Education (GME), a form of immersion schooling, from age 2.5 years unless parents opt out. This means that although the majority of children in this part of Scotland acquire Gaelic, they often do so relying on the school system and mainly use English at home and in social contexts [17].

This study considers the secondary articulations in Gaelic. Most consonants in Gaelic are palatalised or non-palatalised for example the final consonants in *ca**t*** 'cat' /t̪/ vs. *cai**t*** 'cats' /t̪ʲ/ [25]. Sonorants undergo a three-way alternation between palatalised, plain, and velarised for example the medial consonant in *cai**ll**each* 'old woman' /l̪ʲ/, *bai**l**e* 'town' /l/, and *ba**l**ach* /l̪ˠ/. Our previous work with adult speakers found that speakers make robust distinctions between these three phonemes in laterals, nasals, and rhotics, and that there are no indications of change in this system for adult L1 speakers [26, 27, 28]. Here, we focus on the acquisition of the contrast between palatalised and velarised laterals and nasals only; i.e. /l̪ʲ l̪ˠ n̪ʲ n̪ˠ/.

In order to compare development of child speech against adult data, we use measures which aim to capture the complexity of tongue shapes (and thus lingual differentiation) based on ultrasound images of the tongue. Firstly, we measure Modified Curvature Index (MCI). This measure captures the extent of tongue curvature relative to the arc length and produces a number indicating how curled up or stretched out the tongue is [29]. Secondly, we measure Number of Inflections (NINFL) i.e. the number of times a tongue shape changes from convex to concave [30]. These measures have been used to show age-related differences in lingual differentiation among children with Speech Sound Disorder [31], and well as typically developing children's alveolar consonants [32].

Our study was designed as a pilot to a larger planned research project. We aim to test methods for acquiring and analysing child articulatory data in a controlled set of words likely to be known to young Gaelic-speaking children. In doing so, we investigate the following research questions:

1. Do adults and children differ in lingual differentiation?
2. Do palatalised and velarised consonants differ in tongue complexity?
3. Do laterals and nasals differ in tongue shape complexity?
4. Does tongue shape vary according to home language background and gender?

2. Methods

Synchronised audio and ultrasound data were collected from two groups of speakers on the Isle of Lewis, north-west Scotland: 1) eight adults who use Gaelic in professional settings, and 2) sixteen children. The adults were aged 21–72 (4f, 4m) and represent a community target for Gaelic acquisition. The children all attend the same Gaelic Medium primary school and were aged 4–11 years (5f, 11m). Here, we use home language background as a proxy for bilingual acquisition mode and expected Gaelic input and exposure to Gaelic. We thus analyse the data as relating to different categories of child bilingual: children who speak only Gaelic at home and learned English from wider society (sequential bilinguals, Gaelic L1), children who learned Gaelic and English at home (simultaneous bilinguals), and children who learned Gaelic only through schooling and speak English at home (sequential bilinguals, Gaelic L2). Two children came from a Gaelic-only home, six from an English-only home, and eight from a bilingual home.

All data were recorded in Articulate Assistant Advanced [33] using a Telemed Micrus ultrasound machine and a 20mm convex probe, 3 MHz frequency, ∼90 Hz frame rate, and a stabilisation headset [34]. Audio data were recorded with a Beyerdynamic Opus 55 headset microphone connected to an audio interface at sampling rate 22 050 Hz. The data reported here consider word-initial palatalised and velarised laterals and nasals presented to participants as individual words in AAA. The words were displayed to children orthographically and as pictures, and to the adults orthographically only. The total twenty two words, of which we analyse eight here (two per phoneme) and was repeated 2–3 times per participant (total 445 tokens). The children were recorded in a quiet part of their school, and the adults were recorded in their workplace or a community centre.

The word list is shown in Table 1. Seven of the adults were recorded as part of an earlier project. We then later designed the children's word list to include well-known words which were easily displayed as pictures. As such, there are some small differences between the word list for children and one adult, and the word list for the other seven adults where words were lesser known or not easily displayed as pictures.

Table 1: *Word list. The consonant of interest is shown in **bold**. Where adult and child word lists differed, adult words are shown on the row below in brackets.*

Gaelic	English	Phoneme	IPA
litir	*letter*	l̪ʲ	l̪ʲitʃʰɪɾʲ
leabaidh	*bed*	l̪ʲ	l̪ʲapi
latha	*day*	l̪ˠ	l̪ˠa.ə
luchag (**l**ùb)	*mouse* *bend*	l̪ˠ l̪ˠ	l̪ˠuxak l̪ˠuːp
nighean	*girl*	n̪ʲ	n̪ʲi.ən
neoni (**n**each)	*zero* *person*	n̪ʲ n̪ʲ	n̪ʲɔni n̪ʲax
nathair	*snake*	n̪ˠ	n̪ˠahɪɾʲ
naoi (**n**uadh)	*nine* *new*	n̪ˠ n̪ˠ	n̪ˠɯi n̪ˠuəɣ

Acoustic data were exported from AAA and labelled for sonorant duration and following vowel in Praat [35]. The TextGrids were then imported back into AAA so tongue coordinates could be extracted at particular acoustic landmarks. Splines were fitted to the ultrasound images in AAA using fan splines in order for the child data to be comparable with the previously collected adult data.

We then calculated Number of Inflection Points (NINFL) [30] in AAA. The tongue spline coordinates were rotated to each speaker's occlusal plane using a bite plate recording which was made at the start of each speaker's data elicitation [36] and exported from AAA along with the NINFL values. Data were imported into R [37] for further analysis. In this initial pilot study, we consider data from the sonorant acoustic midpoint. We calculated Maximum Curvature Index (MCI) at sonorant midpoint using the Python script provided in [29]. NINFL values above 5 were filtered out following [30, 32, 31].

For analysis, a linear mixed effects model was fitted to the MCI data using the lme4 package [38], and an ordinal mixed effects model was fitted to the NINFL data

[39]. Models contained participant age (child/adult), gender (male/female), consonant (lateral/nasal), secondary articulation (palatalised/velarised), as well as two-way interactions age*consonant, age*secondary articulation, and consonant*secondary articulation. These fixed effects were all sum-coded. Word and speaker were included as random intercepts. Significance testing was carried out by comparing the full models described above to a nested model which did not contain the predictor of interest via ANOVA [40]. Due to the small numbers of children at each age, age differences within the child sample were explored qualitatively, as well as home language differences. Code and data: https://osf.io/ek768/.

3. Results

3.1. Overall results

The results of the statistical modelling are shown in Tables 2 and 3. The significance testing results are obtained from model comparison as described above.

Table 2: *MCI results (linear models).*

Fixed effects	χ^2	df	$p(\chi^2)$
Age group	9.93	3	**.02**
Consonant*Secondary	6.54	1	**.01**
Secondary articulation	8.34	3	**.04**
Consonant	7.04	3	.07
Gender	0.11	1	.74
Consonant*Age group	0.26	1	.61
Secondary*Age group	1.43	1	.23

Table 3: *NINFL results (ordinal models).*

Fixed effects	χ^2	df	$p(\chi^2)$
Age group	15.95	3	**.001**
Consonant*Secondary	6.03	1	**.01**
Secondary articulation	7.60	3	.055
Consonant	6.38	3	.09
Gender	1.34	1	.25
Consonant*Age group	0.10	1	.75
Secondary*Age group	0.09	1	.76

The modelling shows significant results for age group (adults compared to children), and also an interaction between consonant (laterals vs. nasals) and secondary articulation. In the MCI data there is also a significant effect of secondary articulation. The results for age group are plotted in Figure 1. From this figure, it is clear that the MCI values are higher in children than in adults. This is consistent with previous work [31, 32] which found higher MCI values in younger children, and indicates a more curled up tongue shape. Adults on the other hand, are better able to differentiate the different tongue gestures. In terms of NINFL, the results are the opposite, but are consistent with the MCI data. In this case, children have fewer inflections in their tongue indicating that the tongue is less differentiated than adults.

We interpret the differences for secondary articulation and consonant through the significant interaction between these effects. These data are plotted in Figure 2. The NINFL data

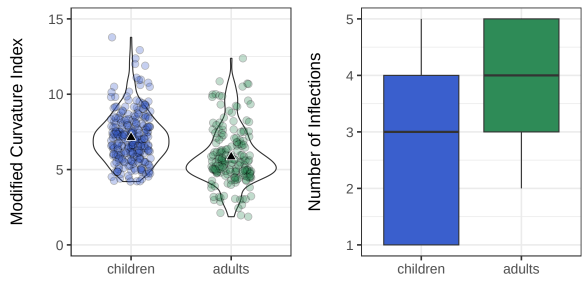

Figure 1: *Age group comparison. Triangles show groups means for the MCI results.*

indicate that there is a difference between palatalised and velarised laterals, but no difference between palatalised and velarised nasals. For the laterals, palatalised sonorants have more inflections than the velarised. The magnitude of the differences in the MCI data is small. However, consistent with the NINFL results there are lower values in the palatalised laterals compared to velarised indicating the tongue is more differentiated.

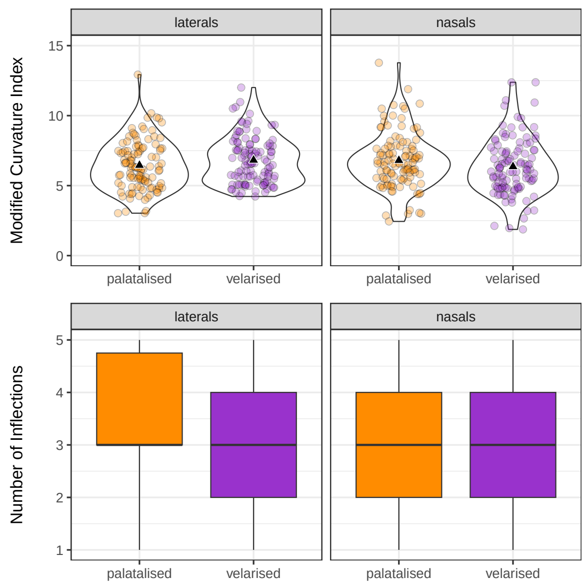

Figure 2: *The interaction between manner of articulation and secondary articulation. Triangles show groups means for the MCI results.*

3.2. Variation within the child sample

We now consider variation within the child sample. The results for individual children plotted by age are shown in Figure 3. For the MCI results, MCI is lower with increasing age. This is consistent with developing tongue differentiation across childhood: the children are able to move different parts of the tongue more independently, reaching a plateau around 108 months (9 years). The NINFL data are more variable and do not seem to indicate any overall developmental pattern. We have plotted Pearson's correlation coefficient on Figure 3 to give an indication of patterns within the child sample. The MCI data correlate negatively with age, as would be predicted from the overall study results (Figure 1). There is no correlation with age in the NINFl data.

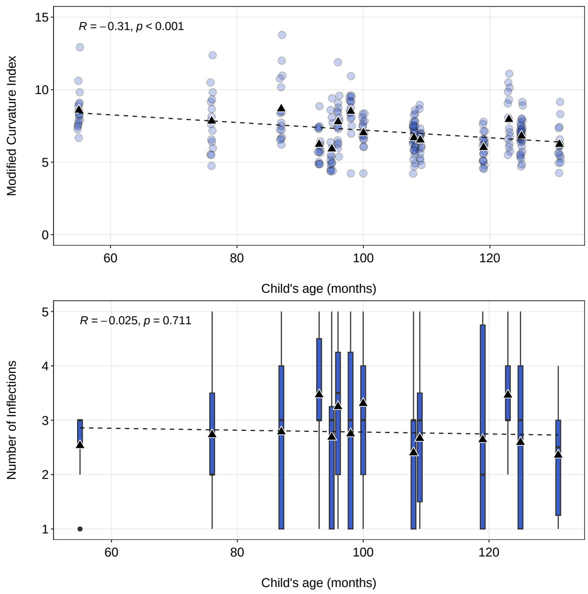

Figure 3: *Age variation within the child sample. Triangles show speaker means for ease of interpretation.*

Finally, we consider the home language background of the children as a proxy for different bilingual acquisition modes. Figure 4 compares the adults with children from three home language backgrounds: children who acquired Gaelic at home and use only Gaelic at home (sequential bilinguals, Gaelic L1), children who acquired Gaelic and English at home (simultaneous bilinguals), and children who acquired Gaelic only through schooling and use English at home (sequential bilinguals, Gaelic L2). The MCI data indicate that children from Gaelic-only homes produce consonants with tongue shapes closer to adult targets. The NINFL data are again more variable. However, the children from Gaelic-only homes use more adult-like values (as well as values at the other end of the scale). Children from English-only homes have more NINFL values at the lower end of the scale.

3.3. Summary of results

To summarise, we found significant differences between adults and children for both Modified Curvature Index and Number of Inflections. For both measures, there was a significant interaction between consonant (lateral vs. nasal) and secondary articulation (palatalised vs. velarised). For MCI, palatalised consonants have higher values overall. Within the child sample, younger children have higher MCI values. For MCI and NINFL, children from Gaelic-only homes have more adult-like values.

4. Discussion

4.1. Do adults and children differ in lingual differentiation?

The MCI results indicate higher values in the child group compared to the adults. This is consistent with previous research using MCI values, although [41] notes that direct comparisons of child and adult data in this area are rare. Previous research within groups of children indicates that for alveolar consonants MCI values decreased with age [32]. Similarly, [31] also found decreasing MCI with age in their sample of children with Speech Sound Disorder (though not the typically developing children). MCI gives a value relating to how curled up or stretched out the tongue shape is. The higher values in children indicate a more curled up tongue shape, and lesser lingual differentiation compared to the adults in the study. This result is consistent with [42] whose ultrasound work indicated that younger children were more likely to produce laterals with a single inflection compared to adults.

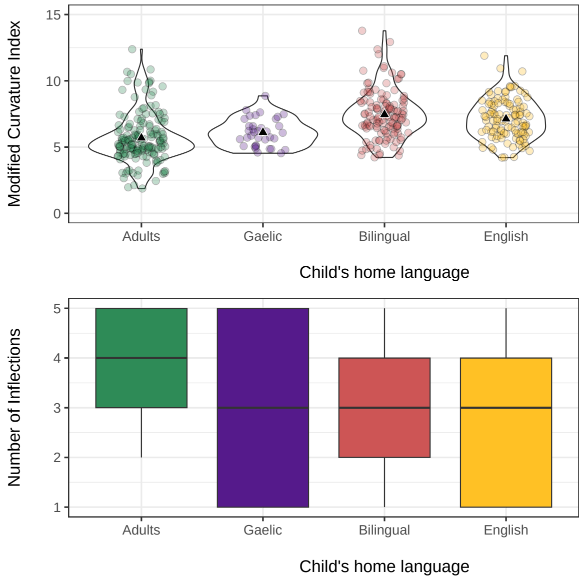

Figure 4: *Home language comparison.*

Similarly, these results are mirrored in our NINFL data which indicate higher values in the adults and more inflections in the tongue. Overall, the picture emerging from our data is of differences in child and adult ability to manipulate the different lingual gestures semi-independently, with this skill being more advanced in adult speakers. Similarly, in the literature on child coarticulation, greater gestural overlap is usually found in child speech [43, 44, 5]. It is suggested in [45] (page 37) that younger children have less inhibitory control and therefore more simultaneously activated gestures. This could also account for the finding observed in our data that children's tongues are less differentiated with fewer inflections.

Our initial analysis of variation within the child sample indicates a negative correlation of MCI values with age in months (Figure 3). This is consistent with the developing lingual differentiation implied by the group differences between adults and children (Figure 1). These findings were not repeated in the NINFL data, which are more variable and do not indicate any patterns within the child sample.

4.2. Do palatalised and velarised consonants differ?

To the best of our knowledge, this is the first time that MCI and NINFL measures have been applied to consonants with phonemic secondary palatalisation and velarisation. As such, we did not have any specific predictions about the results which could be tested. In the speech acquisition literature, consonants with multiple lingual articulations are typically acquired later [6] and/or produced with simplified articulatory strategies [42]. However, all the consonants in this study include multiple lingual articulations so we were not necessarily expecting differences between the consonants. Our modelling of MCI and NINFL indicates a significant interaction between consonant and secondary articulation such that MCI is lower, and NINFl higher, in palatalised laterals compared to velarised laterals. This indicates a more complex tongue shape in the palatalised laterals.

One possibility we would like to investigate in future research is the extent of the tongue tip gesture in producing these consonants for our child speakers. Articulatory work with adult speakers indicates that the consonants of interest in our study are dental as their primary articulation [46]; i.e. /l̪ʲ l̪ˠ n̪ʲ n̪ˠ/. It is possible, however, that children are reducing, or not producing, the dental articulation for velarised laterals, as well as palatalised and velarised nasals – i.e. /l̪ʲ ʟ ɲ ŋ/ – which would explain lower NINFL and higher MCI in these consonants.

4.3. Do laterals and nasals differ?

We did not find a difference overall in tongue shape complexity between laterals and nasals. In this respect, it should be noted that ultrasound captures only the midsagittal dimension, where laterals and nasals do not substantially differ in tongue shape. This might explain why the consonants are not significantly different in our study. Laterals and nasals are not compared in previous work using these measures [29, 32, 41, 31].

4.4. Does tongue shape vary according to home language background and gender?

Our analysis of home language background effects was necessarily qualitative due to the small amount of data we have currently. Figure 4 shows that children from Gaelic-only homes have more adult-like MCI values, and NINFL values within the range of adult values compared to children from English-only, or bilingual homes. In studies of childhood bilingualism it is usually observed that there are differences according to mode of acquisition and age of onset of learning (reviewed in [16]). In this study, we have aimed to capture differences in bilingual experience by using home language background as a proxy. Typically, earlier bilinguals have more L1-like productions and it is argued that this is due to greater input, exposure, and use of the languages compared to sequential bilingualism for example in an education setting [47]. It is possible that earlier and greater exposure to Gaelic has allowed children from Gaelic-only homes to develop the motor routines, and therefore gestural sequences, needed for adult-like production of secondary articulation ahead of children from other home language backgrounds.

It should be noted that the data included in this study were intelligible productions of the target words. We are not arguing that children from bilingual or English-only homes have not acquired Gaelic consonants, but instead we suggest that the acquisition of speech articulations could be a source of the different production outcomes observed between different bilingual acquisition modes. The children from Gaelic-only homes were aged 7 and 10 years, and the children from English-only homes were aged 8, 9, and 11 years. It is not the case that English-only children were younger and Gaelic-only older, meaning that developmental factors alone cannot explain these results for differences in home language background.

There were no significant gender differences in our analyses. We did not expect to find sex-related differences in articulation strategy, but it is possible that performative gender might have led to different productions [48]. This was not the case in terms of tongue shape complexity.

5. Conclusions and future research

This pilot study aimed to provide an initial investigation into the bilingual acquisition of articulation in child speech. In doing so, we also wished to test methods for ultrasound data collection and an analysis pipeline for child speech. Our analysis of MCI and NINFL in eight words indicates a development pattern similar to reports from previous research: children have lower MCI values and higher NINFL indicating lesser lingual differentiation. In terms of the interaction of bilingualism and developmental factors, our analysis should be treated with caution due to the small numbers of participants who only use Gaelic at home. However, this first analysis indicates that early and extensive exposure to Gaelic results in earlier acquisition of the tongue shapes used in adult speech by this community.

Our next steps will be to gather more data, with a larger word list and more linguistic contexts and participants. Our eventual aim is to develop a model of bilingual child speech production building on models for adult bilinguals such as the Speech Learning Model [14], as well as infant perception [10], which will include articulatory learning [49].

6. References

[1] R. Kent, "The biology of phonological development," in *Phonological development: Models, research, implications*, C. Ferguson, L. Menn, and C. Stoel-Gammon, Eds. Timonium, MD: York Press, 1992, pp. 65–90.

[2] H. K. Vorperian, R. D. Kent, M. J. Lindstrom, C. M. Kalina, L. R. Gentry, and B. S. Yandell, "Development of vocal tract length during early childhood: A magnetic resonance imaging study," *The Journal of the Acoustical Society of America*, vol. 117, no. 1, pp. 338–350, 2005.

[3] S. Fletcher, "Palatometric specification of stop, affricate, and sibilant sounds," *Journal of Speech, Language, and Hearing Research*, vol. 32, no. 4, pp. 736–748, 1989.

[4] S. Kelso and B. Tuller, "'compensatory articulation' under conditions of reduced afferent information: A dynamic formulation," *Journal of Speech, Language, and Hearing Research*, vol. 26, no. 2, pp. 217–224, 1983.

[5] D. Abakarova, S. Fuchs, and A. Noiray, "Developmental changes in coarticulation degree relate to differences in articulatory patterns: An empirically grounded modeling approach," *Journal of Speech, Language, and Hearing Research*, vol. 65, no. 9, pp. 3276–3299, 2022.

[6] S. McLeod and K. Crowe, "Children's consonant acquisition in 27 languages: A cross-linguistic review," *American Journal of Speech-Language Pathology*, vol. 27, no. 4, pp. 1546–1571, 2018.

[7] F. Gibbon, "Undifferentiated lingual gestures in children with articulation/phonological disorders," *Journal of Speech, Language, and Hearing Research*, vol. 42, no. 2, pp. 382–397, 1999.

[8] J. Cleland and J. Scobbie, "The dorsal differentiation of velar from alveolar stops in typically developing children and children with persistent velar fronting," *Journal of Speech, Language, and Hearing Research*, vol. 64, no. 6, pp. 2347â–2362, 2021.

[9] M. Vihman and V.-A. Vihman, "From first words to segments: A case study in phonological development," in *Experience, variation and generalization: Learning a first language*, I. Arnon and E. Clark, Eds. Amsterdam: John Benjamins, 2011, pp. 109–133.

[10] S. Curtin, K. Byers-Heinlein, and J. F. Werker, "Bilingual beginnings as a lens for theory development: Primir in focus," *Journal of Phonetics*, vol. 39, no. 4, pp. 492–504, 2011.

[11] E. M. Thomas, N. Williams, L. A. Jones, S. Davies, and H. Binks, "Acquiring complex structures under minority language conditions: Bilingual acquisition of plural morphology in Welsh," *Bilingualism: Language and Cognition*, vol. 17, no. 3, pp. 478–494, 2014.

[12] H. Kennard and A. Lahiri, "Mutation in breton verbs: Pertinacity across generations," *Journal of Linguistics*, vol. 53, no. 1, pp. 113–145, 2015.

[13] C. Nance, "Sound change or community change? the speech community in sound change studies: A case study of Scottish Gaelic," *Linguistics Vanguard*, vol. 8, no. s5, pp. 677–689, 2022.

[14] J. Flege and O.-S. Bohn, "The revised Speech Learning Model (SLM-r)," in *Second language speech learning: Theoretical and empirical progress*, R. Wayland, Ed. Cambridge: Cambridge University Press, 2021, pp. 84–118.

[15] W. Baker and P. Trofimovich, "Interaction of native- and second-language vowel system(s) in early and late bilinguals," *Language and Speech*, vol. 48, no. 1, pp. 1–27, 2005.

[16] M. Amengual, "Phonetics of early bilingualism," *Annual Review of Linguistics*, vol. 10, no. 1, pp. 191–210, 2024.

[17] C. Nance, "Bilingual language exposure and the peer group: Acquiring phonetics and phonology in Gaelic Medium Education," *International Journal of Bilingualism*, vol. 24, no. 2, pp. 360–375, 2020.

[18] R. Mayr, J. Morris, I. Mennen, and D. Williams, "Disentangling the effects of long-term language contact and individual bilingualism: The case of monophthongs in Welsh and English," *International Journal of Bilingualism*, vol. 21, no. 3, pp. 245–267, 2017.

[19] I. Wilson and B. Gick, "Bilinguals use language-specific articulatory settings," *Journal of Speech, Language, and Hearing Research*, vol. 57, pp. 361–373, 2014.

[20] C. Nance and S. Kirkham, "Producing a smaller sound system: Acoustics and articulation of the subset scenario in gaelic-english bilinguals," *Bilingualism: Language and Cognition*, vol. 27, no. 4, pp. 572–584, 2024.

[21] C. Stow and S. Pert, "SLT assessment and intervention: Best practice for children and young people in bilingual settings," Position paper, Royal College of Speech and Language Therapy, https://www.rcslt.org/-/media/Project/RCSLT/slt-assessment-and-invention-summary.pdf, 2015.

[22] National Records of Scotland, *Scotland's Census 2022*. Edinburgh: National Records of Scotland, 2022.

[23] G. Munro, I. Taylor, and T. Armstrong, *The state of Gaelic in Shawbost: Language attitudes and abilities in Shawbost*. Inverness: Bòrd na Gàidhlig, 2011.

[24] C. Ó Giollagáin, G. Camshron, P. Moireach, B. Ó Curnáin, I. Caimbeul, B. Macdonald, and T. Péterváry, *The Gaelic crisis in the vernacular community: A comprehensive sociolinguistic survey of Scottish Gaelic*. Aberdeen: Aberdeen University Press, 2020.

[25] C. Nance and R. Ó Maolalaigh, "Scottish Gaelic," *Journal of the International Phonetic Association*, vol. 51, no. 2, pp. 261–275, 2021.

[26] C. Nance and S. Kirkham, "The acoustics of three-way lateral and nasal palatalisation contrasts in Scottish Gaelic," *Journal of the Acoustical Society of America*, vol. 147, no. 4, pp. 2858–2872, 2020.

[27] ——, "Phonetic typology and articulatory constraints: The realisation of secondary articulations in Scottish Gaelic rhotics," *Language*, vol. 98, no. 3, pp. 419–460, 2022.

[28] S. Kirkham and C. Nance, "Diachronic phonological asymmetries and the variable stability of synchronic contrast," *Journal of Phonetics*, vol. 94, pp. 101–176, sep 2022.

[29] K. Dawson, M. Tiede, and D. H. Whalen, "Methods for quantifying tongue shape and complexity using ultrasound imaging," *Clinical Linguistics and Phonetics*, vol. 30, no. 3-5, pp. 328–344, 2016.

[30] J. L. Preston, P. McCabe, M. Tiede, and D. H. Whalen, "Tongue shapes for rhotics in school-age children with and without residual speech errors," *Clinical Linguistics and Phonetics*, vol. 33, no. 4, pp. 334–348, 2019.

[31] M. Dokovova, E. Sugden, G. Cartney, S. Schaeffler, and J. Cleland, "Tongue shape complexity in children with and without speech sound disorders," *Journal of Speech, Language, and Hearing Research*, vol. 66, no. 7, pp. 2164–2183, 2023.

[32] H. Kabakoff, D. Harel, M. Tiede, D. H. Whalen, and T. McAllister, "Extending ultrasound tongue shape complexity measures to speech and development disorders," *Journal of Speech, Language, and Hearing Research*, vol. 64, pp. 2557–2574, 2021.

[33] A. Wrench, *Articulate Assistant Advanced version 2.21.4*. Edinburgh: Articulate Instruments, 2024.

[34] L. Spreafico, M. Pucher, and A. Matosova, "UltraFit: A speaker-friendly headset for ultrasound recordings in speech science," in *Interspeech 2018*, 2018.

[35] P. Boersma and D. Weenink. (2022) Praat: Doing phonetics by computer [computer program]. Version 6.3.03. [Online]. Available: http://www.praat.org/

[36] J. M. Scobbie, E. Lawson, S. Cowen, J. Cleland, and A. Wrench, "A common co-ordinate system for mid-sagittal articulatory measurement," *QMU CASL Working Papers*, vol. 20, 2011.

[37] S. Coretta, *rticulate: Ultrasound Tongue Imaging in R*, 2021, r package version 1.7.2. [Online]. Available: https://CRAN.R-project.org/package=rticulate

[38] D. Bates, M. Machler, B. Bolker, and S. Walker, "Fitting Linear Mixed-Effects Models Using lme4," *Journal of Statistical Software*, vol. 67, no. 1, pp. 1–48, 2015.

[39] R. H. B. Christensen, *ordinal—Regression Models for Ordinal Data*, 2023, r package version 2023.12-4. [Online]. Available: https://CRAN.R-project.org/package=ordinal

[40] B. Winter, *Statistics for linguistics: An introduction using R*. London: Routledge, 2020.

[41] H. Kabakoff, S. P. Beames, M. Tiede, D. H. Whalen, J. L. Preston, and T. McAllister, "Comparing metrics for quantification of children's tongue shape complexity using ultrasound imaging," *Clinical Linguistics and Phonetics*, vol. 37, no. 2, pp. 169–195, 2023.

[42] S. Lin and K. Demuth, "Children's acquisition of english onset and coda /l/: Articulatory evidence," *Journal of Speech, Language, and Hearing Research*, vol. 58, no. 1, pp. 13–27, 2015.

[43] S. Nittrouer and D. H. Whalen, "The perceptual effects of child–adult differences in fricative-vowel coarticulation," *Journal of the Acoustical Society of America*, vol. 86, no. 4, pp. 1266–1276, 1989.

[44] A. Noiray, A. Popescu, H. Killmer, E. Rubertus, S. Krüger, and L. Hintermeier, "Spoken language development and the challenge of skill integration," *Frontiers in Psychology*, vol. 10, 2019.

[45] E. Rubertus, "Coarticulatory changes across childhood: Implications for speech motor and phonological development," Ph.D. dissertation, University of Potsdam, Potsdam, Germany, 2024.

[46] C. Shuken, "An instrumental investigation of some Scottish Gaelic consonants," Ph.D. dissertation, University of Edinburgh, Edinburgh, 1980.

[47] M. Amengual, "Type of early bilingualism and its effect on the acoustic realization of allophonic variants: Early sequential and simultaneous bilinguals," *International Journal of Bilingualism*, vol. 23, no. 5, pp. 954–970, 2017.

[48] P. Eckert, "Vowels and nail polish: the emergence of linguistic style in the preadolescent heterosexual marketplace," in *Gender and belief systems: proceedings of the fourth Berkely women and language conference*, N. Warner, J. Ahlers, L. Bilmes, M. Olivee, S. Werheim, and M. Chen, Eds. Berkeley: Berkeley women and language group, 1996, pp. 183–190.

[49] L. Colantoni and J. Steele, "Integrating articulatory constraints into models of second language phonological acquisition," *Applied Psycholinguistics*, vol. 29, no. 3, pp. 489â–534, 2008.