Voice Quality in Voiceless Coda Stop Contexts: Evidence from Australian English Speakers with English and Arabic Language Backgrounds

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Abstract

Voice quality has the potential to index social characteristics but it remains understudied in sociophonetics. We examined voice quality in vowels preceding voiceless coda stops in Australian English speakers from monolingual English backgrounds and Arabic language backgrounds. In general, the Arabic background group used breathier voice quality (higher spectral tilt). We also found voice quality differences related to coda place of articulation. While both groups showed evidence of glottal constriction preceding /t/ and breathiness preceding /k/, the Arabic background group produced increased breathiness in non-alveolar contexts compared to the English background group, suggesting laryngeal setting differences for achieving voicelessness.

Index Terms: voice quality, phonation, voiceless stops, Australian English, ethnolects.

1. Introduction

In recent years, there has been increasing attention in research on Australian English (AusE) to how phonetic variation may be linked to speakers' ethnolinguistic backgrounds. A particular focus has been on how the use of certain phonetic features may index a 'non-mainstream' identity, or a level of divergence from speakers of the mainstream variety of AusE (MAusE) that is spoken by the majority of the population [1, 2, 3, 4]. Although not the only language background group to be included in such analyses, speakers with Arabic language backgrounds (particularly Lebanese Arabic) have been shown to exhibit differences to MAusE speakers for a range of features: for example, the timing of constituent components of VC rhymes [5], voice onset time [6], degree of /l/ velarisation [7], and the use of glottalisation as a hiatus breaking strategy [8]. A complete account of the features involved and whether the identified differences from MAusE represent a specific ethnolect, or rather form part of a more general multiethnolectal variety of AusE, is not yet well understood and is the subject of ongoing analysis [e.g. 9].

Previous research has provided some indication that in addition to the features described above, differences in voice quality may also exist between AusE speakers with Arabic language backgrounds and MAusE speakers. In an analysis of monosyllabic CV words, [10] found an overall breathier voice quality in speakers with Arabic backgrounds compared to MAusE speakers. [10] also identified that Arabic background speakers produced breathier offsets at the right edge of CV syllables, which they speculated may be due to phonotactic influences from Arabic.

Voice quality differences have been identified more broadly between speakers of mainstream varieties and those with non-mainstream backgrounds in a number of language varieties. In New Zealand English, [11] found that speakers with Māori backgrounds had both higher F0 and more creaky voice compared to Pakeha (i.e. white European) speakers (cf. [12], who also found a voice quality difference between Māori and Pakeha speakers but in the opposite direction). [13] identified a breathier voice quality as a feature of American English speakers with Chinese and Korean backgrounds that contributes to them "sounding Asian". In British English, [14] found that male speakers of the multiethnolectal variety Multicultural London English produced speech with a breathier voice quality than Anglo speakers from outside of London, and in a subsequent analysis showed that creaky voice was a feature of Anglo speakers from outside London [15]. A breathier voice quality has also been identified in speakers of the multiethnolectal German variety Kiezdeutsch compared to speakers of Standard German [16]. With regard to AusE, [17] found that male speakers of Aboriginal Australian English produce lower F0 and a creakier voice quality compared to MAusE speakers. In an analysis specifically examining creaky voice prevalence in different areas of Sydney, [18] found that the use of creaky voice varied according to gender and area, pointing towards potential differences within and across the dominant ethnic groups who live in these different areas.

Differences in voice quality are also known to result from phonological context in AusE: glottalisation is reported to occur in association with voiceless coda stops, resulting in laryngealisation (i.e. a period of creaky voice) of preceding vowels [19, 20]. While this has primarily been studied in coda /t/ contexts, [21] found acoustic evidence for glottalisation preceding voiceless coda stops occurring at all three places of articulation (/p, t, k/) in the unstressed syllables of trochees. [22] also found evidence of laryngealisation in voiceless coda stop contexts at all three places of articulation in the speech of AusE children. However, more recent analyses utilising electroglottography (EGG) found that the voice quality of vowels preceding voiceless coda stops in monosyllabic words varied according to stop place of articulation [23, 24]: vowels preceding /t/ and (to a lesser extent) /p/ showed increased glottal constriction towards the offset of the vowel, whereas increased glottal spreading was observed in vowels preceding /k/.

The results from the EGG analyses [23, 24] suggest that different strategies may be used to achieve voicelessness depending on the place of articulation of the coda stop, and this may result in different voice qualities during phonation for the preceding vowel: breathiness (or increased glottal spreading) preceding /k/ and creakiness (or increased glottal constriction) preceding /t, p/. However, these findings were based on speakers of MAusE with monolingual English backgrounds only. It remains an open question as to whether speakers with non-mainstream AusE backgrounds also exhibit this differential pattern of achieving voicelessness. To address this question, in this study we analyse voice quality in vowels occurring in voiceless coda stop contexts in two groups of speakers: AusE speakers with monolingual English backgrounds and AusE speakers with Arabic language backgrounds.

2. Methods

2.1. Participants and data collection

The data for this analysis were extracted from the Multicultural Australian English –Voices of Sydney (MAE-VoiS) project [9], in which the speech of 183 adolescents from various areas of Sydney was recorded. The participants in MAE-VoiS were sampled from parts of Sydney that differ in the level of linguistic diversity in the community and the dominant non-English languages spoken. Participants' speech was recorded as they engaged in a picture naming elicitation task and a spontaneous conversation with a peer facilitated by a research assistant from the community. Full details of the corpus, participants, and recording are available in [25].

For this analysis, a subset of 23 male participants aged 15-16 years (mean = 15.6 years) were selected to enable a comparison of speakers from monolingual English backgrounds and from Arabic language backgrounds. Only male speakers are examined as the corpus contains only a small number of female speakers with Arabic language background. 10 of the speakers were from monolingual English backgrounds; the other 13 were from Arabic language backgrounds. Note that the speakers with Arabic backgrounds varied in terms of their proficiency in and use of Arabic. All of the speakers included in this analysis were recorded in a face-to-face setting via a Zoom H6 digital recorder through a Rode HS2 headset microphone, with 44.1kHz sampling rate and 16-bit quantisation.

Only data collected in the picture naming task is included in this analysis. For each speaker, we extracted their productions of a set of single words with coda voiceless stops /p, t, k/. Each voiceless coda was preceded by a monophthongal vowel, with all of the AusE monophthongs sampled except for /eː/, which occurs in open monosyllables or followed by alveolar consonants only [26]. Onsets varied across the words. Each word was produced once by each participant; however, in some cases participants did not produce all of the words and in other cases a single word may have been repeated. All repetitions were included. In total, 615 items are included in the analysis. Table 1 provides an overview of the number of items according to coda context and language background group. We note that the bilabial coda context is underrepresented compared to alveolar and velar, as will be discussed below.

Table 1. Number of items according to voiceless coda context and language background group.

Group	Bilabial	Alveolar	Velar	Total
Arabic	39	205	103	347
English	30	158	80	268
Total	**69**	**363**	**183**	**615**

2.2. Acoustic analysis

All items were processed through WebMaus [27] to provide segmentation and forced alignment at the level of the phoneme. Segment boundaries were subsequently checked and hand corrected by trained research assistants. Acoustic measures of voice quality were extracted using VoiceSauce [28]. H1*-H2* is a measure of spectral tilt that is correlated with degree of glottal constriction: higher values of H1*-H2* indicate increased glottal opening whereas lower values of H1*-H2* indicate increased glottal constriction [29, 30, 31, 32]. H1*-H2* was estimated in 1 millisecond increments across each vowel. F0 measures were estimated using REAPER [33] through a custom script implemented in VoiceSauce [28]. Accurate estimation of harmonics requires reliable F0 estimation; REAPER produces robust F0 estimation even in the presence of irregular voicing and low pitch that may occur during creaky phonation [33]. The presence of nearby vowel formants can increase the amplitude of the harmonics. Therefore, in order to enable comparison across different vowel qualities, a correction algorithm was applied [34], as indicated by the asterisks (H1*-H2*). Formant measures for the amplitude correction were estimated by Praat [35] with default settings. All values were time normalised across the duration of the vowel.

2.3. Statistical analysis

The data were modelled with a generalised additive mixed model (GAMM), implemented in the mgcv [36] and itsadug [37] packages in R [38]. To examine the interaction between language background and place of articulation (POA), we created a hardcoded interaction variable: Lang-POA, with the following levels: English-Alveolar, English-Bilabial, English-Velar, Arabic-Alveolar, Arabic-Bilabial, Arabic-Velar. This was an ordered factor with English-Alveolar as the reference level. Lang-POA was included as a parametric effect in the model, to examine overall effects language background and POA. In order to examine potential differences in H1*-H2* trajectory shape, the model also included a reference smooth over normalised time, and a smooth over normalised time by Lang-POA, fitted with thin plate regression splines with 10 knots. We also included a random effect of word to account for the different onsets and different vowels present in the items, and a factor smooth over normalised time by participant, to account for individual speaker differences.

(1)

bam(T1 ~ Lang-POA + s(normalised_time) + s(normalised_time, by= Lang-POA, bs="tp" k = 10) + s(word, bs = "re") + s(normalised_time, participant, bs = "fs", m = 1)

An AR1 error model was incorporated into the final model to account for the fact that autocorrelation is likely to be present in vowel trajectory data [39, 40]. The model code is shown in (1) below. To reduce the likelihood of increased type I error, we follow [39] and consider effects significant at an alpha of $p < 0.025$ in our interpretation of the model results.

3. Results

Table 2 displays mean H1*-H2* values for each language background according to POA and overall. As can be seen, the Arabic background group exhibited higher mean H1*-H2* values compared to the English background group both overall and in each POA, indicative of less glottal constriction in this group.

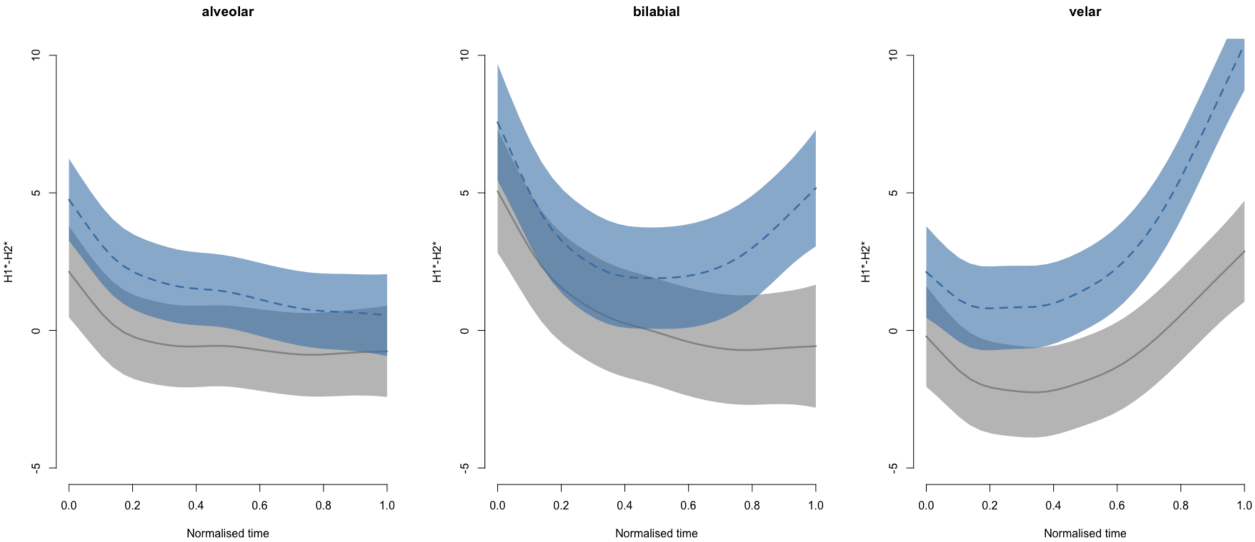

Figure 1. Model predictions of H1-H2* across the vowel preceding alveolar (left panel), bilabial (middle panel), and velar (right panel) coda contexts for speakers with monolingual English (solid grey lines) and Arabic (dashed blue lines) language backgrounds. Error ribbons show 95% CIs.*

Table 2. Mean H1-H2* values (dB) according to place of articulation and language background group.*

Group	Bilabial	Alveolar	Velar	Overall
Arabic	2.8	1.58	2.97	2.13
English	0.2	-0.46	-0.65	-0.46

The results of the GAMM are given in Table 3. Compared to the reference of English-Alveolar, there was no significant parametric difference in either /p/ or /k/ for the English background group. For the Arabic background group, there was no significant parametric difference from the reference for the alveolar POA (at an alpha of $p < .025$), but there were significant parametric differences for both bilabial and velar POAs. This indicates that overall differences between POAs were not significant within the English background group, nor were overall differences significant between the groups for the alveolar POA (although this might be considered a trend at $p = .033$). On the other hand, the Arabic group had overall significantly higher H1*-H2* in the bilabial and velar POAs compared to the reference. Pairwise comparisons using [41] show that the differences between the groups were significant for the velar ($p = 0.003$) but not the bilabial POA ($p = 0.08$).

Turning to the smooth terms, within the English background group the smooths for both bilabial and velar POAs were significantly different from the reference. For the Arabic background group, the smooth for the alveolar POA did not differ significantly from the reference, but those for the bilabial and velar POAs did. This indicates that the H1*-H2* trajectories differ across the three POAs in both of the groups, although there are differences between the groups in how these differences manifest. This can be seen in Figure 1: in the left panel, which represents the alveolar context, both groups exhibit a similar decrease in H1*-H2* from early in the vowel, with H1*-H2* remaining low throughout the rest of the trajectory. In the velar context, shown in the right panel, both groups show an initial drop in H1*-H2* followed by an increase from roughly midway through the vowel's trajectory. However, the Arabic background group demonstrate a sharper increase towards the end of the vowel's trajectory than the English background group. The most striking difference between the groups is evident in the bilabial context, shown in the middle panel: the English background group show a gradual decrease in H1*-H2* across the trajectory of the vowel, beginning from a slightly higher position compared to the alveolar context; the Arabic background group also show a similar decrease at the start of the vowel, but this diverges from the English background group's trajectory with an increase from approximately the middle of the vowel, similar to in the velar context. Inspection of the estimated differences between smooths for the two groups confirm that the differences are significant (i.e. confidence intervals show no overlap with zero [39]) throughout the vowel in the velar context, and in the second half of the vowel in the bilabial context.

4. Discussion

The results described above accord with recent findings from articulatory analysis using EGG; namely, that MAusE speakers appear to be use different strategies to achieve coda stop voicelessness depending on the place of articulation of the coda stop, and that these strategies have implications for voice quality produced during the preceding vowel. As reported in [23, 24], we here observed acoustic evidence of increased glottal constriction in vowels preceding coda /t/ and coda /p/ for speakers in the English language background group. On the contrary, acoustic evidence of increased breathiness was observed for these speakers in coda /k/ contexts, suggesting voicelessness in this context is achieved through glottal spreading [23]. While glottal constriction in coda /t/ contexts, and to a lesser extent /p/ contexts, is consistent with previous reports of glottalisation in AusE [19, 20], a few previous studies have also found acoustic evidence of glottal constriction occurring in coda /k/ [21, 22], which differs from the pattern observed here. While we note that the focus of [21, 22] differed somewhat from this analysis and the EGG study reported above—one study analysed the unstressed syllables of trochaic feet and the other focused on children's speech—it remains an empirical question as to why conflicting results have been observed. We leave this to future research to investigate.

Table 3. Summary of the results of the generalised additive mixed model.

Parametric coefficients	Estimate	SE	*t*	*p*
(Intercept)	-0.446	0.739	-0.603	0.546
English-Bilabial	0.874	0.707	1.236	0.217
English-Velar	-0.482	0.485	-0.993	0.321
Arabic-Alveolar	1.969	0.926	2.127	0.033
Arabic-Bilabial	3.474	1.146	3.032	0.002
Arabic-Velar	3.338	1.026	3.252	0.001
Smooth terms	edf	Ref. df	*F*	*p*
s(normalised time)	6.238	7.218	6.918	<0.0001
s(normalised time): English-Bilabial	2.024	2.549	4.545	0.006
s(normalised time): English-Velar	3.430	4.389	31.783	<0.0001
s(normalised time): Arabic-Alveolar	1.001	1.001	2.110	0.146
s(normalised time): Arabic-Bilabial	3.289	4.232	6.026	<0.0001
s(normalised time):Arabic-Velar	4.741	5.978	34.114	<0.0001
s(word)	21.362	24.0	9.506	<0.0001
s(normalised time, participant)	100.286	205.0	5.880	<0.0001

While the pattern of increased glottal constriction in /t/ and /p/ contexts and increased breathiness in /k/ contexts in English language background speakers corresponds with previous articulatory research on MAusE, we observed divergence from this pattern in the speakers with Arabic language backgrounds. These speakers exhibited a pattern of glottal constriction in the /t/ context but breathiness in both the /p/ and /k/ contexts, indicating group level differences in how coda voicelessness is achieved in specific phonological contexts. According to the results shown in this analysis, speakers with English language backgrounds and speakers with Arabic language backgrounds both realise coda voicelessness through increased glottal constriction (resulting in laryngealisation/creakiness on the preceding vowel) in alveolar contexts and, conversely, through increased glottal spreading (resulting in breathiness on the preceding vowel) in velar contexts. In bilabial contexts, speakers with English language backgrounds use glottal constriction, whereas speakers with Arabic language backgrounds use glottal spreading. It should here be pointed out that the bilabial context was not as well sampled as either of the other two places of articulation, as shown in Table 1. Therefore, the interpretation of the results specific to this context should be treated with caution, particularly as this is the very context where the largest differences between the groups were observed.

Nevertheless, the Arabic language background group showed evidence of greater breathiness compared to the English language background group in the velar context, and this group also exhibited higher H1*-H2* values overall in each place of articulation (although with an alpha of p = .025 this difference was not significant in the alveolar context, there was a trend towards significance). These results are consistent with previous research that found evidence for increased breathiness in the vowels and at the offset of CV syllables in Arabic background speakers. We therefore tentatively suggest that breathiness may be a more general voice quality feature indicative of this group [10].

We acknowledge that this analysis is based on a relatively small sample of only male adolescent speakers producing speech in a highly constrained task. It remains to be seen if differences in voice quality such as those observed here will also be present in a larger, more varied, sample of speakers, including female speakers, different age groups, and in spontaneous speech. Future research should also examine whether differences in voice quality are due to influences from a speaker's heritage language, whether these differences might be due to social or rather articulatory differences, and to what extent differences in voice quality are encoded in listeners' perception of different ethnolinguistic identities. We note that a breathier voice quality has been identified in some multiethnolectal varieties, for example speakers of Multicultural London English [14] and Kiezdeutsch [16], but it has also been linked to a specific 'Asian' ethnolect in American English speakers [13]. As noted above, differences in voice quality (specifically creaky voice) have previously been identified in speakers from different areas of Sydney [18]. It will therefore be interesting to examine whether increased breathiness is evident in AusE speakers with other non-English language backgrounds, or if this is specific to those with Arabic language backgrounds.

5. Conclusion

In this study, we have shown voice quality differences in vowels preceding voiceless coda stops, indicating differential strategies for achieving coda voicelessness in AusE speakers according to the place of articulation of the coda stop. Additionally, we observed differences according to speakers' language background: speakers with Arabic backgrounds have an overall breathier voice quality and exhibit a different strategy in bilabial coda contexts compared to those with monolingual English backgrounds. Future research will examine the extent to which such differences in voice quality contribute to a (multi)ethnolectal variety of AusE.

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7. References

[1] Clothier, J., "Ethnolectal variability in Australian Englishes", in L. Willoughby and H. Manns [Eds.], Australian English reimagined: Structure, features and developments, 155-172, Routledge, 2019.

[2] Clyne, M., Eisikovits, E. and Tollfree, L., "Ethnic varieties of Australian English", in D. Blair and P. Collins [Eds.], English in Australia, 223-238, Benjamins, 2001.

[3] Cox, F. M., "Australian English: Phonetics and Phonology", in L. Willoughby and H. Manns [Eds.], Australian English Reimagined: Structure, Features and Developments, Taylor & Francis/Routledge, 2020.

[4] Grama, J., Travis, C. and Gonzalez, S., "Ethnolectal and community change ov(er) time: Word-final (er) in Australian English", Australian Journal of Linguistics, 40(3):346-368, 2020.

[5] Cox, F. and Palethorpe, S., "Timing differences in the VC rhyme of standard Australian English and Lebanese Australian English", Proceedings of the 17th International Congress of Phonetic Sciences, Hong Kong, 528-531, 2011.

[6] Clothier, J. and D. Loakes, "Coronal stop VOT in Australian English: Lebanese Australians and mainstream Australian English speakers", Proceedings of 17th Australasian International Conference on Speech Science and Technology, Sydney, Australia, 13-16, 2018.
[7] Clothier, J., "A sociophonetic analysis of /l/ darkness and Lebanese Australian Ethnic Identity in Australian English", Proceedings of the 19th International Congress of Phonetic Sciences, Melbourne, Australia, 1888-1892, 2019.
[8] Cox, F., Penney, J. and Palethorpe, S., "Fifty years of change to prevocalic definite article allomorphy in Australian English", Journal of the International Phonetic Association, 53(3):804-834, 2023.
[9] Cox, F. and Penney, J., "Multicultural Australian English: Voices of Sydney (MAE-VoiS)", 2024. Available: https://doi.org/10.25949/25572153.v1.
[10] Penney, J. and Cox, F., "Vowel and voice quality differences between mainstream and non-mainstream Australian English speakers". Paper presented at Forum on Englishes in Australia, La Trobe University, 2021.
[11] Szakay, A., "Voice quality as a marker of ethnicity in New Zealand: From acoustics to perception. Journal of Sociolinguistics", 16(3):382-397, 2012.
[12] Szakay, A. and King, J., "Voice quality transfer effects between English and Māori". Paper presented at the 22nd Sociolinguistics Symposium, Auckland, New Zealand, 2018.
[13] Newman, M. and Wu, A., "Do you sound Asian when you speak English? Racial identification and voice in Chinese and Korean Americans' English", American Speech, 86:152-178, 2011.
[14] Szakay, A. and Torgersen, E. N., "An acoustic analysis of voice quality in London English: The effect of gender, ethnicity and f0", Proceedings of the 18th International Congress of Phonetic Sciences, Glasgow, Scotland, 2015.
[15] Szakay, A. and Torgersen, E., "A re-analysis of F0 in ethnic varieties of London English using REAPER", Proceedings of the International Congress of Phonetic Sciences, Melbourne, Australia, 1675-1878, 2019.
[16] Penney, J., Weirich, M. and Jannedy, S., "Increased breathiness in adolescent Kiezdeutsch speakers: A marker of mulitethnolectal group affiliation?", Language and Speech, in press.
[17] Loakes, D. and Gregory, A., "Voice quality in Australian English", *JASA Express Letters*, 2(8), 2022.
[18] White H., Penney, J., Gibson, A., Szakay, A. and Cox, F., "Creaky voice prevalence across Sydney", Journal of the Acoustical Society of America, 154:A335, 2023.
[19] Penney, J., Cox, F., Palethorpe, S. and Miles, K. "Glottalisation as a cue to coda stop voicing", Journal of Phonetics, 66:161-184, 2018.
[20] Penney, J., Cox, F. and Szakay, A., "Glottalisation, coda voicing and phrase position in Australian English", Journal of the Acoustical Society of America, 148:3232-3245, 2020.
[21] Penney, J., Cox, F. and Szakay, A., "Glottalisation of word-final stops in Australian English unstressed syllables", Journal of the International Phonetic Association, 51:229-260, 2021.
[22] Millasseau, J., Bruggeman, L., Yuen, I. and Demuth, K., "Temporal cues to onset voicing contrasts in Australian English-speaking children", Journal of Child Language, 48(6): 1262-1280, 2021.
[23] Ratko, L., Penney, J. and Cox, F., "Opening or closing? An electroglottographic analysis of voiceless coda consonants in Australian English", Proceedings of INTERSPEECH 2023, Dublin, Ireland, 1823-1827, 2023.
[24] Ratko, L., Penney, J. and Cox, F., "An electroglottographic study on the effect of following context on glottal constriction in Australian English coda /t/", Journal of the Acoustical Society of America, 154:A244, 2023.
[25] Cox, F. and Penney, J., "Multicultural Australian English: The new voice of Sydney", Australian Journal of Linguistics, 2024.
[26] Harrington, J., Cox, F. and Evans, Z., "An acoustic phonetic study of broad, general, and cultivated Australian English vowels", Australian Journal of Linguistics, 17:155-184, 1997.
[27] Kisler, T., Reichel, U. and Schiel, F., "Multilingual processing of speech via web services", Computer Speech and Language, 45:326-347, 2017.
[28] Shue, Y.-L., Keating, P., Vicenik, C. and Yu, K. "VoiceSauce: A program for voice analysis," Proceedings of the International Congress of Phonetic Sciences, Hong Kong, 1846–1849, 2011.
[29] Hillenbrand, J., Cleveland, R. and Erickson, R., "Acoustic correlates of breathy vocal quality", Journal of Speech, Language, and Hearing Research, 37:769-778, 1994.
[30] Holmberg, E. B., Hillman, R. E., Perkell, J., Guiod, P. and Goldman, S. L., "Comparisons among aerodynamic, electroglottographic, and acoustic spectral measures of female voice", Journal of Speech, Language, and Hearing Research, 38: 1212-1223, 1995.
[31] Garellek, M., "The phonetics of voice", in W. F. Katz and P. F. Assmann [Eds.], The Routledge Handbook of Phonetics, 75-106, Routledge, 2019.
[32] Keating, P., Kuang, J., Garellek, M., Esposito, C. M. and Khan, S. D., "A cross-language acoustic space for vocalic phonation distinctions", Language, 99(2):351-389, 2023.
[33] Talkin, D., "REAPER: Robust epoch and pitch EstimatoR," 2015, [Computer program]. Available: https://github.com/google/REAPER.
[34] Iseli, M., Shue, Y.-L. and Alwan, A., "Age, sex, and vowel dependencies of acoustic measures related to the voice source", Journal of the Acoustical Society of America, 121:2283-2295, 2007.
[35] Boersma, P., and Weenink, D., "Praat: Doing phonetics by computer" (6.4.04), http://www.praat.org, 2024.
[36] Wood, S N., "Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models", Journal of the Royal Statistical Society, 73:3-36, 2011.
[37] van Rij, J., Wieling, M., Baayen, H. and van Rijn, H., 2020, "itsadug: Interpreting Time series and autocorrelated data using GAMMs", version 2.4, 2020 [R package]. Available: https://cran.r-project.org/web/packages/itsadug.
[38] R Core Team, "R: A language and environment for statistical computing", version 4.3.3, 2024 [Computer program]. Available: https://www.R-project.org/.
[39] Soskuthy, M., "Evaluating generalised additive mixed modelling strategies for dynamic speech analysis", Journal of Phonetics, 84, 101017, 2021.
[40] Wieling, M., "Analyzing dynamic phonetic data using generalized additive mixed modeling: a tutorial focusing on articulatory differences between L1 and L2 speakers of English", Journal of Phonetics, 70:86-116, 2018.
[41] Lenth, R., "emmeans: Estimated marginal means, aka least-squares means", version 1.4.8, 2020 [R package]. Available: https://CRAN.R-project.org/package=emmeans.