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# Australian English Monophthong Change across 50 Years: Static versus Dynamic Measures

**Felicity Cox *, Joshua Penney and Sallyanne Palethorpe**

Centre for Languages Sciences, Department of Linguistics, Faculty of Medicine, Health and Human Sciences, Macquarie University, North Ryde, NSW 2109, Australia; joshua.penney@mq.edu.au (J.P.); sallyanne.palethorpe@mq.edu.au (S.P.)
* Correspondence: felicity.cox@mq.edu.au

**Abstract:** Most analyses of monophthong change have historically relied on static acoustic measures. It is unclear the extent to which dynamic measures can shed greater light on monophthong change than can already be captured using such static approaches. In this study, we conducted a real-time trend analysis of vowels in corpora collected from female Mainstream Australian English (MAusE) speakers under 30 years of age across three time periods: the 1960s, 1990s, and 2010s. Using three different methods for characterising the first and second formants (the target-based approach, discrete cosine transform (DCT), and generalised additive mixed model (GAMM)), we statistically examined differences for each of 10 monophthongs to outline change over the fifty-year period. Results show that all three methods complement each other in capturing the changing vowel system, with the DCT and GAMM analyses superior in their ability to provide greater nuanced detail that would be overlooked without consideration of dynamicity. However, if consideration of the vowel system as a whole is of interest (i.e., the relationships between the vowels), visualising the vowel space can facilitate interpretation, and this may require reference to static measures. We also acknowledge that locating the source of vowel dynamic differences in sound change involves reference to surrounding phonetic context.

**Keywords:** vowel acoustics; vowel change; sound change; Australian English; VISC; monophthongs

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**Citation:** Cox, Felicity, Joshua Penney, and Sallyanne Palethorpe. 2024. Australian English Monophthong Change across 50 Years: Static versus Dynamic Measures. *Languages* 9: 99. https://doi.org/10.3390/languages9030099

Academic Editor: Jaydene Elvin

Received: 3 December 2023
Revised: 14 February 2024
Accepted: 23 February 2024
Published: 13 March 2024

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## 1. Introduction

One of the challenges in phonetics is to understand how and why change occurs in vowel systems. There is a vast literature on vowel change but historically the majority of studies, particularly of monophthongs, have been based on static acoustic measures (e.g., see Labov et al. 2013). In the static target-based approach, a single time slice at the vowel midpoint or a point of formant inflection is chosen to represent the vowel "target", allowing for a comparison across vowels, across speakers, and across dialects and languages. Vowels, however, are dynamic—their articulatory configurations change over the interval of their production, influencing and being influenced by the articulatory gestures of surrounding sounds (e.g., Cole et al. 2010; Harrington et al. 2013). There is also dynamicity associated with the vowel itself. Such dynamicity holds the key to phonemic identity in the case of diphthongs, but research shows that vowel inherent spectral change (VISC) is a feature of vowels more generally (e.g., Nearey and Assmann 1986; Nearey 2013). Many studies have shown that VISC has a sociophonetic function (see e.g., Jacewicz and Fox 2011, 2013; Docherty et al. 2018; Farrington et al. 2018; Kirkham et al. 2019; Sóskuthy et al. 2019; Renwick and Stanley 2020; Stanley et al. 2021). Dynamic characteristics of vowels also change diachronically (see e.g., Jacewicz and Fox 2013; Gubian et al. 2019; Harrington et al. 2019a; Sóskuthy et al. 2019; Cox et al., forthcoming), and such patterns of change may be obscured by purely static analyses.

Not only have studies demonstrated dynamicity associated with vowel production, but importantly, they have also shown that listeners attend to the dynamic properties of the speech signal (see Morrison 2013). These findings have led to greater attention to how dynamic and fine-grained temporal and spectral characteristics of vowels can be captured. Researchers have employed a range of techniques for measuring VISC (e.g., Jacewicz et al. 2011; Jin and Liu 2013; Williams et al. 2015; Elvin et al. 2016; Schwartz 2021), including discrete cosine transform (DCT; see e.g., Zahorian and Jagharghi 1993; Watson and Harrington 1999; Harrington et al. 2019b), generalised additive mixed models (GAMMs; Winter and Wieling 2016; Sóskuthy 2017; Wieling 2018; Chuang et al. 2020), smoothing spline analysis of variance (SS-ANOVA; Docherty et al. 2015), and functional principal components analysis (Gubian et al. 2019).

In this study we are interested in dynamicity associated with sound change and whether dynamic measures can provide greater insight into change processes associated with monophthongs compared to static measures. Our analysis focusses on Australian English (AusE), a variety that contains monophthongs that vary in their degree of inherent dynamicity (Harrington et al. 1997). In addition, the AusE vowel inventory contains a small set of vowels that contrast by length, which is known to be realised not only by duration, but also by time-varying dynamic detail (Ratko et al. 2023a, 2023b). We use two common methods to capture the dynamic characteristics of monophthongs: DCT analysis, a data reduction technique where time-varying frequency information for each formant can be encoded using the first three DCT coefficients (i.e., the mean, slope, and curvature) (Zahorian and Jagharghi 1993), and GAMMs (Winter and Wieling 2016; Sóskuthy 2017; Wieling 2018; Chuang et al. 2020), which incorporate both parametric and smooth terms, enabling analysis of non-linear time series data and facilitating comparison of formant trajectory shape between datasets.

### *1.1. Vowel Change*

Diachronic analyses show that vowel systems respond to pressures that prioritise symmetricity, presumably to ensure sufficient contrast and dispersion (Liljencrants and Lindblom 1972), although the mechanism by which this occurs remains a hot topic in the sound change literature (Harrington et al. 2018; de Boer 2000). Through such pressures, realignment of the vowel system may arise over time. Realignment occurs because shifting vowels vary in concert with each other during sound change (see e.g., Martinet 1952; Hockett 1955; Labov 1994, 2010). Two common types of vowel change are chain shifts and parallel shifts. In chain shifts, successive changes in the position of neighbouring vowels within the vowel space occur. The changes typically preserve the separation between the changing vowels, and therefore the system of phonemic contrasts (except in the case of merger—see Gordon 2015 for a review). Chain shifts (see Lubowicz 2011) have been considered as either push chain or drag chain sequences. Push chain patterns describe the change that occurs when a vowel appears to move away from an encroaching neighbour. The short front vowel shift that occurred in New Zealand English (NZE) has been the subject of extensive investigation of vowel change (e.g., Bauer 1986; Watson et al. 2000; Gordon et al. 2004; Maclagan and Hay 2007; Hay et al. 2015). This shift involves the phonetic raising of /e/ in response to a phonetically raised /æ/, with subsequent impact on neighbouring /ɪ/ through a push chain process.

In contrast, in drag chain patterns, changes in a vowel's position may leave a space in the system that can be filled by a neighbouring vowel being "dragged" into the space. For English varieties of the South East of England, Torgersen and Kerswill (2004) describe changes of the drag chain type, where lowering of /æ/ triggered subsequent lowering of neighbouring /e/.

Parallel shifts may occur when vowels appear to shift synchronously (see e.g., Cox 1999; Boberg 2005; Gordon 2015; Fruehwald 2017; Brand et al. 2021). Brand et al. (2021), using an extensive historical dataset of NZE, found covariation (i.e., parallel shifts) in the changes associated with monophthongs sampled at the midpoint. Tamminga (2019) similarly found such covariation in vowel change reversal patterns occurring in the speech of white Philadelphian women.

*1.2. Mainstream Australian English*

We concentrate our attention here on the monophthongs of Mainstream AusE (MAusE), the most common variety of AusE (Cox and Palethorpe 2007), whose vowel inventory consists of twelve monophthongs (six short /ɪ, e, æ, ɐ, ɔ, ʊ/ and six long /iː, eː, ɐː, oː, ʉː, ɜː/), six diphthongs (/əʉ/, æɪ, ɑe, oɪ, æɔ, /ɪə/), and schwa (/ə/)[1] (Cox and Palethorpe 2007; Cox and Fletcher [2012] 2017). Most acoustic analyses of MAusE monophthongs have relied on vowel descriptions derived through a static target-based approach to provide a general indication of the vowel locations within the two-dimensional F1 × F2 vowel space (e.g., Bernard 1970; Harrington et al. 1997; Cox 1999, 2006; Butcher 2006, 2012; Billington 2011; Cox and Palethorpe 2001, 2008; Jones et al. 2011; Grama et al. 2019; Purser et al. 2020). Using this approach, it is challenging to successfully capture the relationship between spectral and temporal change as the vowel unfolds (Nearey and Assmann 1986). However, some studies have included vowel dynamicity in their accounts (e.g., Harrington and Cassidy 1994; Cassidy and Watson 1998; Watson and Harrington 1999), including those aiming to provide fine phonetic detail for sociophonetic analyses (Cox et al. 2014; Docherty et al. 2015; Elvin et al. 2016; Docherty et al. 2018; Cox and Palethorpe 2019; Cox et al., forthcoming). For example, in their study of AusE spoken in Western Australia, Docherty et al. (2018) found that the dynamic characteristics of /æ/ varied according to the socioeconomic status of the speaker's neighbourhood. Studies have also documented the characteristics of certain AusE monophthongs that are well known to vary with regard to dynamicity. One of the distinctive characteristics of the MAusE accent is that /iː/ is typically onglided so that it may be considered diphthongal for some speakers (Harrington et al. 1997; Cox et al. 2014; Elvin et al. 2016; Williams et al. 2018). Cox et al. (2014) used both target and DCT approaches in an analysis of /iː/, showing changes in the dynamic characteristics of the vowel over a fifty-year period. In a separate analysis of the monophthongs /æ, oː, ʉː/ across four major Australian cities, Cox and Palethorpe (2019) found significant dynamic differences for monophthongs using DCT analysis. They showed that males from Perth in Western Australia displayed reduced dynamicity of F1 of /æ/ compared to those from Sydney, Melbourne, and Adelaide. For /oː/, female speakers from Adelaide showed greater offglide compared to those from Sydney, Melbourne, and Perth, and for /ʉː/, speakers from Adelaide and Perth displayed greater fronting as the vowel unfolds compared to speakers from Sydney. In a companion study to that reported here, Cox et al., forthcoming, used GAMMs to detail the dynamic characteristics of four MAusE diphthongs /əʉ, æɪ, ɑe, æɔ/ over a fifty-year period. Non-linear changes in the trajectories of F1 and F2 for all four vowels were found and described with reference to visualisations of the dynamic differences across time periods. However, diachronic vowel studies of MAusE incorporating dynamic analyses such as these are few. Previous studies of MAusE monophthong change based on the target approach have shown the following robust phonetic effects (based on at least two empirical accounts that use independent datasets):

- Lowering/opening of /æ/ from the 1960s to 1990s (Cox 1999; Cox and Palethorpe 2001, 2008; Cox et al., forthcoming) and continued lowering and retraction of this vowel since the 1990s (Cox and Palethorpe 2008; Grama et al. 2019; Cox et al., forthcoming);
- Raising/closing of /ɪ/ from the 1960s to 1990s (Cox 1999; Cox and Palethorpe 2008; Grama et al. 2019);
- Fronting of /ʉː/ from the 1960s to 1990s (Cox 1999; Cox et al., forthcoming);
- Lowering of /e/ since the 1990s (Cox and Palethorpe 2008; Grama et al. 2019; Cox et al., forthcoming);
- Lowering of /ɜː/ since the 1990s (Cox and Palethorpe 2008; Cox et al., forthcoming).

Few studies, however, have examined the full range of monophthongs, so it is likely that certain important changes may not be accounted for in the list above. In what follows, we will document both the static and dynamic changes across 10 monophthongs over the fifty-year period of interest from the 1960s to the 2010s. However, our primary motivation is to compare the different approaches in modelling dynamicity in vowel change.

### *1.3. Aims—Predictions*

This study aims to determine whether and how dynamic measures provide greater insight into changes in the MAusE monophthongs over a fifty-year period in recent history.

Here we present a real-time trend analysis—comparing vowels of MAusE from different speakers available in corpora collected between the 1960s to the 2010s. We examine both static and dynamic characteristics of the monophthongs, using the traditional target-based approach as well as two methods for capturing dynamic detail—DCT and GAMMs. We focus on the relationships between the monophthongs at each historical time point, not only to provide an indication of the chronology of the changes, but also to show how the vowels shift relative to one another within the vowel space throughout the period of change. This will allow us to assess whether chain shifts or parallel shifts may be at play (see e.g., Lubowicz 2011; Gordon 2011, 2015). In addition, we will be able to determine whether the dynamic characteristics of the vowels change over time, and we will consider whether this is related to a change in the global positioning of the vowels in the vowel space.

We predict that the target-based approach will provide a general indication of the vowel shifts within the two-dimensional F1 × F2 vowel space as has been shown previously and described above, but that the DCT and GAMM will provide additional evidence of change associated with dynamicity in the signal. In particular, the GAMM analysis is expected to illustrate nuanced detail as it provides a more holistic analysis of the entire shape of the trajectory that may not be as accessible through decomposition of the curve extracted via the DCT analysis.

Dynamic changes may result from three separate sources. Firstly, if a change in the vowel target occurs, this should also affect the gestures required to realise the target and should require a new trajectory (i.e., a change in the vowel's dynamic characteristics). Such changes on their own would not be the result of VISC. Secondly, if there are changes in the surrounding consonants over time (whether or not there are changes in the intended vowel target) this could affect the dynamic trajectories of the vowel but not necessarily affect the target; these changes, in themselves, would not be the result of shifts in VISC. True VISC may occur in concert with the target-induced and contextual-induced changes, but it would be challenging to disentangle one from the other. Thirdly, true dynamic change resulting from changes in the time-varying spectral characteristics of the vowel (VISC) irrespective of context may occur. The challenge of identifying the source of dynamic change will be discussed.

## 2. Materials and Methods

### *2.1. Speakers and Recordings*

The data for this study were selected from corpora representing three time periods—the 1960s, 1990s, and 2010s. Our speakers would have been in their 20s during these decades and only data from female speakers are analysed here. The same three datasets have been examined and reported in Cox et al., forthcoming, with a focus on dynamic characteristics of diphthongs and which also included a target-based monophthong analysis. Here, the focus is on the dynamicity of the monophthongs. In this study, we take a different approach to the analysis of monophthongs, and include additional speakers and tokens following further data correction (see Section 2.5 for details).

#### 2.1.1. The 1960s Dataset

The 1960s data were extracted from the Mitchell and Delbridge dataset—an archive of recordings of speakers (16–18 years), in their final year of school, collected from 327 schools across Australia between 1958 and 1960 (Mitchell and Delbridge 1965). A total of 7082 high school students are included in the full corpus. Students were recorded by their teachers, using school resources. They engaged in three tasks: reading six words (*so*, *say*, *high*, *how*, *beat*, and *boot*), and two sentences (as described below), and having a brief conversation with the teacher. Data from 121 female speakers were extracted from the full dataset.

Each speaker was from the northern suburbs of Sydney and had least one parent born in Australia.

#### 2.1.2. The 1990s Dataset

The 1990s data for this analysis were selected from a corpus of recordings of 120 female and male students (mean age 15.8 years), made in 1989–1990 (see Cox 2006). Speakers had lived in Sydney's north for over ten years, were at least second-generation Australians, and spoke only English at home. They were recorded using a portable Marantz CP430 cassette recorder and a Beyer M88 dynamic microphone reading four sentences and a set of 18 vowels in the /hVd/ context four times in random order. A short conversation with the researcher was also recorded. Thirty years after original recordings were made, the cassette recordings were digitised at a sampling rate of 44.1 kHz. Data from 60 female speakers from the 1990s dataset are used for the present analysis.

#### 2.1.3. The 2010s Dataset

Sixty-seven female speakers from the Australian Voices corpus (Cox and Palethorpe 2008), recorded between 2004 and 2010, and four speakers from AusTalk (Burnham et al. 2011), recorded in 2013, were selected for the 2010s dataset. The Australian Voices and AusTalk speakers are from the same generation of speakers, all of whom would have been under 30 in 2013 at the time the AusTalk speakers were recorded. Speakers were born in Australia with at least one parent born in Australia and the other parent speaking L1 English, had completed all of their primary and secondary schooling in Australia, and were from the northern suburbs of Sydney with a mean age of 19.6 years. Various scripted (single words and sentences) and spontaneous speech tasks are included in these corpora.

### *2.2. Data Selection*

Here we focus on 10 monophthongs /iː, ɪ, e, æ, ɐ, ɔ, oː, ʊ, ʉː, ɜː/ extracted from words in similar sentences included in the datasets across the three time periods. Words from the following two sentences were extracted. Some words within the sentences varied between the time periods and those relevant to this analysis are italicised below and further described in Table 1, which shows the number of tokens of each vowel and the words from which they have been extracted. Twenty-one tokens were removed due to production errors or noisy recordings.

**Table 1.** Number of tokens of each vowel and words from which they were extracted.

| | **1960s** | ***n*** | **1990s** | ***n*** | **2010s** | ***n*** |
|---|---|---|---|---|---|---|
| /iː/ | *speed* | 119 | *speed* | 60 | *speed* | 71 |
| /ɪ/ | *pick* | 121 | *pick* | 59 | *picked* | 71 |
| /e/ | *let's* | 121 | *spend* | 59 | *spent* | 71 |
| /æ/ | *relaxing* | 121 | *relaxing* | 59 | *relaxing* | 71 |
| /ɐ/ | *sun* | 121 | *sun* | 59 | *sun* | 71 |
| /ɔ/ | *spot* | 121 | *spot* | 56 | *spot* | 71 |
| /oː/ | *water* | 121 | *water* | 59 | *water* | 71 |
| /ʊ/ | *good* | 121 | *good* | 59 | *good* | 71 |
| /ʉː/ | *flew* | 115 | *flew* | 59 | *flew* | 70 |
| /ɜː/ | *surfing* | 121 | *surfing* | 59 | *surfing* | 71 |

Sentence 1.

- 1960s—*Let's pick* a *good spot* near the *water* and pass the morning *surfing* and *relaxing* in the *sun*.
- 1990s—Let's *pick* a *good spot* near the *water* and *spend* the morning *surfing* and *relaxing* in the *sun*.
- 2010s—Helen *picked* a *good spot* near the *water* and *spent* the morning *surfing* and *relaxing* in the *sun*.

Sentence 2.

- The plane *flew* down low over the runway, increased *speed* and circled the aerodrome/airfield a second time.

Note that the vowel /ɐː/ is not included in this analysis because it was not recorded in the sentences across all three time periods. /eː/ is also excluded because the varying contexts across the datasets would affect dynamicity of this vowel in an uncontrolled manner. The vowel /ɐ/ is taken from the nasal context *sun* at all time points. /e/ is extracted from a non-nasal context (*let's*) in the 1960s dataset and a nasal context (*spend/spent*) in the 1990s and 2010s datasets; however, the following coda consonant is coronal in each case, adding a degree of articulatory consistency. It is important to note that for high and mid vowels such as /e/, the nasal resonance may have the effect of lowering F1 through increased amplitude of the second harmonic (Stevens 2000).

### 2.3. Acoustic Analysis

Target words were automatically aligned using WebMAUS (Kisler et al. 2017), with subsequent analyses carried out using the EMU system and emuR (Winkelmann et al. 2017) in R (R Core Team 2020). The first four formant frequencies were calculated using EMU wrassp (Winkelmann et al. 2016) with the following specifications: a 25 ms Blackman window, a frame shift of 5 ms, a pre-emphasis of 0.95, and a nominal F1 of 550 Hz. All tokens from the three datasets were visually checked in EMU and misplaced boundaries or mistracked formants were manually corrected. The present analysis includes 2499 monophthongs (1960s: 1202; 1990s: 588; 2010s: 709).

Formant values (in Hertz) were recorded at 17 data points in 5% increments across normalised time from 10% to 90% of the vowel. The central 80% interval was selected for analysis in order to reduce some of the impact of surrounding phonetic context. Targets were identified according to common target-based criteria for MAusE vowels (see e.g., Harrington et al. 1997; Cox 2006; Billington 2011):

- Maximum F2 for the high non-back vowels /iː, ɪ, e, ʉː/;
- Maximum F1 for the low vowels /æ, ɐ/;
- Minimum F2 for the high back vowels /ɔ, oː, ʊ/;
- Temporal midpoint for the central vowel /ɜː/.

For the DCT analysis, we used the first three discrete cosine transform (DCT) coefficients to encode some features of time-varying frequency information for each individual hertz-scaled formant trajectory (see Watson and Harrington 1999; Williams and Escudero 2014; Harrington and Schiel 2017 for a similar approach). The mean of the formant trajectory is modelled using the zeroth DCT coefficient and the first DCT coefficient models the slope of the formant as it unfolds in time (encoding the direction and magnitude of the time series change). The second DCT coefficient models the curvature of the trajectory (Zahorian and Jagharghi 1993). The DCT coefficients were extracted from formants sampled at 17 equally spaced time points across the central 80% interval of each time-normalised vowel.

We have not applied vowel formant normalisation (Adank et al. 2004) to this dataset as such normalisation strategies may introduce artificial variation when the comparative datasets are not equivalent (Disner 1980). In this analysis, the data across the three time periods cannot be considered equivalent for the purposes of normalisation because the most open vowel (i.e., that with the highest F1) at each time point varies, leading to systems that do not lend themselves to vowel extrinsic normalisation. As we exclusively examine data from female speakers, sex-based physiological differences are greatly reduced.

### 2.4. Reliability

The third author reanalysed a randomly selected 17% set of the data. Reanalysis involved WebMAUS (Kisler et al. 2017) reprocessing, boundary checking and correction, and formant checking and correction. Intraclass coefficient (ICC) analysis from the irr package (Gamer et al. 2019) was used to assess reliability of F1 and F2, using a two-way model, agreement between ratings, a single unit of analysis, and a 95% confidence interval (CI) (Shrout and Fleiss 1979; Koo and Li 2016). The ICC values for both F1 and F2 demonstrate excellent reliability (Koo and Li 2016): F1–ICC: 0.969, $F(539,518) = 64.8$, $p = 0.000$; 95% CI: 0.964–0.974; F2–ICC: 0.991, $F(539,539) = 232$, $p = 0.000$; 95% CI 0.990–0.993.[2]

### 2.5. Statistical Analysis

For the target-based and DCT analyses, we fitted simple linear regression models using the stats package in R (R Core Team 2020). For the target-based analysis, separate models were fitted for F1 and F2 of each vowel, with the formant value (F1 or F2 in Hz) at the vowel target as the dependent variable. For the DCT analysis, separate models were fitted for F1 and F2 of each vowel with each of the zeroth, first, and second DCT coefficients for each formant included as a dependent variable. The independent variable in all target-based and DCT models was the time period (the 1960s, 1990s, and 2010s, with the 1990s group set as the reference level). The 1960s–1990s comparison and the 1990s–2010s comparison allow us to consider the chronology of the changes.

For the GAMM analysis, we fitted generalised additive mixed models using the mgcv (Wood 2011, [2006] 2017; version 1.8–31) and itsadug (van Rij et al. 2020) packages in R (R Core Team 2020). As the inclusion of interactions of multiple predictors (such as time period and vowel) is not straightforward in GAMMs, separate models were fitted for F1 and F2 of each of the vowels to enable interpretation of potential changes in each vowel over time. Time period (1960s, 1990s, 2010s) was included as an ordered factor with the 1990s group set as the reference level. In all models, a parametric term was included for time period, as well as a smooth over normalised vowel duration, a smooth over normalised vowel duration by time period, and a (random) factor smooth over-normalised vowel duration by speaker. For each model, basis functions were set to ten (i.e., $k = 11$).[3]

Note that for examination of vowel change over time using the target-based and/or DCT approaches, we would ordinarily fit linear mixed effects regression models including the independent variables of vowel and time period as fixed factors, and an interaction term between these fixed factors (e.g., as in Cox et al., forthcoming). Such an approach enables modelling of potential speaker-specific variability in the data through the inclusion of random intercepts and slopes. In the case of significant interactions between vowel and time period, we would then conduct post hoc pairwise comparisons of each vowel across the time periods to examine whether any differences between them were significant. This would involve $p$-value adjustment to reduce the increased likelihood of Type I errors when conducting multiple tests. As this paper is primarily methodological, with the aim of comparing different techniques in vowel analysis, here we present simple linear regression analyses per vowel for the target-based and DCT approaches, to maintain maximum comparability with the GAMMs, which model formant trajectories separately for each vowel (and hence without $p$-value adjustment for multiple comparisons).

## 3. Results

### 3.1. Target-Based Analysis

Figure 1 shows the mean values from the target-based analysis of each monophthong across the three time periods with ellipses representing 95% CIs. Figure 2 shows the average trajectory of each vowel through the vowel space (using the same monophthong ellipses as displayed in Figure 1) for each time period. The changes over the time periods for each of the monophthongs are represented in Figure 3, which displays the mean for each monophthong target at each time point. Arrows represent the progression across time.

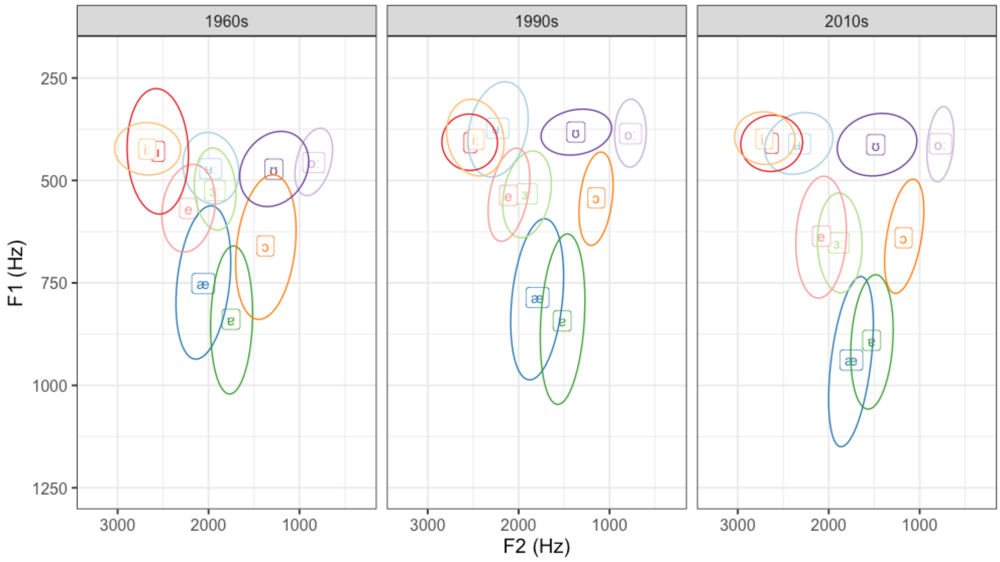


**Figure 1.** F1 and F2 (Hz) values for monophthongs across three time periods (**left** panel = 1960s; **middle** panel = 1990s; **right** panel = 2010s). Vowel labels represent mean values; ellipses represent 95% confidence intervals.

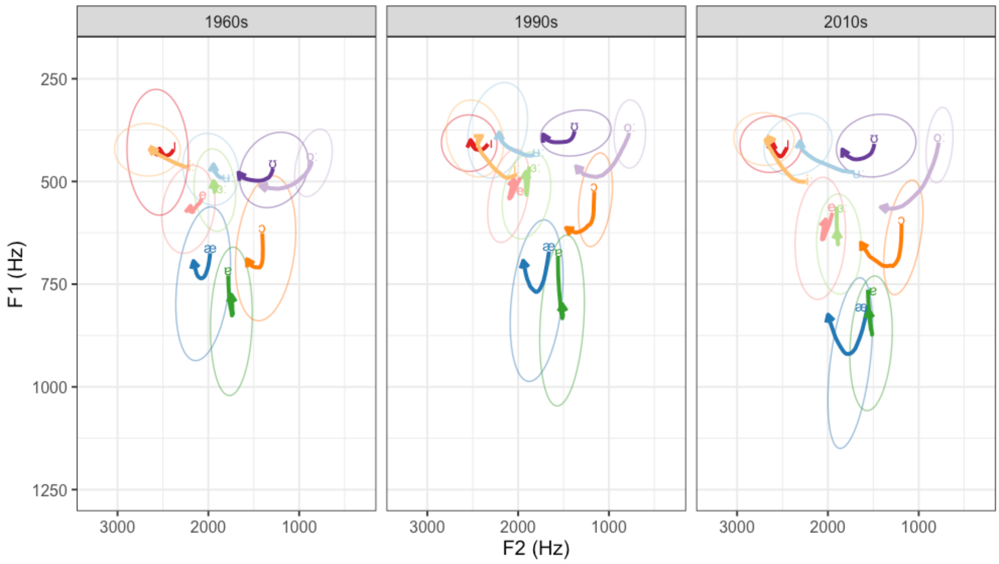


**Figure 2.** F1/F2 (Hz) trajectories for each monophthong across three time periods (**left** panel = 1960s; **middle** panel = 1990s; **right** panel = 2010s). Arrows indicate the direction of the trajectory; ellipses (corresponding to Figure 1) represent 95% confidence intervals around the target mean.

A summary of the target-based comparisons of each monophthong for F1 and F2 between the 1960s and 1990s and between the 1990s and 2010s is included in Table 2. The full set of results is given in Appendix A. The two separate comparisons provide some clues as to the chronology of the changes that have been observed through this target analysis. It is important to note that the intervals between the time points vary: 1960s–1990s: 30 years; 1990s–2010s: 20 years.

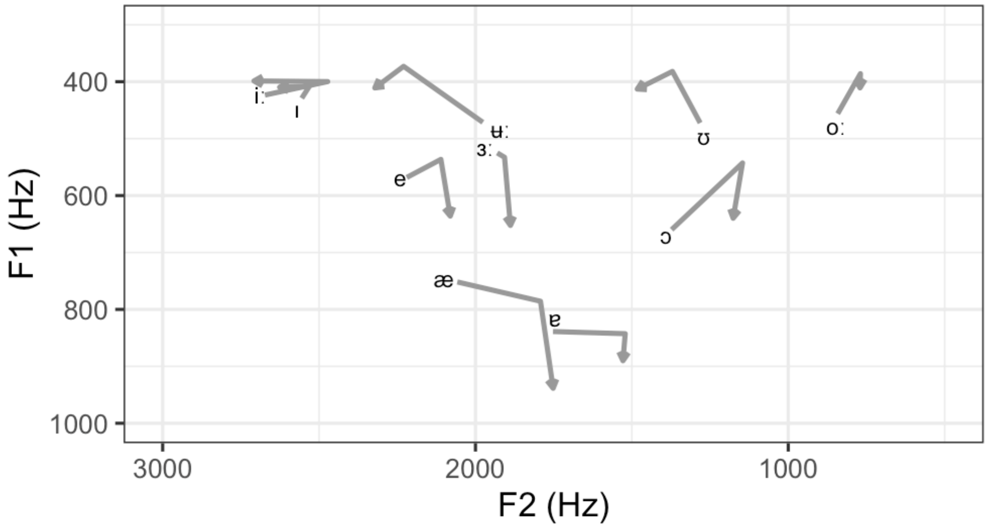


**Figure 3.** Mean F1 and F2 (Hz) target values for monophthongs across three time periods (vowel label = 1960s; elbow = 1990s; arrowhead = 2010s).

**Table 2.** Summary of the target-based analysis results comparing the time periods (1960s–1990s and 1990s–2010s) for F1 and F2 of each monophthong. Asterisks represent significant differences: * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001. Arrows indicate the direction of phonetic change (F1: raised ↑ or lowered ↓; F2: fronted ← or retracted →) relative to the older time point.

| | **1960s–1990s** | | | | **1990s–2010s** | | | |
|---|---|---|---|---|---|---|---|---|
| | **F1** | ↕ | **F2** | ⟷ | **F1** | ↕ | **F2** | ⟷ |
| /iː/ | *** | ↑ | *** | → | – | | *** | ← |
| /ɪ/ | ** | ↑ | – | | – | | *** | ← |
| /e/ | *** | ↑ | *** | → | *** | ↓ | – | |
| /æ/ | * | ↓ | *** | → | *** | ↓ | – | |
| /ɐ/ | – | | *** | → | *** | ↓ | – | |
| /ɜː/ | – | | – | | *** | ↓ | – | |
| /ɔ/ | *** | ↑ | *** | → | *** | ↓ | – | |
| /oː/ | *** | ↑ | *** | → | *** | ↓ | – | |
| /ʊ/ | *** | ↑ | ** | ← | *** | ↓ | *** | ← |
| /ʉː/ | *** | ↑ | *** | ← | *** | ↓ | *** | ← |

For the oldest comparison 1960s–1990s, the following significant changes were found: raising of /ɪ/ (see also Cox 1999; Cox and Palethorpe 2008; Grama et al. 2019), raising and retraction of /iː/ and /e/, lowering and retraction of /æ/ (Cox 1999; Cox and Palethorpe 2001, 2008), and retraction of /ɐ/; for the back vowels, raising and retraction of /ɔ/ and /oː/. Raising and fronting was also found for /ʉː/ (see Cox 1999) and /ʊ/.

For the more recent 1990s–2010s comparison we found significant fronting of /iː/ and /ɪ/, lowering of /e/, /æ/, /ɐ/, /ɜː/, /ɔ/, and /oː/, and there is also fronting and lowering of /ʊ/ and /ʉː/. The fronting of /iː/ and lowering of /e/, /ɔ/, /oː/, /ʊ/, and /ʉː/ represent reversals of results for the previous time interval (see Figure 3). Vowel change reversal is attested in the literature (see e.g., Cox and Palethorpe 2008; Labov et al. 2013; Zellou and Tamminga 2014; Tamminga 2019; D'Onofrio and Benheim 2020), but to provide an explanation for these sound change reversals would require greater examination of the sociocultural context, which is beyond the scope of the present analysis. What we know is that lowering and retraction of /æ/ and fronting of /ʉː/ are changes identified here in the 1960s–1990s comparison, confirming previous analyses of historical vowel change in MAusE. These changes are likely the catalyst for the future changes found in the 1990s–2010s comparison.

As described in Section 2.2 above, /e/ in the 1960s dataset is in the non-nasal *let's* context. In the 1990s and 2010s datasets, /e/ is taken from the nasal context *spend*/*spent*. It is possible, therefore, that the F1 value for the 1990s/2010s /e/ may be actually lower (that is, appear more raised phonetically) than it would be if sampled in a non-nasal context. This is because nasalisation of high and mid vowels induces lower F1 values (Stevens 2000). Future work will help to determine whether even greater phonetic lowering (i.e., higher F1 values) of /e/ has taken place across this timespan than is suggested here.[4] Figure 2 displays the vowel trajectories that will be quantified below in the dynamic DCT and GAMM analyses. Of particular interest is the apparent increase in dynamicity of the vowels /iː/ and /ʉː/ across the time points.

### 3.2. DCT Analysis

A summary of the comparisons for each monophthong between the 1960s and 1990s for DCT0, DCT1, and DCT2 for both F1 and F2 is included in Table 3 and the comparison for the 1990s–2010s is given in Table 4. The full set of results is included in Appendix B.

The results for DCT0 (i.e., the mean of the formant) provide the closest correspondence with the target-based analysis and they are in general agreement (see Section 3.4 below). For the 1960s–1990s DCT0 comparison, the following phonetic changes were found: for the front and low vowels, raising of /ɪ/, retraction of /iː/, /æ/, and /ɐ/, and raising and retraction of /e/; for the back vowels, raising and retraction of /ɔ/ and /oː/. Raising and fronting were found for /ɔ/ and /oː/. For the 1990s–2010s comparison we found fronting of /iː/ and /ɪ/, and lowering of all other vowels with concomitant fronting of /ɔ/ and /ʊ/.

DCT1 and DCT2 provide greater detail of each time-varying formant across the interval of the vowel by deconstructing each curve into its the slope and curvature. The specific details of the slope and curvature measures are of less importance for this analysis than the statistical differences between the groups of speakers because we are interested in changing dynamicity rather than the specific details of the slope or curvature, although this could form the basis of a future analysis. The combined DCT1 and DCT2 most closely approximate the GAMM approach, which takes a more a holistic approach to the time-varying formant change. Combining both DCT1 and DCT2, the models showed significant differences between the 1960s and 1990s data for all vowels except /ɪ/ and /ʊ/ for F1, and all vowels except /ɐ/ and /ɜː/ for F2. For the 1990s–2010s comparison, all vowels except /ɪ/ (although there is a trend; $p = 0.06$), /e/, /ʊ/, and /ʉː/ showed an effect for F1, and all except /ɪ/, /e/, and /ʊ/ showed an effect for F2.

**Table 3.** Summary of the results of the DCT analyses for F1 and F2 of each monophthong for the 1960s–1990s comparison. Asterisks represent significant differences: * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001. Arrows indicate the direction of phonetic change. For DCT0 (mean) (F1: raised ↑ or lowered ↓; F2: fronted ← or retracted →) relative to the older time point. DCT1 and DCT2 are not indicated by arrows.

| | **1960s–1990s** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **F1** | | | | **F2** | | | |
| | **DCT0** | ↕ | **DCT1** | **DCT2** | **DCT0** | ⟷ | **DCT1** | **DCT2** |
| /iː/ | – | | *** | *** | *** | → | * | ** |
| /ɪ/ | * | ↑ | – | – | – | | * | – |
| /e/ | *** | ↑ | – | *** | *** | → | *** | *** |
| /æ/ | – | | – | *** | *** | → | *** | – |
| /ɐ/ | – | | *** | * | *** | → | – | – |
| /ɜː/ | – | | ** | *** | – | | – | – |
| /ɔ/ | *** | ↑ | ** | – | *** | → | *** | ** |
| /oː/ | *** | ↑ | ** | *** | * | → | * | *** |
| /ʊ/ | *** | ↑ | – | – | *** | ← | – | *** |
| /ʉː/ | *** | ↑ | *** | * | *** | ← | *** | ** |

**Table 4.** Summary of the results of the DCT analyses for F1 and F2 of each monophthong for the 1990s–2010s comparison. Asterisks represent significant differences: * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001. Arrows indicate the direction of phonetic change. For DCT0 (mean) (F1: raised ↑ or lowered ↓; F2: fronted ← or retracted →) relative to the older time point. DCT1 and DCT2 are not indicated by arrows.

| | 1990s–2010s | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | F1 | | | | F2 | | | |
| | DCT0 | ↕ | DCT1 | DCT2 | DCT0 | ⟷ | DCT1 | DCT2 |
| /iː/ | – | | – | *** | *** | ← | – | *** |
| /ɪ/ | – | | – | – | *** | ← | – | – |
| /e/ | *** | ↓ | – | – | – | | – | – |
| /æ/ | *** | ↓ | – | * | – | | *** | – |
| /ɐ/ | ** | ↓ | ** | – | – | | * | * |
| /ɜː/ | *** | ↓ | *** | – | – | | ** | ** |
| /ɔ/ | *** | ↓ | *** | *** | *** | ← | *** | *** |
| /oː/ | *** | ↓ | *** | – | – | | * | – |
| /ʊ/ | *** | ↓ | – | – | *** | ← | – | – |
| /ʉː/ | *** | ↓ | – | – | – | | *** | *** |

### 3.3. GAMM Analysis

The GAMM analysis was conducted separately for each formant of each vowel with comparisons made between the time periods. A summary of the results for the parametric and non-linear analyses for the 1960s–1990s comparison is presented in Table 5 and for the 1990s–2010s comparison in Table 6. Full details are given in Appendix C.

For the GAMM parametric analysis (comprising the mean of the formant trajectory), all vowels showed significant differences between time points in the 1960s–1990s comparisons except /iː/, /æ/, /ɐ/, and /ɜː/ for F1, and all vowels except /ɪ/ and /ɜː/ for F2. For the 1990s–2010s comparison, all vowels except /iː/ and /ɪ/ showed parametric differences for F1. However, for F2, only /iː/, /ɪ/, /ɔ/, and /ʊ/ showed parametric effects.

For the non-linear differences between the 1960s and 1990s data, all vowels except /ɪ/ and /ʊ/ for F1, and all vowels except /ɐ/ and /ɜː/ for F2, showed significant effects, as was found for the combined DCT1 and DCT2 above. For the 1990s–2010s comparison, all vowels except /e/ and /ʊ/ showed an effect for F1, and all except /ɪ/, /e/, /oː/, and /ʊ/ showed an effect for F2. There are some discrepancies between the GAMM and the DCT1 and DCT2, and these will be further discussed below.

**Table 5.** Summary of parametric and non-linear differences for each monophthong in the GAMMs analysis for the 1960s–1990s comparison. Asterisks represent significant differences: * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001.

| Vowel | F1 Parametric | F1 Non-Linear | F2 Parametric | F2 Non-Linear |
|---|---|---|---|---|
| /iː/ | - | *** | *** | *** |
| /ɪ/ | * | - | - | ** |
| /e/ | *** | *** | *** | *** |
| /æ/ | - | *** | *** | *** |
| /ɐ/ | - | *** | *** | - |
| /ɜː/ | - | *** | - | - |
| /ɔ/ | *** | * | *** | *** |
| /oː/ | *** | *** | * | *** |
| /ʊ/ | *** | - | *** | *** |
| /ʉː/ | *** | *** | *** | *** |

**Table 6.** Summary of parametric and non-linear differences for each monophthong in the GAMMs analysis for the 1990s–2010s comparison. Asterisks represent significant differences: * ≤ 0.05, ** ≤ 0.01, *** ≤ 0.001.

| Vowel | F1 Parametric | F1 Non-Linear | F2 Parametric | F2 Non-Linear |
|---|---|---|---|---|
| /iː/ | - | *** | *** | *** |
| /ɪ/ | - | ** | *** | - |
| /e/ | *** | - | - | - |
| /æ/ | *** | * | - | *** |
| /ɐ/ | ** | *** | - | ** |
| /ɜː/ | *** | *** | - | *** |
| /ɔ/ | *** | *** | *** | *** |
| /oː/ | *** | *** | - | - |
| /ʊ/ | *** | - | *** | - |
| /ʉː/ | *** | *** | - | *** |

### 3.4. Comparison between the Target, DCT, and GAMM Analyses

We refer to the target, DCT0 analysis, and GAMM parametric analysis collectively as the *static analysis set*. The GAMM non-linear analysis is most similar in approach to the combined DCT1 and DCT2 analyses. We refer to these as the *dynamic analysis set.*

In Tables 7 and 8, we provide a summary of the results from the static and dynamic analyses for the 1960–1990s and 1990s–2010s comparisons, respectively. Firstly, we consider the target, DCT0, and GAMM parametric analysis set (i.e., the static analysis set) for both formants across the time-point analyses, and then we consider the combined DCT1 and DCT2 compared with the non-linear GAMMs analysis (i.e., the dynamic analysis set).

**Table 7.** Summary of the differences across the three different analyses for the 1960s–1990s comparison. ✓ in a cell for the Static F1 and F2 columns indicates that all three analyses show the same effect. ✓ in a cell for the Dynamic F1 and F2 columns indicates that the combined DCT1/DCT2 and the GAMM non-linear analyses show the same effect. –✓ indicates that the analyses agree that no time-point effect is present. For the Static effects, arrows indicate the direction of phonetic change (F1: raised ↑ or lowered ↓; F2: fronted ← or retracted →) relative to the older time point.

| | Static: Target, DCT0, GAMM Parametric | | Dynamic: DCT1/DCT2, GAMM Non Linear | |
|---|---|---|---|---|
| Vowel | F1 | F2 | F1 | F2 |
| /iː/ | ↑ target only | → ✓ | ✓ | ✓ |
| /ɪ/ | ↑ ✓ | – ✓ | – ✓ | ✓ |
| /e/ | ↑ ✓ | → ✓ | ✓ | ✓ |
| /æ/ | ↓ target only | → ✓ | ✓ | ✓ |
| /ɐ/ | – ✓ | → ✓ | ✓ | – ✓ |
| /ɜː/ | – ✓ | – ✓ | ✓ | – ✓ |
| /ɔ/ | ↑ ✓ | → ✓ | ✓ | ✓ |
| /oː/ | ↑ ✓ | → ✓ | ✓ | ✓ |
| /ʊ/ | ↑ ✓ | ← ✓ | – ✓ | ✓ |
| /ʉː/ | ↑ ✓ | ← ✓ | ✓ | ✓ |

**Table 8.** Summary of the differences between the three different analyses for the 1990s–2010s comparison. ✓ in a cell for the Static F1 and F2 columns indicates that all three analyses show the same effect. ✓ in a cell for the Dynamic F1 and F2 columns indicates that the combined DCT1/DCT2 and the GAMM non-linear analyses show the same effect. –✓ indicates that the analyses agree that no time-point effect is present. For the Static effects, arrows indicate the direction of phonetic change (F1: raised ↑ or lowered ↓; F2: fronted ← or retracted →) relative to the older time point.

| | **Static: Target, DCT0, GAMM Parametric** | | **Dynamic: DCT1/DCT2, GAMM Non Linear** | |
|---|---|---|---|---|
| **Vowel** | **F1** | **F2** | **F1** | **F2** |
| /iː/ | –✓ | ←✓ | ✓ | ✓ |
| /ɪ/ | –✓ | ←✓ | GAMM only (DCT2 trend 0.06) | –✓ |
| /e/ | ↓✓ | –✓ | –✓ | –✓ |
| /æ/ | ↓✓ | –✓ | ✓ | ✓ |
| /ɐ/ | ↓✓ | –✓ | ✓ | ✓ |
| /ɜː/ | ↓✓ | –✓ | ✓ | ✓ |
| /ɔ/ | ↓✓ | ← GAMM/DCT0 only | ✓ | ✓ |
| /oː/ | ↓✓ | –✓ | ✓ | DCT1 only (GAMM trend 0.054) |
| /ʊ/ | ↓✓ | ←✓ | –✓ | –✓ |
| /ʉː/ | ↓✓ | ← target only | GAMM only | ✓ |

In the 1960s–1990s comparison, for F1, all three static methods are in agreement for all vowels, except that the target-based analysis shows significant effects for raising of /iː/ and lowering of /æ/ that are not shown in the DCT0 or GAMM parametric results. An explanation for this difference may lie in the target method of pinpointing an inflection point to represent the vowel, whereas the DCT0 and GAMM parametric analyses are based on average values across the entire trajectory. In this sense, the target-based analysis may be superior in its ability to find a point that best represents the vowel target and hence small differences between datasets that could be obscured by the averaging approach. For F2, all three static methods yield the same set of results across the 1960s–1990s comparison.

In the 1990s–2010s comparison, for F1, all static methods show the same effects. For F2, all three methods are comparable for eight of the ten vowels but differ for /ɔ/, where DCT0 and GAMM find fronting that was not found in the target-based analysis, and for /ʉː/, where only the target approach finds a fronting effect. The difference in the target-based result compared to DCT0 and GAMM may be explained, as above, by suggesting that the averaging process may obscure differences that are found when an inflection point is used as in the target-based approach. A difference across the time points for /ɔ/ might be indicated in the dynamic analysis because the average of the F2 trajectory varies between the 1990s and 2010s dataset but not the target.

For the dynamic analyses, comparing the combined DCT1/DCT2 and GAMM, the 1960s–1990s analyses for both F1 and F2 showed the same effects regardless of method used. For the 1990s–2010s comparison, the dynamic analyses again showed the same effects across time points except for F1 of /ɪ/ and /ʉː/, where the GAMM identified differences in the time-varying vowel characteristics across the time points that were not found in the DCT1/DCT2 (although there was a trend for DCT2 of /ɪ/ ($p$ = 0.06). For F2, the DCT1/DCT2 identified an effect for /oː/ with a strong trend for GAMM ($p$ = 0.054).

### *3.5. Results Summary*

In summary (best visualised with reference to Figure 3), the phonetic changes identified across the three static analyses for the 1960s to 1990s include raising (target only) and retraction of /iː/; raising of /ɪ/; raising and retraction of /e/, /ɔ/, and /oː/; lowering (target only) and retraction of /æ/; retraction of /ɐ/; and raising and fronting /ʊ/ and /ʉː/, but no change for /ɜː/. Raising of /iː/ and lowering of /æ/ are only indicated in the target-based analysis.

For the 1990s–2010s changes, we found fronting for /iː/ and /ɪ/; lowering of /e/, /æ/, /ɐ/, and /ɜː/; lowering and fronting of /ʊ/ and /ɔ/ (with only DCT0 and GAMM finding fronting for /ɔ/); lowering and fronting (target-based analysis only) for /ʉː/; and lowering of /oː/.

The relationships between the static and dynamic results are complex (see Tables 7 and 8). There are three categories that summarise the effects: consistent significant differences across the static and dynamic analyses; differences in the dynamic analyses only and not in the static analyses; and differences in the static analyses that were not found in the dynamic analyses.

For F1 of the 1960s–1990s comparison, static and dynamic changes were present and consistently found for four of the ten vowels: /e/, /ɔ/, /oː/, and /ʉː/. For /iː/ and /æ/, which only showed target-based effects and not DCT0 or GAMM parametric effects, there were dynamic differences between the time points. /ɐ/ and /ɜː/ did not show static effects but dynamic differences were found. For /ɪ/ and /ʊ/, no dynamic effects between the time points were shown despite significant static effects. For F2, seven of the ten vowels, /iː/, /e/, /æ/, /ɔ/, /oː/, /ʊ/, and /ʉː/, showed effects across both static and dynamic analyses, and /ɜː/ showed no change in either type of analysis. /ɪ/ showed no static effect but dynamic effects were present. /ɐ/ showed a static effect but no dynamic effects.

For F1 of the 1990s–2010s comparison, five vowels, /æ/, /ɐ/, /ɜː/, /ɔ/, and /oː/, displayed consistent results across the static and dynamic analyses. The static effect showing /ʉː/ lowering was revealed as a dynamic change only in the GAMM analysis. No static effects were found for /iː/ and /ɪ/ but dynamic effects were found for /iː/, with only the GAMM showing an effect for /ɪ/ (a trend is seen for DCT2). For /e/ and /ʊ/, static analyses found lowering but dynamic analyses did not show differences. For F2, /iː/ fronting and non-linearity associated with F2 (onglide) was confirmed. No static or dynamic effects were found for F2 of /e/. For /ɔ/, GAMM parametric and DCT0 effects were supported by dynamic changes, and for /ʉː/, the identified target-only effect was further found in the dynamic analyses. Although the static analyses showed no significant time-point differences for F2 of /æ/, /ɐ/, /ɜː/, and /oː/, the dynamic analyses found that a non-linear change occurs across the time points for these vowels. /ɪ/ and /ʊ/ fronting were not associated with differences in dynamicity.

Across the board, the vowels that showed a static change, but no dynamic change, were restricted to short vowels (see Section 1.2): 1960s–1990s comparison: F1 of /ɪ/ and /ʊ/, F2 of /ɐ/; and 1990–2010s comparison: F1 of /e/ and /ʊ/, F2 of /ɪ/ and /ʊ/. The vowels that showed dynamic change but no static effects were: 1960s–1990s comparison: F1 of /ɐ/ and /ɜː/, F2 of /ɪ/; and 1990s–2010s comparison: F1 of /iː/ and /ɪ/, F2 of /æ/, /ɐ/, /ɜː/, and /oː/.

It is interesting to examine the effects where there is a change in the dynamic characteristics of the vowel over time for which the static analyses showed no effect. These cases have the potential to reveal changes that would be obscured by a simple target-based approach. To illustrate this point, we present GAMM visualisations for the comparison for F1 of the vowels /ɜː/ (from the word *surfing*) and /iː/ (from the word *speed*), and F2 of /æ/ (from the word *relaxing*), which showed such dynamic effects in the absence of static effects. F2 of /ʉː/ (from the word *flew*) is also displayed, which showed both static and dynamic effects for the 1960s–1990s comparison and target-only plus dynamic effects for the 1990s–2010s comparison. Figure 4 shows the estimated non-linear smooth for each time period for these vowels. Differences between the time periods across the trajectories are indicated where there is no overlap between the CIs for each time point. The upper left panel of Figure 4 shows that although the target of F1 for /ɜː/ overlaps across the 1960s and 1990s datasets, and hence no target effect was found, the 1960s trajectory is relatively flat, whereas the 1990s trajectory is curved, showing a difference in dynamicity for the vowel which appears in the same context across the three time points. Similarly, the upper right panel shows that a dynamic difference is present for F1 of /iː/ where no effect was found in the static analysis between the 1990s and 2010s. These differences are likely to be linked to changes in the degree and characteristics of dynamicity for /iː/, which is known to be variably diphthongised in AusE (Cox et al. 2014). In agreement with Figure 4, Figure 2 suggests increasing diphthongisation of /iː/ from the 1960s through to the 2010s. For /æ/, shown in the lower left panel, the 1990s–2010s static comparison found no difference for F2, but the dynamic analysis showed differences in the slope of the trajectories. For F2 of /ʉː/, shown in the lower right panel, both target and dynamic effects were found for the 2010s data, showing the greatest fronting trajectory of the three time points and suggesting an increasingly onglided vowel (see Cox and Palethorpe 2019) (see also Figure 2).

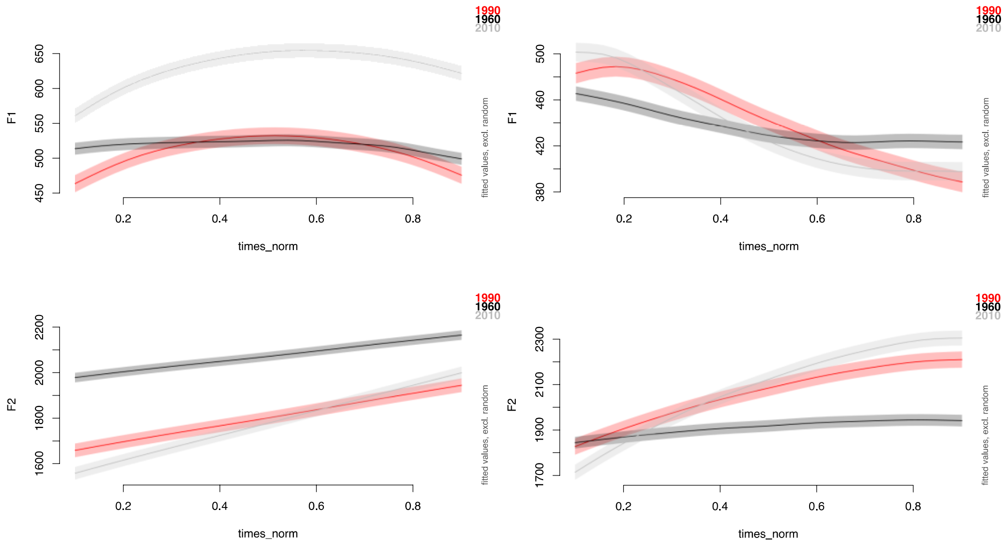


**Figure 4.** Non-linear smooths (fitted values) for F1 of /ɜː/ from the word *surfing* (**upper left**); F1 of /iː/ (**upper right**) from the word *speed*; F2 of /æ/ (**lower left**) from the word *relaxing*; F2 of /ʉː/ (**lower right**) from the word *flew*. 1990s = red (reference level); 1960s = black; 2010s = grey. Intervals in which the groups differed significantly are indicated by non-overlapping CIs. Error ribbons represent 95% CIs.

These findings illustrate that documenting the dynamic features of the vowels during sound change provides greater insight into the evolving system of vowel contrasts. This is particularly important where static changes do not indicate change but dynamic changes are shown to be present.

## 4. Discussion

The aims of this analysis were to determine whether and how dynamic measures may provide greater insight into changes in the MAusE monophthongs over a fifty-year period. In this analysis we used three methods (target-based, DCT, and GAMMs), which allowed us to compare static and dynamic approaches in our exploration of vowel change. The methods often yield similar results but also complement each other when disparate results are obtained, showing that a composite approach may be the best solution to shedding new light on changing vowel systems.

The static approaches (target-based, DCT0, and GAMM parametric analyses) deliver a set of results that show changes in the relationships between the vowels. They also provide a mechanism for suggesting the broad time frame of the changes. Results support and extend previous analyses of MAusE vowel change over similar time periods (as outlined in Section 1.2). The static analyses show that raising of the short front vowels /ɪ/ and /e/ remained in progress until the 1990s, as suggested by Cox and Palethorpe (2008) (see also Cox 1999; Grama et al. 2019). Short front vowel raising has been long described as a feature of Southern Hemisphere varieties of English (Gordon et al. 2004). The results presented here confirm that a reversal of this raising process first began during the 1960s–1990s period with lowering of /æ/ accompanied by retraction (see also Cox 1999; Cox and Palethorpe 2001). Retraction of /ɐ/ was also found in the present analysis, suggesting some influence (possibly a push chain) from /æ/, but equally, raised and retracted /ɔ/ could have initiated a drag chain effect on /ɐ/. More detailed analysis is required to tease apart the chronology of these short vowel effects, and particularly whether chain shifts or parallel shifts are involved. The changes in /æ/ and /ɐ/, along with raised and retracted /oː/, and fronted and raised /ʊ/ and /ʉː/ (Cox 1999 previously found fronted /ʉː/ for this period), suggest anticlockwise rotation.

The more recent comparison from the 1990s to the 2010s also supports Cox and Palethorpe's (2008) suggestion that short front vowel raising reached completion prior to the 1990s before reversing, possibly in response to the lowering and retracting of /æ/. The present results are consistent with previous findings of continued lowering and retraction of /æ/, and lowering of /e/, /ɜː/, and /ɐ/ (Cox and Palethorpe 2008; Grama et al. 2019; Cox et al., forthcoming), along with progressive fronting of /ʊ/ and /ʉː/ (Cox 1999). Lowering of /e/ suggests a drag chain process as it occurs subsequently to the lowering of /æ/ seen in the previous (and current) time periods. The apparently concurrent lowering of /ɜː/ and /e/ during this more recent time interval suggests a parallel shift (see also Cox and Palethorpe 2008). Hickey (2018) describes the phenomenon of short front vowel lowering as becoming increasingly common in the anglophone world and found in Canada, California, South Africa, Ireland, and Australia. Fronting of /ʊ/ and /ʉː/ is common in many varieties of English (Harrington et al. 2011), with /ʉː/ fronting typically preceding fronting of /ʊ/ through a drag chain shift (Hawkins and Midgley 2005), although here such an effect is unclear. However, fronting of /ʉː/ in the 1960s–1990s comparison is more extreme than that for /ʊ/ (see Figure 3), which may suggest /ʉː/ as the initiating change. The changes identified here provide a composite picture of general and progressive anticlockwise rotation of vowels within the F1/F2 space.

The three static methods (target, DCT0, and GAMM parametric) returned highly similar results (see columns 2 and 3 of Tables 7 and 8). However, there were four instances out of forty analyses (i.e., F1 and F2 for 10 vowels across two time-point analyses) where there were discrepancies. For three of those static measures, the target-based analysis revealed significant effects between specific time periods that were not found in the DCT0 or GAMM parametric analyses (1960s–1990s F1 of /iː/ and /æ/, 1990s–2010s F2 of /ʉː/), and there was a single example of an effect found in the DCT0 and GAMM parametric analyses that was not found in the target-based analysis (F2 of /ɔ/). In target analysis, the designated target representative of the vowel is taken at a time slice determined by an inflection point of a specific formant. In the DCT0 and GAMM parametric approaches, an average value is calculated across each formant. For some vowels, the averaging approach may be too gross a measure to capture differences. Another limitation of the DCT0 and GAMM parametric approaches is that it not possible to visualise the vowel space in the traditional way using these methods because an average across the entire formant trajectory does not provide a satisfactory representation of the vowel due to contextual influences at the vowel extremities. If the relationships between the vowels are of interest, for the purposes of visualising these relationships, we recommend that target or trajectory plots such as those in Figures 1 and 2 provide an accessible way to view vowel spaces.

The dynamic methods (DCT1/DCT2 and GAMMs non-linear) provide tools for assessing the changes in a vowel's time-varying spectral detail. These two approaches yielded highly similar results. There were only two cases (1990s–2010s F1 /ɪ/ and /ʉː/) where GAMMs showed an effect that the DCT did not, although in the case of /ɪ/, DCT2 showed a strong trend ($p$ = 0.062). A single case of discrepancy was found for F2, where DCT1 showed a significant effect for /oː/ whereas GAMM showed a trend ($p$ = 0.054).

As described in Section 1.3, dynamic changes over the time periods may result from three separate sources. Firstly, if the target of a vowel changes over time, changes in the gestures necessary to realise the changed target will be required. Thus, we would expect static effects (target, DCT0, and GAMM parametric) to be accompanied by dynamic effects. Secondly, if there are changes in the surrounding consonants over time (whether or not there are changes in the intended vowel target), this could affect the dynamic trajectories of the vowel. For instance, if a preceding /l/ is darker (i.e., produced with velarisation) at one time point in the diachronic analysis, this could affect the F2 of the vowel at its onset and lead to a changed trajectory through coarticulation rather than VISC. Figure 4 shows that the 2010s group has a lower onset for F2 in both of the lower panels, which may suggest a darker /l/ in the words *relaxing* and *flew* used to represent the vowels /æ/ and /ʉː/ compared to the other speakers. This suggestion requires further investigation. Consonantal change over recent time is an area that has not attracted as much attention as vowel change. Thirdly, a true dynamic change that results from changes in the time-varying spectral characteristics of the vowel may occur irrespective of context. Assessing the contribution of these three sources is challenging but may be possible with a larger dataset from a wider range of consonantal contexts. Future work to examine this issue is critical if we are to fully understand the various sources of dynamicity related to sound change.

For 24/40 separate analysis types, the static and dynamic analyses agreed with respect to whether or not change occurred across the relevant time periods. For these effects, it is not possible with the current datasets to establish the source of the dynamic change. In 7/40 cases, a change identified in the static analyses did not also show a dynamic effect. In all such cases, short vowels /ɪ/, /e/, /ɐ/, and /ʊ/ were involved. It is unclear why this effect should relate to only short vowels unless the approach to examining dynamicity is hampered by short duration. Further examination of the dynamic analyses of short vowels is needed to understand this effect. In 9/40 cases, no change was found in the static analysis, but change was found in the dynamic analysis (1960s–1990s: F1 /ɐ/ and /ɜː/, F2 /ɪ/; 1990s–2010s: F1 /iː/ and /ɪ/, F2 /æ/, /ɐ/, /ɜː/, and /oː/). These are the most interesting cases because they have the potential to reveal changes in VISC that cannot be identified through static analyses alone. There is the possibility that some of these effects may relate to changes in surrounding consonants. Teasing these effects apart requires analyses focused on detailing changes in consonants in parallel to vowel change.

This analysis has a number of limitations. The data were sourced only from female speakers from a particular location in Sydney producing a set of highly controlled scripted sentences, which only allowed examination of 10 of the MAusE monophthongs. We cannot make generalisations to the population from this highly restricted dataset. Future analyses should consider a wider range of contexts from non-scripted speech and from a broader speaker set. Comparing a range of dynamic techniques, such as those considered here, in addition to other techniques such as functional principal components analysis (Gubian et al. 2019), will help to improve the phonetic toolkit in the quest to further our understanding of the mechanisms by which sound change occurs. Further analyses to examine correlations between changing vowels would be of benefit to determine whether and how vowels change in parallel to provide greater insight into systemic change (Brand et al. 2021).

In this work, we restricted our analyses to F1 or F2 for each vowel individually in order to ensure comparability between the three analysis techniques. This was necessary as our approach to the GAMM analysis is to examine a single formant of a single vowel; see Section 2.5 for our rationale for taking this approach. For target-based and DCT analyses we would ordinarily fit linear mixed effects regression models which would include vowel in interaction with time period (e.g., as in Cox et al., forthcoming). This enables the inclusion of random intercepts and slopes to account for speaker-specific effects. The advantage of the target-based approach and the DCT analysis is that they allow for such analyses where the GAMMs do not. The GAMM analysis, however, provides a holistic account and is particularly useful for visualising comparative formant trajectories. The choice of approach is dependent on the specific research questions.

We found that dynamic measures do provide greater nuance to the understanding of vowel change but that the source of the time-varying spectral change must be carefully considered. We also suggest that visualisation of vowels within the F1 $\times$ F2 vowel space remains a powerful way to illustrate the changing vowel system, but this in itself may not be sufficient if we are to more fully understand vowel change.

## 5. Conclusions

This analysis showed that the examination of vowel change can benefit from both static and dynamic approaches. Static analyses provide a way to visualise vowels within the F1 $\times$ F2 delimited vowel space, enabling insight into the relationships between individual vowels. The addition of a dynamic approach such as DCT or GAMMs enhances our understanding of how time-varying spectral characteristics change in the process of vowel shift. These tools complement each other by allowing us to illuminate different aspects of change. The challenge is to explain patterns of spectral change with respect to the surrounding environment.

**Author Contributions:** Conceptualization, F.C., S.P. and J.P.; methodology, F.C., S.P. and J.P.; formal analysis, J.P. and S.P.; investigation, F.C., S.P. and J.P.; resources, F.C., S.P. and J.P.; data curation, F.C. and S.P.; writing—original draft preparation, F.C.; writing—review and editing, F.C., J.P. and S.P.; project administration, F.C.; funding acquisition, F.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Australian Research Council Future Fellowship grant FT180100462 to the first author.

**Institutional Review Board Statement:** Ethical review and approval were waived for this specific study because the data were sourced from existing corpora.

**Informed Consent Statement:** Informed consent was obtained from participants who had been previously recorded for the corpora used in this study.

**Data Availability Statement:** Data are available upon request.

**Acknowledgments:** We thank Benjamin Purser for a selection of the data processing. We are grateful for the insightful and helpful comments of the editor and two anonymous reviewers.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Appendix A

**Table A1.** Summary of results of linear regression models analysing effects of time on vowel targets for F1 and F2. Results are organised according to vowel and formant (in bold).

| | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|
| **/ʉː/ F1** | | | | |
| Intercept | 372.992 | 5.380 | 69.33 | <0.0001 |
| 1960s | 98.412 | 6.618 | 14.87 | <0.0001 |
| 2010s | 37.906 | 7.303 | 5.19 | <0.0001 |
| **/ʉː/ F2** | | | | |
| Intercept | 2229.74 | 19.59 | 113.835 | <0.0001 |
| 1960s | −253.32 | 24.09 | −10.514 | <0.0001 |
| 2010s | 92.03 | 26.59 | 3.461 | <0.0001 |
| **/iː/ F1** | | | | |
| Intercept | 399.812 | 4.207 | 95.030 | <0.0001 |
| 1960s | 23.653 | 5.160 | 4.584 | <0.0001 |
| 2010s | −1.159 | 5.715 | −0.203 | 0.839 |
| **/iː/ F2** | | | | |
| Intercept | 2472.44 | 20.10 | 123.016 | <0.0001 |
| 1960s | 200.69 | 24.65 | 8.142 | <0.0001 |
| 2010s | 235.68 | 27.30 | 8.633 | <0.0001 |
| **/ɪ/ F1** | | | | |
| Intercept | 407.822 | 6.611 | 61.688 | <0.0001 |
| 1960s | 21.234 | 8.063 | 2.633 | <0.0089 |
| 2010s | 1.849 | 8.946 | 0.207 | 0.836 |
| **/ɪ/ F2** | | | | |
| Intercept | 2530.84 | 19.01 | 133.120 | <0.0001 |
| 1960s | 24.59 | 23.19 | 1.060 | 0.290 |
| 2010s | 95.30 | 25.73 | 3.705 | <0.0003 |
| **/e/ F1** | | | | |
| Intercept | 536.457 | 7.005 | 76.578 | <0.0001 |
| 1960s | 31.738 | 8.544 | 3.715 | <0.0003 |
| 2010s | 99.583 | 9.479 | 10.505 | <0.0001 |
| **/e/ F2** | | | | |
| Intercept | 2110.57 | 15.92 | 132.569 | <0.0001 |
| 1960s | 108.98 | 19.42 | 5.613 | <0.0001 |
| 2010s | −29.98 | 21.54 | −1.392 | 0.165 |
| **/æ/ F1** | | | | |
| Intercept | 785.62 | 11.10 | 70.754 | <0.0001 |
| 1960s | −33.88 | 13.54 | −2.502 | 0.013 |
| 2010s | 152.94 | 15.02 | 10.179 | <0.0001 |

**Table A1.** *Cont.*

| | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|
| **/æ/ F2** | | | | |
| Intercept | 1792.21 | 16.36 | 109.553 | <0.0001 |
| 1960s | 265.85 | 19.95 | 13.324 | <0.0001 |
| 2010s | −40.54 | 22.14 | −1.831 | 0.0682 |
| **/ɐ/ F1** | | | | |
| Intercept | 842.662 | 10.369 | 81.269 | <0.0001 |
| 1960s | −3.807 | 12.647 | −0.301 | 0.764 |
| 2010s | 47.526 | 14.031 | 3.387 | 0.0008 |
| **/ɐ/ F2** | | | | |
| Intercept | 1521.269 | 13.371 | 113.770 | <0.0001 |
| 1960s | 230.902 | 16.309 | 14.158 | <0.0001 |
| 2010s | 7.213 | 18.093 | 0.399 | 0.69 |
| **/ɔ/ F1** | | | | |
| Intercept | 542.717 | 9.113 | 59.551 | <0.0001 |
| 1960s | 117.170 | 11.022 | 10.630 | <0.0001 |
| 2010s | 97.156 | 12.189 | 7.971 | <0.0001 |
| **/ɔ/ F2** | | | | |
| Intercept | 1146.16 | 15.89 | 72.143 | <0.0001 |
| 1960s | 226.77 | 19.22 | 11.802 | <0.0001 |
| 2010s | 30.01 | 21.25 | 1.412 | 0.159 |
| **/oː/ F1** | | | | |
| Intercept | 385.912 | 4.983 | 77.447 | <0.0001 |
| 1960s | 70.286 | 6.078 | 11.565 | <0.0001 |
| 2010s | 24.930 | 6.743 | 3.697 | 0.0002 |
| **/oː/ F2** | | | | |
| Intercept | 769.318 | 10.740 | 71.634 | <0.0001 |
| 1960s | 72.663 | 13.099 | 5.547 | <0.0001 |
| 2010s | 1.216 | 14.532 | 0.084 | 0.933 |
| **/ʊ/ F1** | | | | |
| Intercept | 381.898 | 4.568 | 83.606 | <0.0001 |
| 1960s | 90.555 | 5.571 | 16.254 | <0.0001 |
| 2010s | 31.041 | 6.181 | 5.022 | <0.0001 |
| **/ʊ/ F2** | | | | |
| Intercept | 1370.30 | 23.08 | 59.381 | <0.0001 |
| 1960s | −88.72 | 28.15 | −3.152 | 0.0018 |
| 2010s | 112.44 | 31.23 | 3.601 | <0.0004 |
| **/ɜː/ F1** | | | | |
| Intercept | 532.754 | 6.334 | 84.113 | <0.0001 |
| 1960s | −7.705 | 7.725 | −0.997 | 0.32 |
| 2010s | 119.696 | 8.751 | 13.966 | <0.0001 |

**Table A1.** *Cont.*

| | **Estimate** | *SE* | *t* | *p* |
|---|---|---|---|---|
| **/ɜː/ F2** | | | | |
| Intercept | 1907.14 | 14.22 | 134.164 | <0.0001 |
| 1960s | 23.27 | 17.34 | 1.342 | 0.181 |
| 2010s | −18.88 | 19.23 | −0.982 | 0.327 |

## Appendix B

**Table A2.** Summary of results of linear regression models analysing effects of time on DCTs for F1 and F2. Results are organised according to vowel, formant, and DCT coefficient (in bold).

| | **Estimate** | *SE* | *t* | *p* |
|---|---|---|---|---|
| **/ʉː/ F1 DCT0** | | | | |
| Intercept | 570.860 | 6.389 | 89.351 | <0.0001 |
| 1960s | 105.697 | 7.859 | 13.449 | <0.0001 |
| 2010s | 60.123 | 8.673 | 6.932 | <0.0001 |
| **/ʉː/ F2 DCT0** | | | | |
| Intercept | 2926.57 | 24.91 | 117.479 | <0.0001 |
| 1960s | −224.13 | 30.64 | −7.314 | <0.0001 |
| 2010s | 22.48 | 33.82 | 0.665 | 0.507 |
| **/ʉː/ F1 DCT1** | | | | |
| Intercept | 33.268 | 2.259 | 14.729 | <0.0001 |
| 1960s | −20.474 | 2.778 | −7.369 | <0.0001 |
| 2010s | −2.105 | 3.066 | −0.687 | 0.493 |
| **/ʉː/ F2 DCT1** | | | | |
| Intercept | −156.060 | 8.474 | −18.416 | <0.0001 |
| 1960s | 113.780 | 10.424 | 10.915 | <0.0001 |
| 2010s | −99.274 | 11.504 | −8.629 | <0.0001 |
| **/ʉː/ F1 DCT2** | | | | |
| Intercept | −5.600 | 1.169 | −4.790 | <0.0001 |
| 1960s | 3.555 | 1.438 | 2.472 | 0.0141 |
| 2010s | 2.590 | 1.587 | 1.632 | 0.104 |
| **/ʉː/ F2 DCT2** | | | | |
| Intercept | −29.075 | 4.502 | −6.459 | <0.0001 |
| 1960s | 17.331 | 5.537 | 3.130 | <0.002 |
| 2010s | −21.350 | 6.111 | −3.494 | <0.0006 |
| **/iː/ F1 DCT0** | | | | |
| Intercept | 619.772 | 5.960 | 103.981 | <0.0001 |
| 1960s | −2.954 | 7.310 | −0.404 | 0.686 |
| 2010s | −2.370 | 8.096 | −0.293 | 0.770 |

**Table A2.** *Cont.*

| | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|
| **/i:/ F2 DCT0** | | | | |
| Intercept | 3258.93 | 27.94 | 116.639 | <0.0001 |
| 1960s | 307.00 | 34.27 | 8.959 | <0.0001 |
| 2010s | 358.78 | 37.95 | 9.453 | <0.0001 |
| **/i:/ F1 DCT1** | | | | |
| Intercept | 51.3304 | 2.9937 | 17.146 | <0.0001 |
| 1960s | −32.6658 | 3.6716 | −8.897 | <0.0001 |
| 2010s | 0.8263 | 4.0664 | 0.203 | 0.839 |
| **/i:/ F2 DCT1** | | | | |
| Intercept | −184.581 | 9.824 | −18.788 | <0.0001 |
| 1960s | 29.323 | 12.049 | 2.434 | 0.0157 |
| 2010s | 25.121 | 13.345 | 1.882 | 0.061 |
| **/i:/ F1 DCT2** | | | | |
| Intercept | 0.3541 | 1.4844 | 0.239 | 0.812 |
| 1960s | 7.2213 | 1.8206 | 3.966 | <0.0001 |
| 2010s | 13.6189 | 2.0163 | 6.754 | <0.0001 |
| **/i:/ F2 DCT2** | | | | |
| Intercept | −68.416 | 4.800 | −14.254 | <0.0001 |
| 1960s | −15.592 | 5.887 | −2.649 | 0.0086 |
| 2010s | −23.460 | 6.520 | −3.598 | <0.0004 |
| **/ɪ/ F1 DCT0** | | | | |
| Intercept | 587.731 | 8.421 | 69.790 | <0.0001 |
| 1960s | 22.761 | 10.271 | 2.216 | 0.0276 |
| 2010s | 14.796 | 11.395 | 1.298 | 0.195 |
| **/ɪ/ F2 DCT0** | | | | |
| Intercept | 3458.81 | 25.45 | 135.918 | <0.0001 |
| 1960s | 47.06 | 31.04 | 1.516 | 0.131 |
| 2010s | 142.55 | 34.43 | 4.140 | <0.0001 |
| **/ɪ/ F1 DCT1** | | | | |
| Intercept | 5.712 | 2.218 | 2.576 | 0.0106 |
| 1960s | −3.775 | 2.705 | −1.396 | 0.164 |
| 2010s | 3.316 | 3.001 | 1.105 | 0.270 |
| **/ɪ/ F2 DCT1** | | | | |
| Intercept | −87.100 | 6.733 | −12.936 | <0.0001 |
| 1960s | 16.802 | 8.212 | 2.046 | 0.0418 |
| 2010s | 12.042 | 9.111 | 1.322 | 0.188 |
| **/ɪ/ F1 DCT2** | | | | |
| Intercept | −8.151 | 1.482 | −5.499 | <0.0001 |
| 1960s | 1.639 | 1.808 | 0.906 | 0.366 |
| 2010s | −3.751 | 2.006 | −1.870 | 0.063 |

**Table A2.** *Cont.*

| | **Estimate** | *SE* | *t* | *p* |
|---|---|---|---|---|
| **/ɪ/ F2 DCT2** | | | | |
| Intercept | −13.238 | 2.668 | −4.962 | <0.0001 |
| 1960s | −1.669 | 3.254 | −0.513 | 0.609 |
| 2010s | 4.957 | 3.610 | 1.373 | 0.171 |
| **/e/ F1 DCT0** | | | | |
| Intercept | 740.943 | 9.293 | 79.731 | <0.0001 |
| 1960s | 56.003 | 11.334 | 4.941 | <0.0001 |
| 2010s | 136.747 | 12.575 | 10.875 | <0.0001 |
| **/e/ F2 DCT0** | | | | |
| Intercept | 2918.30 | 21.63 | 134.902 | <0.0001 |
| 1960s | 129.62 | 26.38 | 4.913 | <0.0001 |
| 2010s | −44.60 | 29.27 | −1.524 | 0.129 |
| **/e/ F1 DCT1** | | | | |
| Intercept | −3.297 | 2.779 | −1.186 | 0.237 |
| 1960s | −6.008 | 3.389 | −1.773 | 0.078 |
| 2010s | −3.896 | 3.760 | −1.036 | 0.301 |
| **/e/ F2 DCT1** | | | | |
| Intercept | −29.988 | 5.821 | −5.152 | <0.0001 |
| 19060s | −27.240 | 7.099 | −3.837 | <0.0002 |
| 2010s | −4.169 | 7.876 | −0.529 | 0.597 |
| **/e/ F1 DCT2** | | | | |
| Intercept | −21.912 | 1.698 | −12.906 | <0.0001 |
| 1960s | 13.917 | 2.071 | 6.721 | <0.0001 |
| 2010s | −3.317 | 2.297 | −1.444 | 0.15 |
| **/e/ F2 DCT2** | | | | |
| /e/ Intercept | −38.129 | 2.688 | −14.183 | <0.0001 |
| 1960s | 23.768 | 3.279 | 7.249 | <0.0001 |
| 2010s | 6.225 | 3.638 | 1.711 | 0.088 |
| **/æ/ F1 DCT0** | | | | |
| Intercept | 1043.29 | 14.41 | 72.408 | <0.0001 |
| 1960s | −26.96 | 17.57 | −1.534 | 0.126 |
| 2010s | 202.62 | 19.50 | 10.392 | <0.0001 |
| **/æ/ F2 DCT0** | | | | |
| Intercept | 2558.54 | 19.40 | 131.87 | <0.0001 |
| 1960s | 368.92 | 23.66 | 15.59 | <0.0001 |
| 2010s | −42.80 | 26.25 | −1.63 | 0.104 |
| **/æ/ F1 DCT1** | | | | |
| Intercept | −1.861 | 5.088 | −0.366 | 0.715 |
| 1960s | −4.468 | 6.205 | −0.720 | 0.472 |
| 2010s | −1.722 | 6.884 | −0.250 | 0.803 |

**Table A2.** *Cont.*

| | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|
| **/æ/ F2 DCT1** | | | | |
| Intercept | −123.380 | 8.627 | −14.302 | <0.0001 |
| 1960s | 44.099 | 10.522 | 4.191 | <0.0001 |
| 2010s | −61.731 | 11.674 | −5.288 | <0.0001 |
| **/æ/ F1 DCT2** | | | | |
| Intercept | −38.334 | 2.884 | −13.290 | <0.0001 |
| 1960s | 16.165 | 3.518 | 4.595 | <0.0001 |
| 2010s | −9.708 | 3.903 | −2.487 | 0.0135 |
| **/æ/ F2 DCT2** | | | | |
| Intercept | −3.244 | 3.188 | −1.018 | 0.310 |
| 1960s | 5.332 | 3.889 | 1.371 | 0.172 |
| 2010s | 6.660 | 4.314 | 1.544 | 0.124 |
| **/ɐ/ F1 DCT0** | | | | |
| Intercept | 1136.137 | 13.431 | 84.592 | <0.0001 |
| 1960s | −2.166 | 16.381 | −0.132 | 0.895 |
| 2010s | 56.398 | 18.174 | 3.103 | 0.0021 |
| **/ɐ/ F2 DCT0** | | | | |
| Intercept | 2154.96 | 17.68 | 121.903 | <0.0001 |
| 1960s | 316.13 | 21.56 | 14.662 | <0.0001 |
| 2010s | 10.27 | 23.92 | 0.429 | 0.668 |
| **/ɐ/ F1 DCT1** | | | | |
| Intercept | −34.247 | 3.755 | −9.119 | <0.0001 |
| 1960s | 22.007 | 4.580 | 4.805 | <0.0001 |
| 2010s | 16.076 | 5.082 | 3.163 | 0.0018 |
| **/ɐ/ F2 DCT1** | | | | |
| Intercept | 21.280 | 4.525 | 4.703 | <0.0001 |
| 19060s | −4.170 | 5.519 | −0.756 | 0.451 |
| 2010s | −15.853 | 6.123 | −2.589 | 0.010 |
| **/ɐ/ F1 DCT2** | | | | |
| Intercept | −38.455 | 2.940 | −13.081 | <0.0001 |
| 1960s | 7.290 | 3.586 | 2.033 | 0.043 |
| 2010s | 2.274 | 3.978 | 0.572 | 0.568 |
| **/ɐ/ F2 DCT2** | | | | |
| Intercept | 11.584 | 3.087 | 3.753 | 0.0002 |
| 1960s | 1.930 | 3.765 | 0.513 | 0.609 |
| 2010s | 8.651 | 4.177 | 2.071 | 0.039 |
| **/ɔ/ F1 DCT0** | | | | |
| Intercept | 842.82 | 10.61 | 79.441 | <0.0001 |
| 1960s | 134.49 | 12.83 | 10.481 | <0.0001 |
| 2010s | 113.55 | 14.19 | 8.002 | <0.0001 |

**Table A2.** *Cont.*

| | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|
| **/ɔ/ F2 DCT0** | | | | |
| Intercept | 1786.81 | 21.91 | 81.556 | <0.0001 |
| 1960s | 262.66 | 26.50 | 9.913 | <0.0001 |
| 2010s | 104.86 | 29.30 | 3.579 | 0.0004 |
| **/ɔ/ F1 DCT1** | | | | |
| Intercept | −36.509 | 3.456 | −10.563 | <0.0001 |
| 1960s | 13.184 | 4.180 | 3.154 | 0.0018 |
| 2010s | 16.265 | 4.623 | 3.518 | 0.0005 |
| **/ɔ/ F2 DCT1** | | | | |
| Intercept | −134.637 | 8.801 | −15.297 | <0.0001 |
| 1960s | 69.944 | 10.645 | 6.101 | <0.0001 |
| 2010s | −61.952 | 11.771 | −5.263 | <0.0001 |
| **/ɔ/ F1 DCT2** | | | | |
| Intercept | −17.148 | 2.464 | −6.959 | <0.0001 |
| 1960s | −3.397 | 2.980 | −1.140 | 0.255 |
| 2010s | −17.431 | 3.296 | −5.289 | <0.0001 |
| **/ɔ/ F2 DCT2** | | | | |
| Intercept | 42.278 | 3.865 | 10.938 | <0.0001 |
| 1960s | −12.479 | 4.675 | −2.669 | 0.008 |
| 2010s | 18.757 | 5.170 | 3.628 | <0.0004 |
| **/oː/ F1 DCT0** | | | | |
| Intercept | 623.181 | 7.610 | 81.893 | <0.0001 |
| 1960s | 59.487 | 9.281 | 6.409 | <0.0001 |
| 2010s | 74.324 | 10.297 | 7.218 | <0.0001 |
| **/oː/ F2 DCT0** | | | | |
| Intercept | 1369.49 | 17.88 | 76.595 | <0.0001 |
| 1960s | 48.54 | 21.81 | 2.226 | 0.0269 |
| 2010s | 25.40 | 24.19 | 1.050 | 0.295 |
| **/oː/ F1 DCT1** | | | | |
| Intercept | −49.844 | 4.348 | −11.463 | <0.0001 |
| 1960s | 17.297 | 5.503 | 3.261 | 0.0013 |
| 2010s | −29.499 | 5.884 | −5.014 | <0.0001 |
| **/oː/ F2 DCT1** | | | | |
| Intercept | −234.11 | 10.23 | −22.893 | <0.0001 |
| 1960s | 24.68 | 12.47 | 1.979 | 0.049 |
| 2010s | −29.67 | 13.84 | −2.144 | 0.033 |
| **/oː/ F1 DCT2** | | | | |
| Intercept | −7.117 | 2.359 | −3.017 | 0.0028 |
| 1960s | 10.309 | 2.877 | 3.583 | 0.0004 |
| 2010s | 3.138 | 3.192 | 0.983 | 0.326 |

**Table A2.** *Cont.*

| | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|
| **/oː/ F2 DCT2** | | | | |
| Intercept | 76.018 | 5.536 | 13.731 | <0.0001 |
| 1960s | 29.515 | 6.752 | 4.371 | <0.0001 |
| 2010s | 10.551 | 7.491 | 1.409 | 0.16 |
| **/ʊ/ F1 DCT0** | | | | |
| Intercept | 562.051 | 5.406 | 103.976 | <0.0001 |
| 1960s | 130.038 | 6.593 | 19.723 | <0.0001 |
| 2010s | 52.206 | 7.315 | 7.137 | <0.0001 |
| **/ʊ/ F2 DCT0** | | | | |
| Intercept | 2172.17 | 29.70 | 73.135 | <0.0001 |
| 1960s | −139.26 | 36.23 | −3.844 | <0.0002 |
| 2010s | 157.67 | 40.19 | 3.923 | 0.0001 |
| **/ʊ/ F1 DCT1** | | | | |
| Intercept | −3.336 | 1.866 | −1.788 | 0.075 |
| 1960s | −2.679 | 2.275 | −1.178 | 0.240 |
| 2010s | −3.221 | 2.524 | −1.276 | 0.203 |
| **/ʊ/ F2 DCT1** | | | | |
| Intercept | −163.650 | 10.780 | −15.182 | <0.0001 |
| 1960s | −6.056 | 13.147 | −0.461 | 0.645 |
| 2010s | −4.057 | 14.586 | −0.278 | 0.781 |
| **/ʊ/ F1 DCT2** | | | | |
| Intercept | −9.7961 | 1.3013 | −7.528 | <0.0001 |
| 1960s | −0.2616 | 1.5872 | −0.165 | 0.869 |
| 2010s | −3.2448 | 1.7608 | −1.843 | 0.067 |
| **/ʊ/ F2 DCT2** | | | | |
| Intercept | 14.2258 | 4.7166 | 3.016 | 0.0028 |
| 1960s | 21.2172 | 5.7527 | 3.688 | <0.0003 |
| 2010s | −0.2463 | 6.3822 | −0.039 | 0.969 |
| **/ɜː/ F1 DCT0** | | | | |
| Intercept | 721.853 | 7.797 | 92.585 | <0.0001 |
| 1960s | 11.260 | 9.509 | 1.184 | 0.238 |
| 2010s | 169.169 | 10.550 | 16.035 | <0.0001 |
| **/ɜː/ F2 DCT0** | | | | |
| Intercept | 2693.44 | 19.51 | 138.063 | <0.0001 |
| 1960s | 35.62 | 23.79 | 1.497 | 0.136 |
| 2010s | −13.03 | 26.40 | −0.493 | 0.622 |
| **/ɜː/ F1 DCT1** | | | | |
| Intercept | −5.145 | 2.403 | −2.141 | 0.033 |
| 1960s | 9.747 | 2.931 | 3.325 | 0.001 |
| 2010s | −16.659 | 3.252 | −5.123 | <0.0001 |

**Table A2.** *Cont.*

| | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|
| **/ɜː/ F2 DCT1** | | | | |
| Intercept | −13.739 | 3.927 | −3.498 | <0.0006 |
| 1960s | 3.675 | 4.790 | 0.767 | 0.444 |
| 2010s | 17.063 | 5.314 | 3.211 | 0.0015 |
| **/ɜː/ F1 DCT2** | | | | |
| Intercept | −28.227 | 2.228 | −12.669 | <0.0001 |
| 1960s | 20.114 | 2.717 | 7.402 | <0.0001 |
| 2010s | 1.280 | 3.015 | 0.425 | 0.672 |
| **/ɜː/ F2 DCT2** | | | | |
| Intercept | −5.039 | 2.649 | −1.902 | 0.058 |
| 1960s | 4.636 | 3.231 | 1.435 | 0.153 |
| 2010s | 11.761 | 3.584 | 3.281 | 0.0012 |

## Appendix C

**Table A3.** Summary of results of GAMMs analysing effects of time on formant trajectory for F1 and F2. Results are organised according to vowel and formant (in bold).

| | Time | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|---|
| **/ʉː/ F1** | | | | | |
| Parametric coefficients | Intercept | 415.971 | 3.842 | 108.256 | <0.0001 |
| | 1960s | 63.194 | 4.737 | 13.341 | <0.0001 |
| | 2010s | 31.515 | 5.135 | 6.137 | <0.0001 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 7.798 | 8.117 | 34.62 | <0.0001 |
| | times_norm:1960s | 2.840 | 3.220 | 8.14 | <0.0001 |
| | times_norm:2010s | 1.000 | 1.001 | 13.07 | <0.0001 |
| **/ʉː/ F2** | | | | | |
| Parametric coefficients | Intercept | 2063.02 | 17.06 | 120.931 | <0.0001 |
| | 1960s | −151.58 | 20.98 | −7.224 | <0.0001 |
| | 2010s | 21.84 | 23.16 | 0.943 | 0.346 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 7.407 | 7.635 | 109.80 | <0.0001 |
| | times_norm:1960s | 5.548 | 6.100 | 47.37 | <0.0001 |
| | times_norm:2010s | 5.734 | 6.308 | 27.47 | <0.0001 |
| **/iː/ F1** | | | | | |
| Parametric coefficients | Intercept | 442.184 | 3.809 | 116.083 | <0.0001 |
| | 1960s | −5.988 | 4.675 | −1.281 | 0.200 |
| | 2010s | −5.090 | 5.173 | −0.984 | 0.325 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 8.082 | 8.270 | 54.35 | <0.0001 |
| | times_norm:1960s | 8.029 | 8.537 | 21.56 | <0.0001 |
| | times_norm:2010s | 6.449 | 7.099 | 13.62 | <0.0001 |

**Table A3.** *Cont.*

| | Time | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|---|
| **/iː/ F2** | | | | | |
| Parametric coefficients | Intercept | 2309.01 | 19.05 | 121.212 | <0.0001 |
| | 1960s | 212.45 | 23.34 | 9.101 | <0.0001 |
| | 2010s | 248.56 | 25.89 | 9.601 | <0.0001 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 8.513 | 8.640 | 152.337 | <0.0001 |
| | times_norm:1960s | 4.047 | 4.503 | 4.531 | 0.0007 |
| | times_norm:2010s | 5.891 | 6.560 | 7.257 | <0.0001 |
| **/ɪ/ F1** | | | | | |
| Parametric coefficients | Intercept | 414.864 | 5.716 | 72.579 | <0.0001 |
| | 1960s | 17.080 | 6.916 | 2.470 | 0.0136 |
| | 2010s | 11.119 | 7.789 | 1.428 | 0.154 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 7.138 | 7.406 | 28.553 | <0.0001 |
| | times_norm:1960s | 1.001 | 1.001 | 1.452 | 0.228 |
| | times_norm:2010s | 5.357 | 5.902 | 3.174 | 0.004 |
| **/ɪ/ F2** | | | | | |
| Parametric coefficients | Intercept | 2445.83 | 17.62 | 138.787 | <0.0001 |
| | 1960s | 32.09 | 21.43 | 1.497 | 0.134 |
| | 2010s | 101.80 | 23.90 | 4.260 | <0.0001 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 7.099 | 7.354 | 86.633 | <0.0001 |
| | times_norm:1960s | 1.001 | 1.001 | 10.271 | 0.0014 |
| | times_norm:2010s | 3.962 | 4.410 | 2.049 | 0.069 |
| **/e/ F1** | | | | | |
| Parametric coefficients | Intercept | 524.268 | 6.530 | 80.284 | <0.0001 |
| | 1960s | 39.565 | 7.975 | 4.961 | <0.0001 |
| | 2010s | 95.529 | 8.808 | 10.846 | <0.0001 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 8.260 | 8.385 | 65.094 | <0.0001 |
| | times_norm:1960s | 6.872 | 7.401 | 17.140 | <0.0001 |
| | times_norm:2010s | 2.870 | 3.148 | 2.136 | 0.098 |
| **/e/ F2** | | | | | |
| Parametric coefficients | Intercept | 2060.28 | 14.67 | 140.490 | <0.0001 |
| | 1960s | 95.90 | 17.90 | 5.357 | <0.0001 |
| | 2010s | −27.12 | 19.81 | −1.369 | 0.171 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 8.232 | 8.342 | 80.057 | <0.0001 |
| | times_norm:1960s | 7.225 | 7.653 | 17.792 | <0.0001 |
| | times_norm:2010s | 2.598 | 2.861 | 1.297 | 0.35 |

**Table A3.** *Cont.*

| | Time | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|---|
| **/æ/ F1** | | | | | |
| Parametric coefficients | Intercept | 737.882 | 9.824 | 75.109 | <0.0001 |
| | 1960s | −18.282 | 11.991 | −1.525 | 0.128 |
| | 2010s | 141.971 | 13.265 | 10.702 | <0.0001 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 8.471 | 8.564 | 76.722 | <0.0001 |
| | times_norm:1960s | 6.204 | 6.775 | 8.917 | <0.0001 |
| | times_norm:2010s | 3.618 | 4.002 | 2.945 | 0.019 |
| **/æ/ F2** | | | | | |
| Parametric coefficients | Intercept | 1803.08 | 14.07 | 128.120 | <0.0001 |
| | 1960s | 269.11 | 17.08 | 15.758 | <0.0001 |
| | 2010s | −22.80 | 18.95 | −1.204 | 0.229 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 4.144 | 4.479 | 128.06 | <0.0001 |
| | times_norm:1960s | 1.000 | 1.000 | 46.22 | <0.0001 |
| | times_norm:2010s | 1.002 | 1.002 | 91.39 | <0.0001 |
| **/ɐ/ F1** | | | | | |
| Parametric coefficients | Intercept | 802.190 | 9.394 | 85.391 | <0.0001 |
| | 1960s | 0.250 | 11.451 | 0.022 | 0.983 |
| | 2010s | 41.619 | 12.715 | 3.273 | 0.0010 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 8.588 | 8.685 | 100.304 | <0.0001 |
| | times_norm:1960s | 4.813 | 5.368 | 9.903 | <0.0001 |
| | times_norm:2010s | 5.674 | 6.309 | 6.897 | <0.0001 |
| **/ɐ/ F2** | | | | | |
| Parametric coefficients | Intercept | 1522.862 | 12.404 | 122.776 | <0.0001 |
| | 1960s | 225.413 | 15.038 | 14.990 | <0.0001 |
| | 2010s | 9.951 | 16.848 | 0.591 | 0.555 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 6.476 | 6.953 | 22.724 | <0.0001 |
| | times_norm:1960s | 1.000 | 1.000 | 0.627 | 0.429 |
| | times_norm:2010s | 3.158 | 3.447 | 4.135 | 0.0045 |
| **/ɔ/ F1** | | | | | |
| Parametric coefficients | Intercept | 596.788 | 7.499 | 79.579 | <0.0001 |
| | 1960s | 94.454 | 9.060 | 10.426 | <0.0001 |
| | 2010s | 78.941 | 10.041 | 7.862 | <0.0001 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 7.843 | 8.052 | 36.240 | <0.0001 |
| | times_norm:1960s | 4.400 | 4.880 | 2.370 | 0.042 |
| | times_norm:2010s | 5.934 | 6.549 | 9.905 | <0.0001 |

**Table A3.** *Cont.*

| | Time | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|---|
| **/ɔ/ F2** | | | | | |
| Parametric coefficients | Intercept | 1265.99 | 15.32 | 82.650 | <0.0001 |
| | 1960s | 182.30 | 18.51 | 9.849 | <0.0001 |
| | 2010s | 72.30 | 20.51 | 3.526 | 0.0004 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 7.549 | 7.764 | 105.99 | <0.0001 |
| | times_norm:1960s | 3.961 | 4.384 | 20.92 | <0.0001 |
| | times_norm:2010s | 5.948 | 6.523 | 14.57 | <0.0001 |
| **/o:/ F1** | | | | | |
| Parametric coefficients | Intercept | 440.358 | 5.670 | 77.666 | <0.0001 |
| | 1960s | 42.671 | 6.921 | 6.166 | <0.0001 |
| | 2010s | 53.161 | 7.650 | 6.949 | <0.0001 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 8.422 | 8.536 | 40.513 | <0.0001 |
| | times_norm:1960s | 5.996 | 6.603 | 7.878 | <0.0001 |
| | times_norm:2010s | 4.123 | 4.571 | 12.305 | <0.0001 |
| **/o:/ F2** | | | | | |
| Parametric coefficients | Intercept | 966.38 | 14.22 | 67.951 | <0.0001 |
| | 1960s | 36.41 | 17.40 | 2.092 | 0.037 |
| | 2010s | 20.54 | 19.09 | 1.076 | 0.282 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 8.118 | 8.307 | 179.767 | <0.0001 |
| | times_norm:1960s | 7.060 | 7.668 | 9.526 | <0.0001 |
| | times_norm:2010s | 2.634 | 2.854 | 2.770 | 0.054 |
| **/ʊ/ F1** | | | | | |
| Parametric coefficients | Intercept | 397.804 | 4.201 | 94.687 | <0.0001 |
| | 1960s | 91.880 | 5.135 | 17.893 | <0.0001 |
| | 2010s | 36.156 | 5.657 | 6.391 | <0.0001 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 8.062 | 8.208 | 35.168 | <0.0001 |
| | times_norm:1960s | 7.059 | 7.548 | 0.669 | 0.629 |
| | times_norm:2010s | 2.721 | 2.983 | 1.627 | 0.171 |
| **/ʊ/ F2** | | | | | |
| Parametric coefficients | Intercept | 1534.15 | 19.60 | 78.282 | <0.0001 |
| | 1960s | −95.81 | 23.99 | −3.993 | <0.0001 |
| | 2010s | 113.88 | 26.26 | 4.336 | <0.0001 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 7.348 | 7.554 | 75.360 | <0.0001 |
| | times_norm:1960s | 6.414 | 6.888 | 7.450 | <0.0001 |
| | times_norm:2010s | 1.000 | 1.000 | 0.221 | 0.639 |

**Table A3.** *Cont.*

| | Time | Estimate | *SE* | *t* | *p* |
|---|---|---|---|---|---|
| **/ɜː/ F1** | | | | | |
| Parametric coefficients | Intercept | 509.637 | 5.523 | 92.270 | <0.0001 |
| | 1960s | 9.013 | 6.745 | 1.336 | 0.182 |
| | 2010s | 120.581 | 7.455 | 16.174 | <0.0001 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 8.145 | 8.319 | 68.449 | <0.0001 |
| | times_norm:1960s | 7.635 | 8.179 | 23.446 | <0.0001 |
| | times_norm:2010s | 3.942 | 4.363 | 7.453 | <0.0001 |
| **/ɜː/ F2** | | | | | |
| Parametric coefficients | Intercept | 1898.30 | 13.72 | 138.360 | <0.0001 |
| | 1960s | 32.66 | 16.68 | 1.957 | 0.050 |
| | 2010s | −2.04 | 18.63 | −0.109 | 0.913 |
| Smooth terms | | edf | Ref.df | F | |
| | times_norm | 2.730 | 2.912 | 6.006 | 0.0008 |
| | times_norm:1960s | 1.000 | 1.000 | 0.479 | 0.489 |
| | times_norm:2010s | 3.718 | 4.100 | 5.271 | <0.0003 |

## Notes

1. We use the phonemic symbols for the vowels of Australian English recommended by Harrington et al. (1997), Cox and Palethorpe (2007) and Cox and Fletcher ([2012] 2017). MAusE is non-rhotic.
2. The reliability analysis for the present study is identical to that reported in Cox et al., forthcoming.
3. The code for these models was: bam(F1/F2 ~ Time period + s(normalised vowel duration) + s(normalised vowel duration, by = Time period, bs = "tp", k = 11) + s(normalised vowel duration, Speaker, bs = "fs", m = 1)).
4. In Cox et al., forthcoming, which used a similar dataset to that used here (but with additional tokens and prior to further corrections being applied), the following significant differences found here were not identified: 1960s–1990s raised /iː/, /ɪ/, /e/, fronted /ʊ/, retracted /oː/, 1990s–2010s lowered /ɐ/, /oː/, /ʊ/, /ʉː/, fronted /ɪ/. Note that a different statistical approach to the present analysis has been taken compared to Cox et al., forthcoming. See Section 2.5 for details.

## References


Adank, Patti, Roel Smits, and Roeland van Hout. 2004. A comparison of vowel normalisation procedures for language variation research. *Journal of the Acoustical Society of America* 116: 3099–3107. [CrossRef] [PubMed]

Bauer, Laurie. 1986. Notes on New Zealand English phonetics and phonology. *English World-Wide* 7: 225–58. [CrossRef]

Bernard, John. 1970. Towards the acoustic specification of Australian English. *Zeitschrift für Phonetik* 2: 113–28. [CrossRef]

Billington, Rosey. 2011. Location, location, location! Regional characteristics and national patterns of change in the vowels of Melbourne adolescents. *Australian Journal of Linguistics* 31: 275–303. [CrossRef]

Boberg, Charles. 2005. The Canadian Shift in Montreal. *Language Variation and Change* 17: 133–54. [CrossRef]

Brand, James, Jen Hay, Lynn Clark, Kevin Watson, and Márton Sóskuthy. 2021. Systematic co-variation of monophthongs across speakers of New Zealand English. *Journal of Phonetics* 88: 1–24. [CrossRef]

Burnham, Denis, Dominique Estival, Steven Fazio, Felicity Cox, Robert Dale, Jette Viethen, Steve Cassidy, Julien Epps, Roberto Togneri, Yuko Kinoshita, and et al. 2011. Building an Audio-Visual Corpus of Australian English: Large Corpus collection with an economical portable and replicable Black Box. Paper presented at 12th Annual Conference of the International Speech Communication Association (Interspeech 2011), Florence, Italy, August 27–31; Edited by Piero Cosi, Renato De Mori, Giuseppe Di Fabbrizio and Roberto Pieraccini. pp. 841–44. [CrossRef]

Butcher, Andrew. 2006. Formant frequencies of /hVd/ vowels in the speech of South Australian females. Paper presented at 11th Australasian International Conference on Speech Science and Technology, Auckland, New Zealand, December 6–8; Edited by Paul Warren and Catherine I. Watson. Auckland: Australasian Speech Science and Technology Association Inc., pp. 449–53.

Butcher, Andrew. 2012. Changes in the Formant frequencies of vowels in the speech of South Australian females 1945–2010. Paper presented at 14th Australasian International Conference on Speech Science and Technology, Sydney, Australia, December 3–6; Edited by Felicity Cox, Katherine Demuth, Susan Lin, Kelly Miles, Sallyanne Palethorpe, Jason Shaw and Ivan Yuen. Auckland: Australasian Speech Science and Technology Association Inc., pp. 449–53.

Cassidy, Steve, and Catherine I. Watson. 1998. Dynamic features in children's vowels. Paper presented at Fifth International Conference on Spoken Language Processing, Sydney, Australia, November 30–December 4.

Chuang, Yu-Ying, Janice Fon, and R. Harald Baayen. 2020. Analyzing phonetic data with generalized additive mixed models. *PsyArXiv*. [CrossRef]

Cole, Jennifer, Gary Linebaugh, Cheyenne M. Munson, and Bob McMurray. 2010. Unmasking the acoustic effects of vowel to vowel coarticulation: A statistical modelling approach. *Journal of Phonetics* 38: 176–184. [CrossRef]

Cox, Felicity. 1999. Vowel Change in Australian English. *Phonetica* 56: 1–27. [CrossRef]

Cox, Felicity. 2006. The acoustic characteristics of /hVd/ vowels in the speech of some Australian teenagers. *Australian Journal of Linguistics* 26: 147–79. [CrossRef]

Cox, Felicity, and Janet Fletcher. 2017. *Australian English: Pronunciation and Transcription*, 2nd ed. Melbourne: Cambridge University Press. First published 2012.

Cox, Felicity, and Sallyanne Palethorpe. 2001. The changing face of Australian English vowels. In *English in Australia*. Edited by David Blair and Peter Collins. Amsterdam: John Benjamins Publishing, pp. 17–44.

Cox, Felicity, and Sallyanne Palethorpe. 2007. Illustrations of the IPA: Australian English. *Journal of the International Phonetic Association* 37: 341–50. [CrossRef]

Cox, Felicity, and Sallyanne Palethorpe. 2008. Reversal of short front vowel raising in Australian English. Paper presented at 9th Annual Conference the International Speech Communication Association (Interspeech 2008) incorporating the 12th Australasian International Conference on Speech Science and Technology (SST 2008), Brisbane, Australia, September 22–26; Edited by Janet Fletcher, Deborah Loakes, Roland Göecke, Denis Burnham and Michael Wagner. Brisbane: International Speech Communication Association, pp. 342–45.

Cox, Felicity, and Sallyanne Palethorpe. 2019. Vowel variation across four major Australian cities. Paper presented at 19th International Congress of Phonetic Sciences (ICPhS XIX), Melbourne, Australia, August 5–9; Edited by Sasha Calhoun, Paola Escudero, Marija Tabain and Paul Warren. Canberra: Australasian Speech Science and Technology Association Inc., pp. 577–81.

Cox, Felicity, Sallyanne Palethorpe, and Samantha Bentink. 2014. Phonetic archaeology and fifty years of change to Australian English /iː/. *Australian Journal of Linguistics* 34: 50–75. [CrossRef]

Cox, Felicity, Sallyanne Palethorpe, and Joshua Penney. Forthcoming. 50 years of monophthong and diphthong shifts in Australian English. In *Speech Dynamics: Synchronic Variation and Diachronic Change*. Edited by Felicitas Kleber and Tamara Rathcke. Berlin: Mouton De Gruyter.

D'Onofrio, Annette, and Jaime Benheim. 2020. Contextualizing reversal: Local dynamics of the Northern Cities Shift in a Chicago community. *Journal of Sociolinguistics* 24: 469–91. [CrossRef]

de Boer, Bart. 2000. Self organization in vowel systems. *Journal of Phonetics* 28: 441–65. [CrossRef]

Disner, Sandra Ferrari. 1980. Evaluation of vowel normalization methods. *Journal of the Acoustical Society of America* 67: 253–61. [CrossRef] [PubMed]

Docherty, Gerard, Simon Gonzalez, and Nathaniel Mitchell. 2015. Static vs dynamic perspectives on the realization of vowel nucleii in West Australian English. Paper presented at 18th International Congress of Phonetic Sciences (ICPhS XVIII), Glasgow, UK, August 10–14; Edited by The Scottish Consortium for ICPhS 2015. Glasgow: Scotland.

Docherty, Gerard, Paul Foulkes, Simon Gonzalez, and Nathaniel Mitchell. 2018. Missed connections at the junction of sociolinguistics and speech processing. *Topics in Cognitive Science* 10: 759–74. [CrossRef] [PubMed]

Elvin, Jaydene, Daniel Williams, and Paola Escudero. 2016. Dynamic acoustic properties of monophthongs and diphthongs in Western Sydney Australian English. *The Journal of the Acoustical Society of America* 140: 576–81. [CrossRef] [PubMed]

Farrington, Charlie, Tyler Kendall, and Valerie Fridland. 2018. Vowel Dynamics in the Southern Vowel Shift. *American Speech* 93: 186–222. [CrossRef]

Fruehwald, Josef. 2017. The role of phonology in phonetic change. *Annual Review of Linguistics* 3: 25–42. [CrossRef]

Gamer, Matthias, Jim Lemon, Ian Fellows, and Puspendra Singh. 2019. R Package Irr. Available online: https://cran.r-project.org/web/packages/irr/ (accessed on 26 February 2024).

Gordon, Matthew J. 2011. Methodological and theoretical issues in the study of chain shifting. *Language and Linguistics Compass* 5: 784–94. [CrossRef]

Gordon, Matthew J. 2015. Exploring chain shifts, mergers, and near-mergers as changes in progress. In *The Oxford Handbook of Historical Phonology*. Edited by Patrick Honeybone and Joseph Salmons. Oxford: Oxford University Press, pp. 173–90.

Gordon, Elizabeth, Lyle Campbell, Jen Hay, Margaret Maclagan, Andrea Sudbury, and Peter Trudgill. 2004. *New Zealand English: Its Origins and Evolution*. Cambridge: CUP.

Grama, James, Catherine E. Travis, and Simon González. 2019. Initiation, progression and conditioning of the short-front vowel shift in Australian English. Paper presented at 19th International Congress of Phonetic Sciences (X1X), Melbourne, Australia, August 5–9; Edited by Sasha Calhoun, Paola Escudero, Marija Tabain and Paul Warren. Canberra: Australasian Speech Science and Technology Association Inc., pp. 1769–73.

Gubian, Michele, Jonathan Harrington, Mary Stevens, Florian Schiel, and Paul Warren. 2019. Tracking the New Zealand English NEAR/SQUARE Merger Using Functional Principal Components Analysis. Open Access Te Herenga Waka-Victoria University of Wellington.Paper presented at 20th Annual Conference the International Speech Communication Association Interspeech 2019, Graz, Austria, September 15–19; pp. 296–300.

Harrington, Jonathan, and Steve Cassidy. 1994. Dynamic and target theories of vowel classification: Evidence from monophthongs and diphthongs in Australian English. *Language and Speech* 37: 357–73. [CrossRef]

Harrington, Jonathan, and Florian Schiel. 2017. /u/-fronting and agent-based modeling: The relationship between the origin and spread of sound change. *Language* 93: 414–45. [CrossRef]

Harrington, Jonathan, Felicity Cox, and Zoë Evans. 1997. An acoustic phonetic study of broad, general, and cultivated Australian English vowels. *Australian Journal of Linguistics* 17: 155–84. [CrossRef]

Harrington, Jonathan, Felicitas Kleber, and Ulrich Reubold. 2011. The contributions of the lips and tongue to the diachronic fronting of high back vowels in Standard Southern British English. *Journal of the International Phonetic Association* 41: 137–56. [CrossRef]

Harrington, Jonathan, Hoole Philip, and Marianne Pouplier. 2013. Future directions in speech production. In *The Bloomsbury Companion to Phonetics*. Edited by Mark Jones and Rachael-Anne Knight. London: Bloomsbury, pp. 242–59.

Harrington, Jonathan, Felicitas Kleber, Ulrich Reubold, Florian Schiel, and Mary Stevens. 2018. Linking cognitive and social aspects of sound change using agent-based modeling. *Topics in Cognitive Science* 10: 707–28. [CrossRef]

Harrington, Jonathan, Michele Gubian, Mary Stevens, and Florian Schiel. 2019a. Phonetic change in an Antarctic winter. *The Journal of the Acoustical Society of America* 146: 3327–32. [CrossRef] [PubMed]

Harrington, Jonathan, Felicitas Kleber, Ulrich Reubold, Florian Schiel, and Mary Stevens. 2019b. The phonetic basis of the origin and spread of sound change. In *The Routledge Handbook of Phonetics*. Edited by William F. Katz and Peter F. Assmann. London: Routledge, pp. 401–26.

Hawkins, Sarah, and Jonathan Midgley. 2005. Formant frequencies of RP monophthongs in four age groups of speakers. *Journal of the International Phonetic Association* 35: 183–99. [CrossRef]

Hay, Jennifer B., Janet B. Pierrehumbert, Abby J. Walker, and Patrick LaShell. 2015. Tracking word frequency effects through 130 years of sound change. *Cognition* 139: 83–91. [CrossRef]

Hickey, Raymond. 2018. 'Yes, that's the best': Short front vowel lowering in English today. *English Today* 34: 9–16. [CrossRef]

Hockett, Charles F. 1955. *A Manual of Phonology*. Baltimore: Waverly Press.

Jacewicz, Ewa, and Robert Allen Fox. 2011. Perceptual distinctiveness of vowels in relation to dialectal sound change. *The Journal of the Acoustical Society of America* 129: 2421–21. [CrossRef]

Jacewicz, Ewa, Robert Allen Fox, and Joseph Salmons. 2011. Cross-generational vowel change in American English. *Language Variation and Change* 23: 45–86. [CrossRef] [PubMed]

Jacewicz, Ewa, and Robert Allen Fox. 2013. Cross-Dialectal Differences in Dynamic Formant Patterns in American English Vowels. In *Vowel Inherent Spectral Change*. Edited by Geoffrey Stewart Morrison and Peter F. Assmann. Berlin and Heidelberg: Springer. [CrossRef]

Jin, Su-Hyun, and Chang Liu. 2013. The vowel inherent spectral change of English vowels spoken by native and non-native speakers. *The Journal of the Acoustical Society of America* 133: EL363. [CrossRef] [PubMed]

Jones, Caroline, Felicity Meakins, and Heather Buchan. 2011. Comparing vowels in Gurindji Kriol and Katherine English: Citation speech data. *Australian Journal of Linguistics* 31: 305–26. [CrossRef]

Kirkham, Sam, Claire Nance, Bethany Littlewood, Kate Lightfoot, and Eve Groarke. 2019. Dialect variation in formant dynamics: The acoustics of lateral and vowel sequences in Manchester and Liverpool English. *The Journal of the Acoustical Society of America* 145: 784. [CrossRef] [PubMed]

Kisler, Thomas, Uwe Reichel, and Florian Schiel. 2017. Multilingual processing of speech via web services. *Computer Speech and Language* 45: 326–47. [CrossRef]

Koo, Terry K., and Mae Y. Li. 2016. A guideline of selecting and reporting intraclass correlations for reliability research. *Journal of Chiropractic Medicine* 15: 155–63. [CrossRef] [PubMed]

Labov, William. 1994. *Principles of Linguistic Change: Internal Factors*. Oxford: Blackwell.

Labov, William. 2010. *Principles of linguistic change: Cognitive and Cultural Factors*. Malden: Wiley Blackwell.

Labov, William, Rosenfelder Ingrid, and Fruehwald Josef. 2013. One hundred years of sound change in Philadelphia: Linear incrementation, reversal, and reanalysis. *Language* 89: 30–65. [CrossRef]

Liljencrants, Johan, and Björn Lindblom. 1972. Numerical simulation of vowel quality systems: The role of perceptual contrast. *Language* 48: 839–62. [CrossRef]

Lubowicz, Anna. 2011. Chain shifts. In *The Blackwell Companion to Phonology*. Edited by Marc van Oostendorp, Colin J. Ewen, Elizabeth Hume and Keren Rice. Oxford: Wiley-Blackwell, pp. 1717–35.

Maclagan, Margaret, and Jennifer Hay. 2007. Getting fed up with our feet: Contrast maintenance and the New Zealand English "short" front vowel shift. *Language Variation and Change* 9: 1–25. [CrossRef]

Martinet, André. 1952. Function, structure, and sound change. *Word* 8: 1–32. [CrossRef]

Mitchell, Alexander G., and Arthur Delbridge. 1965. *The Speech of Australian Adolescents*. Sydney: Angus and Robertson.

Morrison, Geoffrey. 2013. Theories of vowel inherent spectral change. In *Vowel Inherent Spectral Change*. Edited by Geoffrey Morrison and Peter F. Assmann. Berlin: Springer, pp. 31–47.

Nearey, Terrance M. 2013. Vowel inherent spectral change in the vowels of North American English. In *Vowel Inherent Spectral Change*. Edited by Geoffrey Morrison and Peter F. Assmann. Berlin: Springer, pp. 49–85.

Nearey, Terrance M., and Peter F. Assmann. 1986. Modeling the role of inherent spectral change in vowel identification. *The Journal of the Acoustical Society of America* 80: 1297–308. [CrossRef]

Purser, Benjamin, James Grama, and Catherine E. Travis. 2020. Australian English over time: Using sociolinguistic analysis to inform dialect coaching. *Voice and Speech* 14: 269–91. [CrossRef]

R Core Team. 2020. R: A Language and Environment for Statistical Computing. Version 4.0.2. Available online: https://www.R-project.org/ (accessed on 26 February 2024).

Ratko, Louise, Michael Proctor, and Felicity Cox. 2023a. Articulation of vowel length contrasts in Australian English. *Journal of the International Phonetic Association* 53: 774–803. [CrossRef]

Ratko, Louise, Michael Proctor, and Felicity Cox. 2023b. Gestural characterisation of vowel length contrasts in Australian English. *Journal of Phonetics* 98: 1–21. [CrossRef]

Renwick, Margaret E. L., and Joseph A. Stanley. 2020. Modelling dynamic trajectories of front vowels in the American South. *The Journal of the Acoustical Society of America* 147: 579–95. [CrossRef] [PubMed]

Schwartz, Geoffrey. 2021. The phonology of vowel VISC-osity—Acoustic evidence and representational implications. *Glossa: A Journal of General Linguistics* 6: 26. [CrossRef]

Shrout, Patrick E., and Joseph L. Fleiss. 1979. Intraclass correlations: Uses in assessing rater reliability. *Psychological Bulletin* 86: 420–28. [CrossRef]

Sóskuthy, Márton. 2017. Generalised Additive Mixed Models for Dynamic Analysis in Linguistics: A Practical Introduction. Available online: https://github.com/soskuthy/gamm_intro (accessed on 26 February 2024).

Sóskuthy, Márton, Jennifer Hay, and James Brand. 2019. Horizontal diphthong shift in New Zealand English. Paper presented at 19th International Congress of Phonetic Sciences (ICPhS), Melbourne, Australia, August 5–9; Edited by Sasha Calhoun, Paola Escudero, Marija Tabain and Paul Warren. Canberra: Australasian Speech Science and Technology Association Inc., pp. 597–601.

Stanley, Joseph A., Margaret E. L. Renwick, Katherine I. Kuiper, and Rachel M. Olsen. 2021. Back vowel Dynamics and distinctions in Southern American English. *Journal of English Language* 49: 389–418. [CrossRef]

Stevens, Kenneth. 2000. *Acoustic Phonetics*. Cambridge, MA: MIT Press.

Tamminga, Meredith. 2019. Interspeaker covariation in Philadelphia vowel changes. *Language Variation and Change* 31: 119–33. [CrossRef]

Torgersen, Eivind, and Paul Kerswill. 2004. Internal and external motivation in phonetic change: Dialect levelling outcomes for an English vowel shift. *Journal of Sociolinguistics* 8: 33–53. [CrossRef]

van Rij, Jacolien, Martijn Wieling, R. Harald Baayen, and Heddrick van Rijn. 2020. Itsadug: Interpreting Time Series and Autocorrelated Data Using GAMMs. R Package Version 2.4. Available online: https://cran.r-project.org/web/packages/itsadug (accessed on 26 February 2024).

Watson, Catherine I., and Jonathan Harrington. 1999. Acoustic evidence for dynamic formant trajectories in Australian English vowels. *The Journal of the Acoustical Society of America* 106: 458–68. [CrossRef] [PubMed]

Watson, Catherine I., Margaret Maclagan, and Jonathan Harrington. 2000. Acoustic evidence for vowel change in New Zealand English. *Language Variation and Change* 12: 51–68. [CrossRef]

Wieling, Martijn. 2018. 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. [CrossRef]

Williams, Daniel, and Paola Escudero. 2014. A cross-dialectal acoustic comparison of vowels in Northern and Southern British English. *The Journal of the Acoustical Society of America* 136: 2751–61. [CrossRef] [PubMed]

Williams, Daniel, Jan-Willem van Leussen, and Paola Escudero. 2015. Beyond North American English: Modelling vowel inherent spectral change in British English and Dutch. Paper presented at Congress of Phonetic Sciences (ICPhS XVIII), Glasgow, UK, August 10–14; Edited by The Scottish Consortium for ICPhS 2015. Glasgow: Scotland.

Williams, Daniel, Paola Escudero, and Adamantios Gafos. 2018. Spectral change and duration as cues in Australian English listeners' front vowel categorization. *The Journal of the Acoustical Society of America* 144: EL215. [CrossRef] [PubMed]

Winkelmann, Raphael, Lasse Bombien, and Michel Scheffers. 2016. Wrassp: An R Wrapper to the ASSP Library. Available online: https://cran.r-project.org/web/packages/wrassp (accessed on 26 February 2024).

Winkelmann, Raphael, Jonathan Harrington, and Klaus Jänsch. 2017. EMU-SDMS: Advanced speech database management and analysis in R. *Computer Speech and Language* 45: 392–410. [CrossRef]

Winter, Bodo, and Martijn Wieling. 2016. How to analyze linguistic change using mixed models, Growth Curve Analysis and Generalized Additive Modeling. *Journal of Language Evolution* 1: 7–18. [CrossRef]

Wood, Simon N. 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. *Journal of the Royal Statistical Society (Series B)* 73: 3–36. [CrossRef]

Wood, Simon N. 2017. *Generalized Additive Models: An Introduction with R*, 2nd ed. Boca Raton: CRC Press. First published 2006.

Zahorian, Stephen A., and Amir Jalali Jagharghi. 1993. Spectral-shape features versus formants as acoustic correlates for vowels. *The Journal of the Acoustical Society of America* 94: 1966–82. [CrossRef]
Zellou, Georgia, and Meredith Tamminga. 2014. Nasal coarticulation changes over time in Philadelphia English. *Journal of Phonetics* 47: 18–35. [CrossRef]

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