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The physiological basis of the phonologization of vowel nasalization: A real-time MRI analysis of American and Southern British English

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ABSTRACT

The diachronic change by which coarticulatory nasalization increases in VN (vowel-nasal) sequences has been modelled as an earlier alignment of the velum combined with oral gesture weakening of N. The model was tested by comparing American (USE) and Standard Southern British English (BRE) based on the assumption that this diachronic change is more advanced in USE. Real-time MRI data was collected from 16 USE and 27 BRE adult speakers producing monosyllables with coda /Vn, Vnd, Vnz/. For USE, nasalization was greater in V, less in N, and there was greater tongue tip lenition than for BRE. The dialects showed a similar stability of the velum gesture and a trade-off between vowel nasalization and tongue tip lenition. Velum alignment was not earlier in USE. Instead, a closer approximation of the time of the tongue tip peak velocity towards the tongue tip maximum for USE caused a shift in the acoustic boundary within VN towards N, giving the illusion that the velum gesture has an earlier alignment in USE. It is suggested that coda reduction which targets the tongue tip more than the velum is a principal physiological mechanism responsible for the onset of diachronic vowel nasalization.

1. Introduction

The focus of the study is on anticipatory coarticulatory nasalization in vowel-nasal (VN) rhymes in English and its connection to sound change. This is a type of regular sound change that has been demonstrated in English (Bell-Berti & Krakow, 1991; Cohn, 1993; Krakow, 1994; Kent et al., 1974; Moll & Daniloff, 1971; Ohala, 1971) and in many other languages (Bengali: Lahiri and Marslen-Wilson, 1991; French: Basset et al., 2001; German: Carignan et al., 2021; Italian: Busà, 2003; Japanese: Hattori et al., 1958; Korean: Jang et al., 2018; Lakota: Scarborough et al., 2015; Mandarin Chinese: Li et al., 2020; Portuguese: Barlaz et al., 2018; Romance languages: Hajek, 1997; Sampson, 1999; Spanish: Solé, 1995). It is also a sound change in which there is a cue-reweighting over time from a coarticulatory source (in this case the coda nasal) to a coarticulatory effect (nasalization in the vowel) and which can result in full nasalization of the vowel and loss of the nasal coda, as in standard French *main*, /mɛ̃/, from Latin *manus*, 'hand'. From this point of view, it is connected to other cue-reweighting or 'transphonologization' (Hyman, 2013; Kiparsky, 2015; Yu, 2021) sound changes including metaphony/umlaut (Iverson & Salmons, 2003; Maiden and Savoia, 1997), tonogenesis (Brunelle et al., 2016,2020; Coetzee et al., 2018; Hagège and Haudricourt, 1978; Hombert et al., 1979), and the diachronic shift of pre- to post-aspiration in Andalusian Spanish (Cronenberg et al., 2020; Ruch, 2018).

The extent of anticipatory coarticulatory nasalization in vowels varies between speakers (Carignan, 2019; Kim & Kim, 2019). Listeners compensate for coarticulatory vowel nasalization often only partially (Beddor & Krakow, 1998; Fowler & Brown, 2000) and in a way that can sometimes be linked to the extent of vowel nasalization in the listener's own speech production (Beddor et al., 2018; Zellou, 2017). There are differences in the extent of coarticulatory vowel nasalization between languages (Beddor & Krakow, 1999; Cohn, 1990; Clumeck, 1976; Solé, 1992), although such differences do not always depend on whether or not vowel nasalization is contrastive (Pouplier et al., 2023). There is also variation in the extent of coarticulatory vowel nasalization between dialects (English: Joo et al., 2019; French: Delvaux et al., 2012; Italo-Romance: Hajek, 1991; Spanish: Bongiovanni, 2021a; b; Lederer, 2003) and the degree of vowel nasalization can be

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affected by social factors (Coetzee et al., 2022; Zellou & Tamminga, 2014). There are numerous well documented influences of context. The extent of vowel nasalization is inversely related to vowel height (Bell-Berti et al., 1979; Moll and Shriner, 1967) and specifically to the physiological height of the tongue dorsum (Kunay et al., 2022). Low (Chen, 1972; Ruhlen, 1973; Schourup, 1973) and long (Hajek & Maeda, 2000) vowels are the first to become contrastively nasal and longer vowels are more likely to be perceived as nasal (Delattre and Monnot, 1968; Hajek and Watson, 1998; Whalen and Beddor, 1989). Cho and colleagues (Cho et al., 2017; Jang et al., 2018,2023) have found that the vowels in nasal contexts become more oral in prosodically focused contexts, thus enhancing the syntagmatic contrast to the nasal consonant compared with prosodically unfocused contexts.

According to Beddor et al., (2007:142), contexts favouring heavy vowel nasalization and concomitant nasal coda shortening are also those that are especially likely to become contrastive or 'phonologized'. For example, different analyses (Beddor et al., 2007; Cohn, 1990; Malécot, 1960; Raphael et al., 1975; Solé, 1995) have shown that American English VN sequences preceding voiceless consonants (e.g., 'sent') typically have more vowel nasalization and a shorter nasal consonant than when they precede voiced consonants ('send'). Comparable results have been obtained for Italian (Busà, 2003; 2007). Even though there is no evidence that contrastive nasalization is developing in standard German, Carignan et al (2021) showed that the size of the nasal gesture in /Vntə/ (e.g., *Ente*, 'duck') was less than in /Vndə/ (*Ende*, 'end'). Compatibly with all these findings, the development of contrastive nasalization is more likely when VN precedes voiceless than voiced consonants (Busà 2007; Hajek, 1997; Ohala & Ohala, 1993; Ruhlen, 1978; Tuttle, 1991; Sampson, 1999 – see Carignan et al., 2021 for a more detailed discussion and the link between these findings and NC̥ repulsion).

Over a number of years, Beddor has developed a model of sound change linking synchronic variation with the phonologization of vowel nasalization (Beddor, 2009, 2012, 2015; Beddor et al., 2018). This model takes over the idea from articulatory phonology (Browman & Goldstein, 1992; Pouplier & Goldstein, 2010) and its forerunner action theory (Fowler, 1983, 1984) that speech production is constituted from overlapping speech gestures. In Beddor's model, the main physiological component linking coarticulatory vowel nasalization with its phonologization is a stable velum gesture that can be variably phased with respect to the preceding vowel. As schematically outlined in Fig. 1, an earlier onset of the velum gesture in this model is associated with both greater vowel nasalization and less nasalization in the coda: that is, there is necessarily an inverse relationship between the two such that the more nasalization there is in the vowel, the less there is in the coda, if the velum gesture is stable i.e., does not change in temporal extent or magnitude.

A perceptual trading relationship is the mechanism by which listeners can cope with the type of variation in Fig. 1. In a perceptual trade-off, listeners have the flexibility to weight cues variably (Boersma et al., 2003; Chandrasekaran et al., 2010; Francis & Nusbaum, 2002; Haggard et al., 1981; Harmon et al., 2019; Idemaru & Holt, 2011). For example, if in a stop voicing contrast, the primary VOT cue is weak, then listeners

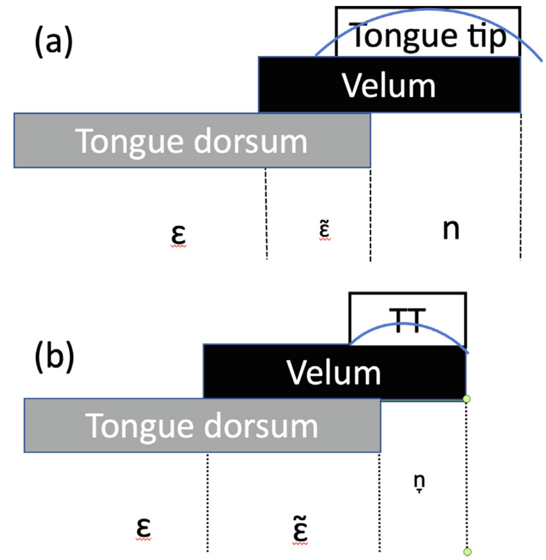

Fig. 1. A schematic extension of Beddor's (2023) model of the temporal coordination of the velum, and tongue dorsum gestures to include the tongue tip in the production of the rhyme of 'Ben'. The blue arc is a schematic outline of the vertical displacement of the tongue tip. The vertical dashed lines represent acoustic boundaries. In (a), the velum is aligned late with respect to the tongue dorsum resulting in a small degree of anticipatory nasalization in the vowel and extensive nasalization in /n/. In (b), the velum is aligned earlier resulting in more and less nasalization in the vowel and /n/ respectively. In addition, the tongue tip gesture is shorter and lenited in (b) compared with (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

can direct their attention more to fundamental frequency and intrinsic pitch differences between voiced and voiceless stops (Yu, 2022 and references therein). Analogously, listeners are more likely to direct their attention to processing nasalization in the vowel when there is an earlier phasing of the velum gesture as in Fig. 1b in which there is greater vowel nasalization and a concomitant weakening of nasalization in the coda (Beddor et al., 2013).

One of the unresolved issues that is explored in this study is how the transfer of nasalization cues from the coda to the vowel in VN affects the *oral* constriction of N. Given that the duration of the nasal coda decreases as nasalization in the vowel increases (Beddor, 2009), then the most likely outcome is a weakening i.e., lenition of the coda nasal's oral constriction (as schematically outlined in Fig. 1). This is because unless the velocity of the oral constriction increases, then a certain degree of target undershoot is inevitable, if there is less time for the gesture to be produced. This issue has, however, scarcely been investigated. A recent exception is Bongiovanni's (2021a) comparative physiological analysis using nasometer recordings of coda VN sequences in two dialects of Spanish. In a separate analysis, Bongiovanni (2021b) had shown that the extent of coarticulatory vowel nasalization was greater in Santo Domingo than in Buenos Aires Spanish. The prediction was that weakening of the oral component of the N coda should also have been greater in this variety. However, this was not the case. There was, nevertheless, an inverse relationship within each dialect between extent of vowel nasalization and N weakening.

The present study follows Bongiovanni's (2021a) approach but it does so by comparing two English dialects, American English (USE) and Standard Southern British English (BRE) that are assumed to differ in the extent to which vowel nasalization is becoming contrastive. Comparisons of anticipatory vowel nasalization across English varieties are rare even within dialects. One of the recent exceptions is Tamminga & Zellou (2015) for American English who used acoustic techniques to show a greater degree of coarticulatory vowel nasalization in Philadelphia than in Columbus and a weakening of vowel nasalization in both varieties for the younger generation. Experimental comparisons of vowel nasalization between American and British English dialects have to our knowledge never been undertaken. The prior evidence that vowel nasalization is more extensive in USE than in BRE is based partly on our and others' (e.g., Hosseinzadeh et al., 2015) auditory impressions. Moreover, there is no evidence of the near phonologization of vowel nasalization in /VnÇ/ ('sent') sequences in BRE as there is for USE (see above), although no comparable analysis for BRE has so far been undertaken. Finally, extensive vowel nasalization of low vowels is associated with their phonetic raising as both physiological (Carignan et al., 2011; Carignan, 2018; Mielke et al., 2017) and perceptual (Beddor & Krakow, 1999; Kawasaki, 1986; Krakow et al., 1988) studies have shown. Using ultrasound, Mielke et al (2017) found more extensive tongue dorsum raising in American and Canadian English /æ/ (e.g., 'ban') before coda nasals but not for the British English control speaker. Taken together, these impressions and analyses suggest that vowel nasalization before nasal coda consonants is likely to be greater in USE than in BRE.

The further motivation for seeking to understand the mechanisms of sound change through comparisons of related dialects has its origins in Schuchardt (1885, p. 22) who notes that in considering a group of related dialects it becomes apparent how the conditions of the sound laws change in many ways from place to place because of a spatial projection of temporal differences.[1] In a related and more recent interpretation, Ramsammy (2015) models synchronic differences between dialects in terms of the so-called life-cycle of phonological change (Bermúdez-Otero & Trousdale, 2012; Bermúdez-Otero, 2020) that is inspired by the framework of lexical phonology (Kiparsky, 1982; Rubach, 2008). The further basis for comparing dialects in the present MRI study is that the same (or similar) phonological innovations can take hold to different degrees across related dialects (Bermúdez-Otero, 2013; Ramsammy, 2015). Moreover, it is not necessary for the sound change to have been completed in either dialect (in the present study to complete phonologization of the vowel and loss of the nasal coda), nor for either dialect to be undergoing a sound change in progress, but only for one of them (in this case American English) to be at a more advanced stage along the same path of sound change than the other (British English).

The overall aim of this study was to test whether the development of contrastive nasalization is associated physiologically with a change in the constellation of gestures from those outlined in Fig. 1a to those in Fig. 1b. Three main predictions follow from this model, on the assumption that BRE is less advanced in this sound change and more like Fig. 1a and that USE is further along the path of the sound change as in Fig. 1b.

i. USE has greater and less nasalization in the vowel and nasal coda respectively compared with BRE.
ii. The velum gesture for the two dialects is of the same magnitude and temporal extent, if contrastive vowel nasalization develops as a consequence of an earlier rephasing of a stable velum gesture.
iii. USE has a shorter and more lenited tongue tip gesture than BRE.

Predictions (i-iii) were tested in the study as follows. Section 3 is concerned with (i) a comparison between the two dialects on the extent of nasalization in the vowel and coda /n/. The focus of the intra-gestural analysis of the velum in section 4 is on (ii) in order to determine whether the velum gesture is stable across both dialects. Section 5 is an intra-gestural analysis of the tongue tip with the aim of testing (iii) whether tongue tip lenition in nasal codas is greater in USE than in BRE. Section 6 takes up the issue of whether there is a trading relationship between coarticulatory source and effect: that is, whether an earlier phasing of the velum gesture in the vowel is associated with greater lenition of the oral constriction of /n/. The final section (7) is a further analysis of (ii) in order to test whether the velum is also phased earlier in USE than BRE with respect to the tongue tip gesture of nasal coda.

2. Method

2.1. Speakers

Data was acquired from 27 native speakers of standard Southern British English (13 female, median age 20 years, range 18–46 years) and 16 native speakers of US English (7 female, median age 26 years, range 20–37 years). The US speakers were approximately equally distributed between Midland, Atlantic, South, and West regions. Participants gave written information about the town and region in which they grew up and went to school, and also about the region of origin of both parents (in a few cases one of the two parents was a native speaker of a language other than English). Detailed demographic information is given in Appendix B. The British speakers were recruited (with two exceptions) in the UK and travelled to Göttingen for the recordings. The American participants were recruited in Germany, mainly from the Göttingen area. For participants recruited in Germany, we set a requirement of a maximum of two years residency in Germany. In addition, no American participants were recruited who had formerly been resident in the UK (and vice-versa). All speakers reported normal hearing and speaking function. Participants filled out informed consent forms approved by the ethics commission of the medical faculty of LMU Munich and they were paid for their participation. The informed consent paid particular attention to participant compatibility with testing in the MRI scanner.

2.2. Stimuli

The target words used for this study consisted of 47 real-word monosyllables selected from a larger corpus. The words

[1] Paraphrased from Schuchardt (1885:22): "Man betrachte auch eine beliebige Gruppe verwandter Mundarten; man wird sehen wie die Bedingungskreise der Lautgesetze von Ort zu Ort mannigfach verändern, man wird hier gleichsam die räumliche Projection zeitlicher Unterschiede erkennen".

were chosen to allow comparison of velar and coronal gestures across the two dialects with a balanced set of vowel and post-vocalic nasal contexts. The words had the form CVn(d|z) with V = /æ, eɪ, ʌ, ɛ, ɪ/. All five vowels were combined with the 3 codas /n, nd, nz/. These 15 combinations of V + Coda were combined with as many as possible of the labial occlusives /p, b, f/ and less frequently with the fricatives /s, ʃ/ (all initial consonants were chosen to have clear velum raising). A complete list of all 47 words is given in Appendix A. Each of the V + Coda combinations occurred on average with three initial consonants (minimum 2, maximum 4). Examples of the materials are:

- Coda /n/: *ban*, *feign*, *bun*, *Ben*, *bin*.
- Coda /nd/: *band, feigned, fund, bend, binned.*
- Coda /nz/: *bans, feigns, buns, Ben's, bins.*

The words were spoken in the carrier phrase "saw <target-word> about two/four/five/six/ten", with narrow focus on the target word. The phrase-final numeral was varied randomly. Each word was typically spoken once per speaker. The combination of 47 word types and 43 speakers gave approximately 2020 tokens for analysis. Note that for the analysis of tongue tip movement, only the vowels /ʌ, ɛ, ɪ/ were used. The vowel /eɪ/ was omitted because the high tongue position in the vowel often resulted in very small amplitudes of tongue tip movement for the coda, and thus poorly defined kinematic measures. The vowel /æ/ was omitted because the particularly salient differences between British and American English in the vowel (widespread pre-nasal raising in American English: Mielke et al., 2017; see also Appendix C) would have distorted any comparison of movement amplitude or duration from vowel to coda.

2.3. Imaging

Real-time magnetic resonance imaging (rt-MRI) data were acquired at the Max Planck Institute for Multidisciplinary Sciences in Göttingen, Germany. For image acquisition, a 3-Tesla MRI system was used (Magnetom Prisma Fit, Siemens Healthineers, Erlangen, Germany). Participants were measured in supine position via a 64-channel head coil with the radiofrequency (RF)-spoiled FLASH sequence. This method is based on highly under-sampled radial gradient echo acquisitions and is combined with serial image reconstruction by regularized non-linear inversion (Uecker et al., 2010). Individual images were obtained from a single set of nine spokes (repetition time (TR) = 2.22 ms), which resulted in a reconstructed frame rate of 19.98 ms or 50.05 frames per second (fps). An in-plane pixel size of 1.41 $\times$ 1.41 mm and a slice thickness of 8 mm were applied, which yielded images of 136 $\times$ 136 voxels (i.e., three-dimensional (3D) volume elements) in a field of view of 192 $\times$ 192 mm.

It should be noted that some influence of supine speaking position on articulatory postures has been documented (e.g., Kitamura et al., 2005). But, equally, Tiede et al. (2000) showed that running speech, as used here, has been found to be much less prone to gravity effects than sustained sounds (the Kitamura et al. study seems to have used isolated vowels; for further discussion see Kunay et al., 2022). Moreover, the focus of the present study is on a cross-dialectal comparison, and there is no reason to expect supine posture to affect the two participant groups differently.

2.4. Data collection

Before the MRI recording, the participants were given the opportunity to familiarize themselves with the speech materials and elicitation procedures. Attention was paid to achieving consistent prosody of the target utterances. Both during the familiarization procedures and during the session in the scanner, the target utterances were divided into blocks of about 15 items and presented as a slide show with slides advancing automatically after 4 s (each new block started with a dummy item). Inside the scanner, the slides were projected onto a mirror just above the head coil. Each block lasted about one minute. The complete experiment (including the speech material not of relevance here) consisted of 23 blocks, giving about 70,000 images per participant. Total time in the scanner including localizer scans amounted to about 1 h.

In addition to the image data, synchronized, noise-suppressed audio was collected during the scanning session using an Optoacoustics FOMRI III fiber-optic dual-channel microphone (Optoacoustics Ltd.) and further processed in MATLAB (The Mathworks Inc. 2017) for additional reduction of scanner noise.

2.5. Image analysis

The images were processed in MATLAB (see Carignan et al., 2020; 2021; Kunay et al., 2022 for further details). For each speaker's data set, the images were first registered by pre-creating a region of interest (ROI) that covered the upper portion of the head (i.e., only covering structures that do not exhibit speech-related movement). Based on this ROI, the Matlab function `imregtform` was used to compute the rigid transformation (translation and rotation) that would map each individual image to a reference image. The reference image was chosen for every speaker from a comparable phonetic context (i.e., a mid-vowel with prosodic focus), after checking that candidate frames did not exhibit clearly unusual head postures. This registration procedure allowed compensation for small movements of the head that occurred during the recording session. This registration procedure will only have limited success if movement of the head out of the original mid-sagittal plane occurs. This was checked by inspecting the correlation between each registered frame and the reference frame. Typically, this correlation was well above 0.9. On this basis, one USE speaker who had many frames with correlations of 0.8 or below was eliminated from further analysis (i.e., we actually recorded a total of 17 USE speakers; cf. 2.1 above).

2.5.1. Velum movement

To create a signal for kinematic analysis of velum raising and lowering, a second ROI was manually defined for each speaker around the spatial range encompassing the velum movements, i.e., the region contained all pixels that could be occupied by any part of the velum tissue over maximum raising to maximum lowering during speech. This typically comprised approximately 700 pixels, which were defined as dimensions in principal component analysis (PCA). The ROI was chosen so that tongue movement would not impinge on it.[2] As there was only one primary degree of freedom associated with the lowering and raising gesture, the first principal component (PC1) necessarily referred to the velum movement and explained an average (over speakers) of 59 % of the data variance.

We consider the PCA approach to be a robust procedure, not just because it uses many pixels, but also because it does not depend on tracking a specific tissue boundary (fraught with difficulties given the complex changes in velum shape while moving). Moreover, it covers the full range of velar movement. In contrast, measuring velum aperture would saturate at zero when the velum contacts the rear pharyngeal wall and would therefore be insensitive to the onset of velum lowering movements when they are initiated from a higher position, as is usually the case (see Kunay et al., 2022, Fig. 2, for further exemplification of the relationship between PC score and velar configuration).

To create the velum signal used for further analysis, the scores from PC1 were logged for each individual image. If necessary, the polarity of the PC1 scores was reversed, so that high values corresponded for every speaker to velum lowering, low values to velum raising. With this method, we obtained velum movement as a scalar-valued function of time with a sampling rate of 50.05 Hz. The PC1 scores were scaled between 0 and 1, corresponding to the minimum and maximum PC1 scores for each speaker's data set (see Kunay et al., 2022, Figs. 1 and 2 for further details of the application of the PCA method to the velum ROI and for the relationship between raw images and resulting PCA scores).

2.5.2. Tongue position

In addition to the analysis of the velar movements, a separate method was applied to capture tongue tip movement patterns for the post-vocalic coronal consonants in the target words (based on Carignan et al., 2020). After image registration, a semi-polar grid consisting of 28 lines was applied semi-manually to the vocal tract, reaching from the glottis up to the alveolar ridge. This was achieved by manually selecting the locations of the glottis, velopharyngeal port, and alveolar ridge as well as a location of air. The midpoint of the line from the alveolar ridge to the glottis was accordingly located within the genioglossus muscle in all subjects and served as the origin for the semi-polar grid. The gridlines terminated at the automatically detected posterior or superior boundary of the vocal tract (see Kunay et al., 2022, Fig. 3 for illustration of the grid system). The pixel intensities along each of the 28 gridlines were further processed in the following way. First, the mean pixel intensity per gridline was calculated. This mean intensity can be expected to vary with the degree of articulatory constriction, since stronger constrictions result in more tongue tissue (high intensity) and less air (low intensity) along the gridline.[3] Second, the mean intensities per gridline were grouped into five articulatory regions: alveolar, palatal, velar (independent of the velum lowering signal from the velum PCA), hyperpharyngeal, and hypopharyngeal. Only the signal for the alveolar region was relevant in the following analyses.[4] It was calculated as the mean of the mean intensity from the three or four frontmost gridlines (with slight variation to take individual anatomy into account), and with subject-specific scaling of the resulting minimum and maximum value from 0 to 1.

As the final stage in preparation for the kinematic analyses described in detail below, the velum and tongue tip signals were up-sampled by a factor of 10 (i.e., to a sample rate of 500.5 Hz) by spline interpolation, and smoothed with a Kaiser-design low-pass filter at cut-off frequencies of 12 Hz for the velum signal and 16 Hz for the tongue tip signal. Velocity signals were obtained by calculating the first derivative with a 3-point central-difference method.

3. Nasalization relative to the acoustic VN boundary

The purpose of the following section was to test whether the extent of nasalization in the vowel and in the nasal coda was more and less respectively for USE than BRE. The test follows from the hypothesis that USE is further along the path of sound change VN > Ṽ and that the velum gesture is timed earlier relative to the VN boundary than BRE.

3.1. Method

Two parameters for the materials in section 2.2 were calculated in order to measure the temporal alignment of the velum gesture and the degree of nasalization in the nasal coda. The first was i_1/i_2 in Fig. 2. This is the duration from the time of peak velum lowering to the acoustic boundary between the vowel and following nasal consonant, normalized by the articulatory duration of the nasal gesture (defined as the interval between the velum's peak lowering and raising velocities). When this ratio (i_1/i_2 in Fig. 2) is zero, then the peak velum lowering is at the acoustic VN boundary, while negative and positive values denote that it precedes and follows this boundary respectively.

The second parameter was the log. area under the velum signal in the nasal coda normalized by the area under the velum signal in the entire VN sequence: thus, the ratio of the blue shaded area to the gold and blue shaded areas combined in Fig. 2. If the areas under the curve in V (Fig. 2: gold) and N (Fig. 2: blue) are equal, then this parameter has the value of log(1/2) = $-$ 0.693 (see also the horizontal dashed line in row 2, Fig. 3).

The statistical analysis made use of the mixed model function lmer() from the lmerTest package (Kuznetsova et al., 2020) in the R programming environment (version 4.3.1) and was of the form:

$$\text{model} = \text{lmer}(\text{param} \sim \text{dialect} * \text{vowel} * \text{coda} + (\text{dialect}|\text{stem}) + (\text{vowel} + \text{coda}|\text{speaker}) \quad (1)$$

in which *param* was one of these two parameters and with fixed factors dialect (USE, BRE), vowel (/æ, eɪ, ʌ, ɛ, ɪ/), and coda (/n, nd, nz/), and with random factors stem (e.g., *be-* for *Ben*, *bens*, *bend*) and speaker (the 43 speakers of the study). The model

[2] See Kunay et al. (2022), Fig. 1, for an example of the ROI. In order for the PCA procedure to work correctly, it is important that tongue tissue should not move into this area. For the present study this was straightforward because the corpus did not require use of velar consonants or high back vowels.

[3] The use of a semi-polar grid as a framework for analysis of tongue movement in rt-MRI is similar in spirit to the work of Proctor et al. (2019), but differs in detail since we use a purely pixel-intensity based method along each gridline, rather than detecting edges of tongue tissue (in turn, for further discussion of the motivation behind intensity-based methods see e.g., Proctor et al., 2011).

[4] With the exception of the palatal region that was analysed in Appendix C in order to determine the extent of pre-nasal raising in USE.

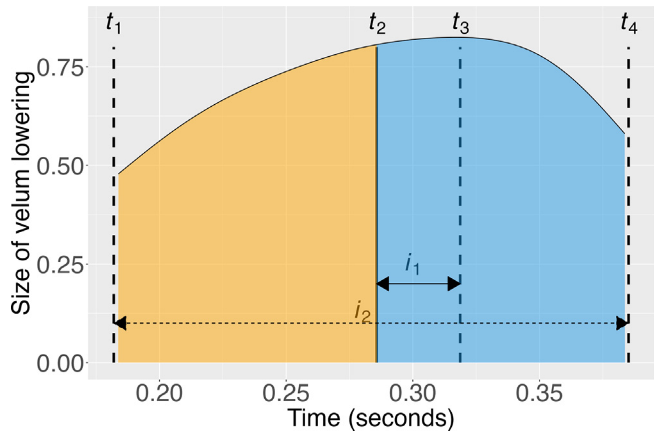

Fig. 2. Velum lowering as a function of time in VN. The vertical lines from left to right are at the following times. t_1: peak velum lowering velocity. t_2: (solid line) acoustic boundary between V and N. t_3: peak velum lowering. t_4: peak velum raising velocity. The two shaded areas are the extent of nasalization in the vowel (orange) and in the nasal coda (blue). The two duration parameters are: $i_1 = t_3 - t_2$ and $i_2 = t_4 - t_1$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was simplified whenever possible using the `step()` function in the same package. If the model failed to converge, the random factors were minimally simplified by removing the slope calculations (e.g., a simplification of the second random factor in (1) to any of (*vowel*|*speaker*), (*coda*|*speaker*), or (1|*speaker*)). Any interactions in the remaining model were tested with the `emmeans()` function in the package of the same name (Lenth et al., 2023). Results that are reported as 'significant' in the post-hoc tests were so at $p < 0.05$ after Bonferroni adjustment depending on the number of post-hoc tests that were carried out. Estimated marginal (least-squares) means, $\hat{m}$, derived from the `emmeans()` package in R, are also reported for significant results.

3.2. Results

Fig. 3, row 1 shows that the peak velum lowering was timed earlier for USE than for BRE for all vowels and coda types. The statistical analysis with the parameter in Fig. 3, row 1 as the dependent variable showed a significant influence of dialect (F1(, 41.05) = 26.90, $p < 0.001$. BRE: $\hat{m}$ = 0.280; USE: $\hat{m}$ = 0.125), vowel (F(4, 1969.14) = 342.94, $p < 0.001$. /æ/: $\hat{m}$ = 0.00527; /eɪ/: $\hat{m}$ = 0.08011; /ʌ/: $\hat{m}$ = 0.27816; /ɛ/: $\hat{m}$ = 0.29068; /ɪ/: $\hat{m}$ = 0.35969), of coda (F(2,1969.10) = 16.00, $p < 0.001$. /n/: $\hat{m}$ = 0.226; /nd/: $\hat{m}$ = 0.179; /nz/: $\hat{m}$ = 0.204), and a significant (F(8,1969.14) = 1.97, $p < 0.05$) vowel × coda interaction, but no interaction between any of the fixed factors with dialect. Post-hoc tests showed a significantly earlier alignment of the velum for /æ, eɪ/ than for /ʌ, ɛ, ɪ/ and for /ʌ, ɛ/ than for /ɪ/. Additionally, the alignment was earlier for /æ/ than for /eɪ/ before /nd, nz/. The only significant coda effect was an earlier alignment for /nd/ than for /n/ following /æ/.

The proportional area under the curve for N was less in USE than in BRE as Fig. 3, row 2 shows. The statistical analysis with the parameter in Fig. 3, row 2 as the dependent variable showed significant main effects for all three fixed factors (dialect: F (1,41.02) = 28.72, $p < 0.001$. BRE: $\hat{m}$ = −0.372; USE: $\hat{m}$ = −0.646; vowel: F(4,928.0) = 591.60, $p < 0.001$. /æ/:$\hat{m}$ = −0.960; /eɪ/: $\hat{m}$ = −0.716; /ʌ/: $\hat{m}$ = −0.337; /ɛ/: $\hat{m}$ = −0.312;

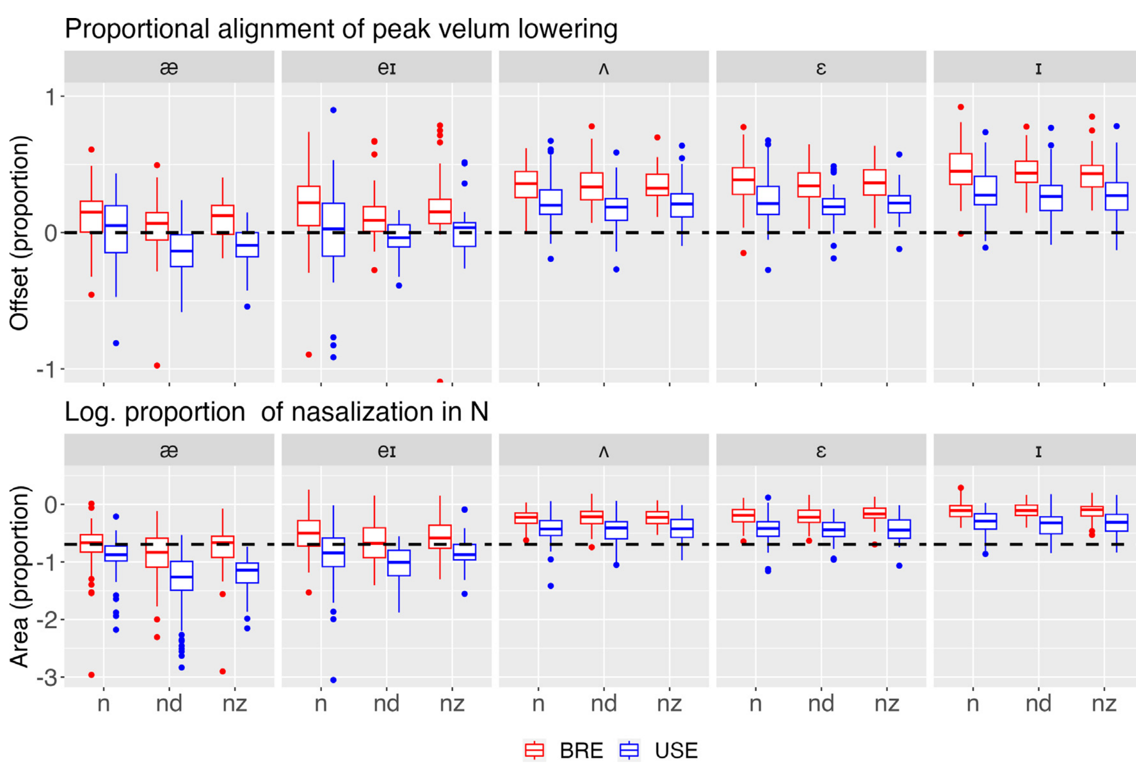

Fig. 3. Row 1: The proportional time of the peak velum lowering relative to the acoustic VN boundary (i_1/i_2 in Fig. 2). The horizontal dashed line in row 1 is when the time of the peak velum lowering coincides with the acoustic boundary between V and N. Row 2: The log proportion of the area under the velum curve in N relative to VN. The horizontal dashed line is the value for which the areas under the curve in V and N are equal.

/ɪ/: $\hat{m} = -0.222$; coda: $F(2, 1856.99) = 61.73$, $p < 0.001$. /n/: $\hat{m} = -0.475$; /nd/: $\hat{m} = -0.559$; /nz/: $\hat{m} = -0.494$) as well as a significant ($F(8, 1853.76) = 8.38$, $p < 0.01$) vowel × coda interaction. Post-hoc tests showed that the proportional area under the curve for all nasal consonants was less when the nasal was preceded by /æ/ than by /eɪ/ than by /ʌ, ɛ, ɪ/. In addition, the proportional area under the curve in /n, nd/ was less when these were preceded by /ʌ, ɛ/ than by /ɪ/. Finally, the post-hoc tests also showed that the proportional area under the curve in the nasal consonant was less in /nd/ than in /nz/ than in /n/ when the preceding vowel was /æ/; and less in /nd/ than in either /nz/ or /n/ when the preceding vowel was /eɪ/.

3.3. Discussion

The results are compatible with the hypothesis that, for USE compared with BRE, the velum gesture was timed earlier relative to the acoustic boundary between the vowel and nasal coda in all contexts. In addition, the extent of vowel nasalization in the coda was less in USE than in BRE. (For an overview of whether there are differences in velum timing between the dialects at acoustic vowel onset, see Appendix D).

As Fig. 3 shows – and as partly confirmed by the statistics – longer vowels like /æ, eɪ/ tended to be associated with an earlier peak alignment and less nasalization in the coda than the shorter vowels /ʌ, ɛ, ɪ/. It is unlikely that this effect is due to vowel height for at least two reasons. Firstly, USE /æ/ when nasalized is at least a mid or even mid-high vowel (Mielke et al., 2017: see also Appendix C). Secondly, in both varieties /ʌ/ is lower than /eɪ/.

The results of greater nasalization in the vowel and less in the coda for USE vs. BRE are compatible with the model in Fig. 1 in which a stable velum gesture is variably aligned with respect to the VN boundary (see also Appendix E for results compatible with this finding based on V and N duration). The extent to which the velum is stable across dialects and contexts is tested in the next section.

4. Intra-gestural velum analysis

4.1. Method

The three parameters shown in Fig. 4 were extracted over the VN interval for the materials in 2.3. These were the magnitude of peak velum lowering, the peak lowering velocity of the velum, and the duration of the velum gesture defined as the interval between the times of the velum's peak lowering and raising velocities (Fig. 4). The first of these was averaged between plateau onset and offset of peak velum lowering since there was often no single point that defined the displacement peak (onset and offset were defined by a velocity criterion, i.e., the first point falling below 20 % of peak velocity (onset), and the first point rising again above 20 % (offset)).

The mixed model in (1) was applied separately with each of these three parameters as the dependent variable.

4.2. Results

There is not much evidence from Fig. 5 for differences between the two dialects in velum lowering and velocity (the latter being indicated by slope differences). The main difference between the varieties that stands out in Fig. 5 is USE's earlier phasing of the velum gesture compared with BRE (consistently with the earlier results in section 3.2).

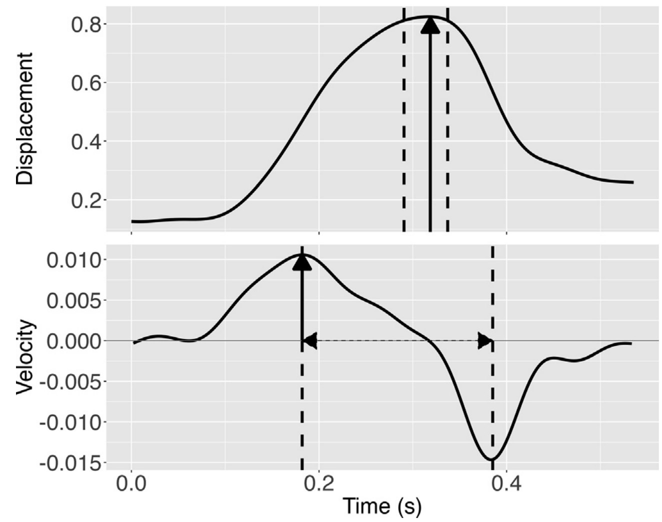

Fig. 4. Velum displacement and velocity in VN (velocity corresponds to displacement change per sample interval). The three parameters shown are: (1) magnitude of peak velum lowering (vertical solid line row 1) averaged between the plateau onset and offset (vertical dashed lines, row 1). (2) the peak lowering velocity of the velum (vertical solid line, row 2). (3) the articulatory duration of the velum gesture extending between the times of the velum's peak lowering and raising velocities (between the two vertical dashed lines in row 2: this is the same as interval i_2 in Fig. 2).

The results of the statistical analysis were consistent with the apparent lack of differences between the two dialects in Fig. 5. For the magnitude of peak velum lowering, there was a significant effect of the vowel ($F(4,48.35) = 10.87$, $p < 0.001$. /æ/: $\hat{m} = 0.701$; /eɪ/: $\hat{m} = 0.650$; /ʌ/: $\hat{m} = 0.719$; /ɛ/: $\hat{m} = 0.689$; /ɪ/: $\hat{m} = 0.660$) and coda ($F(2,52.46) = 8.94$, $p < 0.01$. /n/: $\hat{m} = 0.697$; /nd/: $\hat{m} = 0.670$; /nz/: $\hat{m} = 0.684$), no overall effect of dialect, but a significant ($F(4, 51.46) = 3.50$, $p < 0.05$) vowel × dialect interaction. Post-hoc tests showed, however, no significant differences between the dialects. The only differences were within BRE. Where '>' denotes 'peak velum lowering was significantly greater than', then the post-hoc tests showed for BRE only /æ, ʌ / > / ɛ/ > /eɪ, ɪ/. Post-hoc tests on the coda showed a greater peak displacement for /n, nz/ than for /nd/.

The results for the peak lowering velocity of the velum were similar to those for displacement. There was a significant effect of the vowel ($F(4,1576.02) = 24.6$, $p < 0.001$. /æ/: $\hat{m} = 6.39$; /eɪ/: $\hat{m} = 5.72$; /ʌ/: $\hat{m} = 6.47$; /ɛ/: $\hat{m} = 6.05$; /ɪ/: $\hat{m} = 6.06$) and coda ($F(2,1940.78) = 9.84$, $p < 0.01$. /n/: $\hat{m} = 5.99$; /nd/: $\hat{m} = 6.19$; /nz/: $\hat{m} = 6.24$), no overall effect of dialect, but a significant ($F(4,1966.85) = 7.93$, $p < 0.001$) vowel × dialect interaction. Post-hoc tests showed, however, no significant differences between the dialects. Where '>' denotes 'the peak velum lowering velocity was significantly greater than', then the post-hoc tests showed for BRE /æ, ʌ/ > /ɛ/ > /eɪ, ɪ/ and for USE /eɪ/ > /ɪ/. Post-hoc tests on the coda showed a greater peak lowering velocity for /nd, nz/ than for /n/.

The articulatory duration of the velum gesture (i.e., the duration between the peak velocities) was significantly influenced by the vowel ($F(4,1099.80) = 59.19$, $p < 0.001$. /æ/: $\hat{m}$ = 339 ms; /eɪ/: $\hat{m}$ = 307 ms; /ʌ/: $\hat{m}$ = 297 ms; /ɛ/: $\hat{m}$ = 278 ms;

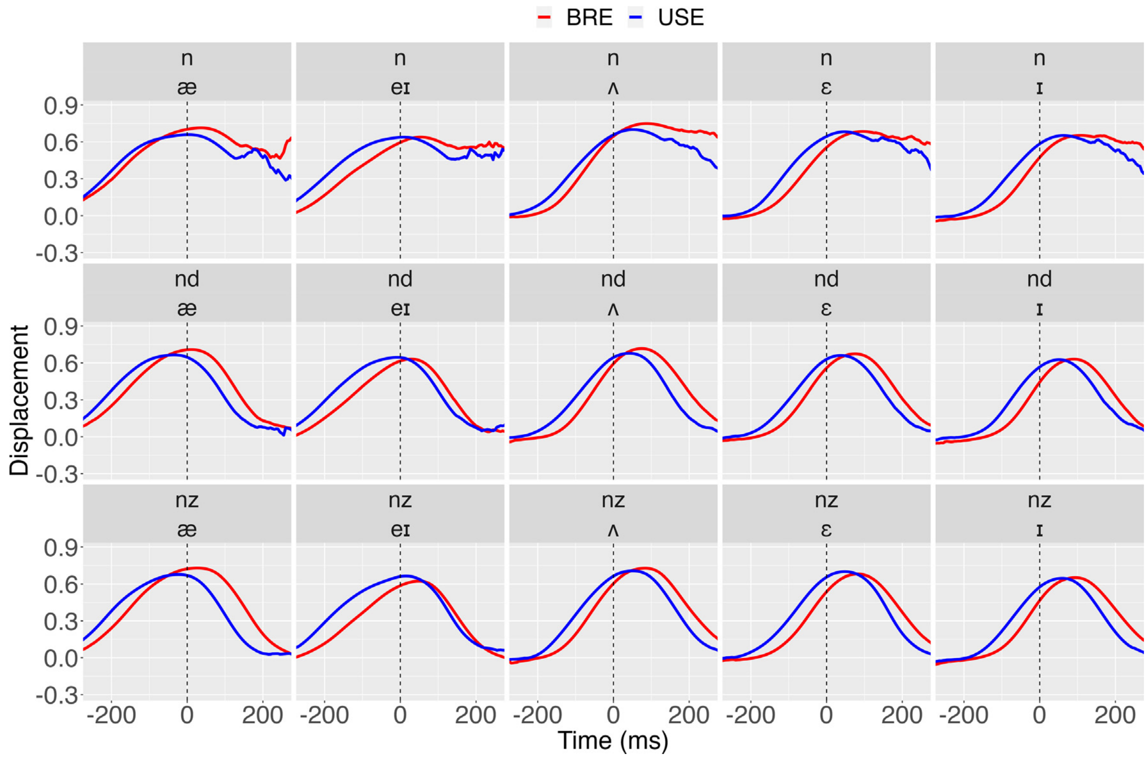

Fig. 5. Velum lowering over the vowel + coda interval aggregated without time normalization by dialect, vowel, and coda after time-alignment at the acoustic boundary (t = 0 ms) between V and N.

/ɪ/: $\hat{m}$ = 264 ms) and by the coda ($F(2,1904.70) = 365.62$, $p < 0.001$. /n/: $\hat{m}$ = 357 ms; /nd/: $\hat{m}$ = 260 ms; /nz/: $\hat{m}$ = 274 ms) but not by dialect. There was also a significant ($F(8, 1966.85) = 2.77$, $p < 0.01$) vowel × coda interaction. Where '>' denotes 'the articulatory duration of the velum gesture was significantly greater than', then the post-hoc tests showed in both dialects and for all five vowels within-coda differences of /n/ > /nd, nz/. In addition, preceding coda-/n/, /æ, ʌ/ > /eɪ, ɪ/ and /æ/ > /eɪ/; preceding coda-/nd/, /æ/ > / ʌ, ɛ, ɪ/ and /eɪ/ > /ɛ, ɪ/; preceding coda-/nz/, /æ/ > the other four vowels, and /eɪ/ > /ɪ/.

4.3. Discussion

The dialects differed neither in the peak displacement nor velocity of velum lowering, nor in the articulatory duration of the velum gesture. These findings are consistent with the predictions of Beddor (2009) that the realignment of a stable velum gesture relative to oral gestures is the cause of the increase and decrease of nasalization in the vowel and nasal coda respectively.

The only systematic differences in the kinematics of the velum gesture were due to the nasal coda which showed a greater peak lowering velocity and shorter articulatory duration for /nd, nz/ than for /n/. The shortening of the nasal gesture in the coda clusters is likely to come about because of the need to raise the velum abruptly for the following oral consonant, a shortening which is compensated for by increased velocity in the lowering gesture.

A prediction of the model of sound change VN > Ṽ is that the greater extent of nasalization in the vowel should be accompanied by reduction of N. The reduction of the oral gesture in the nasal coda is tested in the next section.

5. Intra-gestural tongue tip analysis

The progression of the sound change VN > Ṽ involves not only greater vowel nasalization but also an increasing lenition of the nasal coda so that in the extreme case it disappears (as in certain varieties of American English in which the 'set'/'sent' contrast depends mostly on nasalization in the vowel – e.g., Beddor et al., 2013). On the assumption that USE has progressed further along this path of sound change than BRE, then the prediction is that the oral (lingual) gesture of the nasal coda should be more reduced in USE.

5.1. Method

Four parameters were extracted over VN(C) sequences in the materials for which there was tongue tip data i.e., only for the vowels /ʌ, ɛ, ɪ/, as explained in section 2.3. These were (1) peak tongue tip displacement magnitude, (2) the duration between the time of tongue tip peak raising velocity and the time of tongue tip peak raising (3) the duration between the times of the peak tongue raising and lowering velocities (4) the peak tongue tip raising velocity (Fig. 6).

The prediction was that most of these should be less for USE than for BRE if the USE tongue tip gesture in the nasal coda is more reduced and lenited. The time of the peak tongue tip displacement typically occurred during the nasal part of the coda i.e., within an interval in which the velum was lowered (see Appendix F for further details).

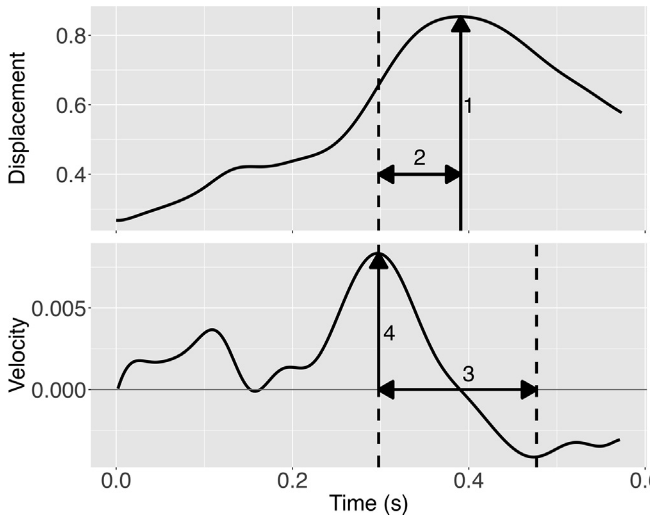

Fig. 6. Displacement and velocity of tongue tip raising over a VN(C) interval. The four parameters shown are: (1) peak tongue tip displacement magnitude (2) the duration between the time of peak tongue tip raising velocity and peak tongue tip raising (3) the duration between the times of peak tongue tip raising and lowering velocities (4) the peak tongue tip raising velocity.

5.2. Results

Fig. 7 suggests that the peak displacement and articulatory duration of the tongue tip raising gesture were less in USE than BRE. As far as peak tongue tip displacement magnitude was concerned, the results showed a significant influence of dialect ($F(1,40.9) = 20.54$, $p < 0.001$. BRE: $\hat{m} = 0.353$; USE: $\hat{m} = 0.258$), of vowel $F(2,44.26) = 262.21$, $p < 0.001$. /ʌ/: $\hat{m} = 0.474$; /ɛ/: $\hat{m} = 0.294$; /ɪ/: $\hat{m} = 0.148$), and of coda ($F(2,47.75) = 43.44$, $p < 0.001$. /n/: $\hat{m} = 0.253$; /nd/: $\hat{m} = 0.320$; /nz/: $\hat{m} = 0.342$). There were also significant vowel × coda ($F(4,883.56) = 4.87$, $p < 0.001$) and vowel × dialect $F(2,40.46) = 3.81$, $p < 0.05$) interactions. Where '>' denotes 'peak tongue tip raising was greater', then post-hoc tests showed /ʌ/ > /ɛ/ > /ɪ/ for all nasal codas, /n/ < /nd, nz/ for all vowels and BRE > USE in all cases.

The results for the two duration parameters (2 and 3 in Fig. 6) are as follows. For the interval (2) between the time of the peak tongue raising velocity and peak tongue tip displacement, there was a significant influence of dialect ($F(1,40.02) = 20.20$, $p < 0.001$. BRE: $\hat{m} = 133$ ms; USE: $\hat{m} = 90$ ms), of vowel $F(2,7.12) = 11.042$, $p < 0.01$. /ʌ/: $\hat{m} = 124$ ms; /ɛ/: $\hat{m} = 112$ ms; /ɪ/: $\hat{m} = 98$ ms) and of the nasal coda ($F(2,44.41) = 16.20$, $p < 0.001$. /n/: $\hat{m} = 93$ ms; /nd/: $\hat{m} = 117$ ms; /nz/: $\hat{m} = 124$ ms) and no significant interaction between the fixed factors. For the interval (3) between the times of the peak tongue raising and lowering velocities, there was a significant influence of dialect ($F(1,41.16) = 16.53$, $p < 0.001$. BRE: $\hat{m} = 296$ ms; USE: $\hat{m} = 226$ ms) and of coda ($F(2,43.28) = 85.65$, $p < 0.001$. n/: $\hat{m} = 199$ ms; /nd/: $\hat{m} = 254$ ms; /nz/: $\hat{m} = 331$ ms) and no significant interactions.

The results for the peak tongue tip velocity showed a significant influence of the vowel ($F(2, 1024.2) = 851.50$, $p < 0.001$. /ʌ/: $\hat{m} = 6.21$; /ɛ/: $\hat{m} = 3.95$; /ɪ/: $\hat{m} = 2.16$) and of the coda

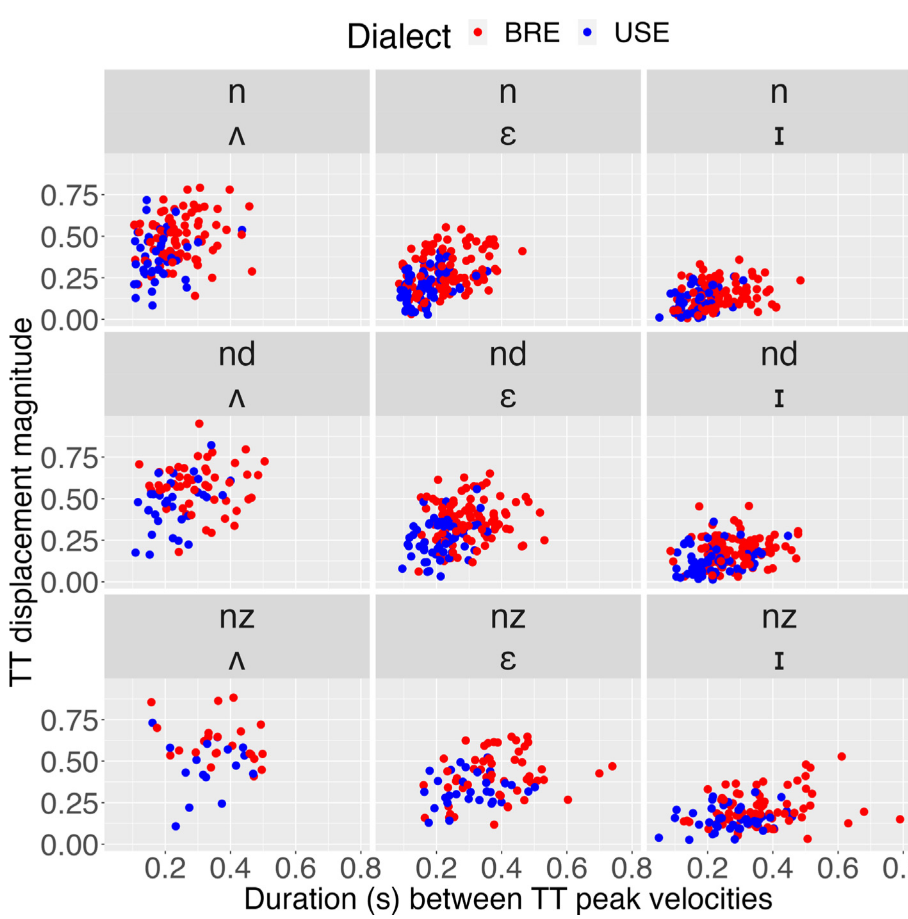

Fig. 7. Peak tongue tip displacement magnitude (vertical) as a function of the duration between tongue tip peak raising and lowering velocities.

(F(2,1028.8) = 39.58. /n/: $\hat{m}$ = 3.65; /nd/: $\hat{m}$ = 4.23; /nz/: $\hat{m}$ = 4.44), no influence of dialect, and no significant interactions.

5.3. Discussion

Both the peak displacement magnitude and the two duration measures of tongue tip raising were less in USE than in BRE. However, there was no difference between the varieties in the peak tongue tip raising velocity. This suggests that the tongue tip gesture in nasal codas is smaller and shorter but not slower for USE.

Overall, these results are consistent with a sound change model by which the increased nasalization in the vowel and the associated diminished nasalization (section 3) in the nasal coda are also associated with reduction or lenition of the tongue tip gesture. The next section tests whether there is a correlation between the two: that is, whether as predicted by the proposed extension to Beddor's model in Fig. 1, the more extensive nasalization in the vowel was also associated with greater tongue tip reduction.

6. Vowel nasalization and tongue tip lenition

6.1. Method

The analysis was applied to the data for which tongue tip data was available (i.e., for the vowels /ʌ, ɛ, ɪ/ only: section 2.3) and consisted of establishing the association between two parameters. The first of these was the proportional time of peak velum lowering relative to the time of the peak tongue tip raising velocity and is given by i_1/i_2 in Fig. 8. This is the same parameter as analyzed in Fig. 2, except that in this case the offset is relative to the time of the peak velocity of tongue tip raising as opposed to the acoustic boundary between the vowel and nasal coda (as in Fig. 2). A greater degree of vowel nasalization is associated with a lower value of i_1/i_2. When i_1/i_2 has negative and positive values, then the time of peak velum lowering precedes and follows respectively the peak velocity time of tongue tip raising. The second parameter (Fig. 8, row 2) was the magnitude of peak tongue tip raising. As Appendix F shows, peak tongue tip raising tended to precede the time of the peak velocity of velum raising which means it typically occurred during N i.e., in the interval within which the velum was still lowered. The prediction was that more extensive vowel nasalization should be associated with greater tongue tip lenition. If so, then these two analysed parameters shown in Fig. 8 should be positively correlated (so that lower values of i_1/i_2, implying a greater degree of vowel nasalization, are associated with an increasing lowering of the tongue tip).

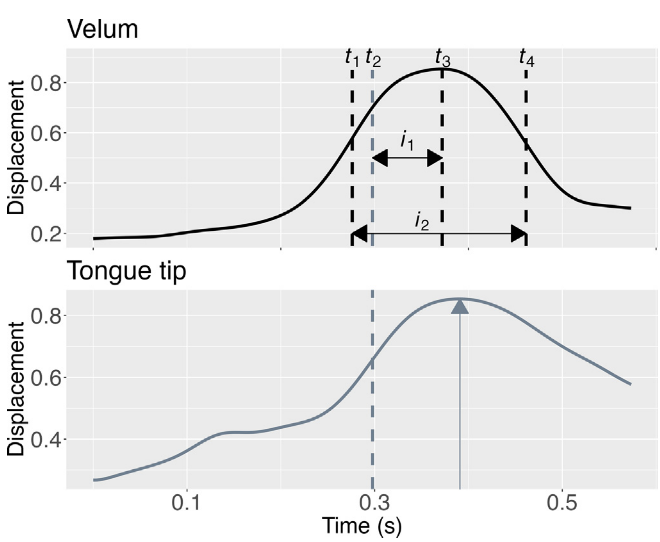

Fig. 8. Synchronized velum and tongue tip trajectories over a VN(C) interval. The times of the vertical dashed lines in row 1 are from left to right as follows. t_1: peak velocity of velum lowering. t_2: (grey) peak velocity of tongue tip raising. t_3: peak displacement of velum lowering. t_4: peak velocity of velum raising. The intervals i_1 and i_2 are the same as in Fig. 2, except that for i_1, the left boundary is at the peak velocity of tongue tip raising (as opposed to the acoustic vowel offset in Fig. 2). The two analysed parameters were (1) i_1/i_2 (row 1), the proportional alignment of peak velum lowering, and (2) the magnitude of the peak tongue tip raising (row 2, vertical grey line).

Because of the sparsity of the data, it was not possible to achieve convergence in a mixed model with the same three factors as in (1) as well as with the magnitude of peak tongue displacement. For this reason, the mixed model was rearranged with the magnitude of peak tongue displacement and dialect as fixed factors and in which the vowel and coda were random factors (see Riverin-Coutlée et al., 2023 et al, section 3.3 for a similar approach). Thus, the mixed model was as in (2):

$$\text{model} = \text{lmer}(i_1/i_2 \sim TT_{pd} * \text{dialect} + (\text{dialect} + TT_{pd}|\text{vowel\_coda}) + (TT_{pd}|\text{speaker})) \quad (2)$$

in which *vowel_coda* represents the vowel and coda combined into a single factor with nine levels (3 vowels × 3 codas) and TT_{pd} the magnitude of peak tongue tip displacement. Post-hoc tests were carried out with the `emtrends` function of the `emmeans` package as in (3):

$$\text{emtrends}(\text{model}, \text{pairwise} \sim \text{dialect}, \text{var} = '\text{TTpd}') \quad (3)$$

6.2. Results

The scatter plots in Fig. 9 with superimposed regression lines of the relationship between proportional alignment of peak velum lowering (i_1/i_2) and the magnitude of peak tongue tip raising (TT_{pd}) show a positive relationship between these two variables for 6/9 of the possible vowel × coda combinations in each of the two dialects. The results of the mixed model in (2) showed a significant influence on i_1/i_2 of TT_{pd} (F(1,10.39) = 28.72, $p < 0.001$) and of dialect (F(1,37.37) = 1 7.79, $p < 0.001$) as well as a not quite significant (F(1,49.25) = 2.95, $p < 0.1$) interaction between these two factors. The post-hoc test using (3) showed a significantly positive relationship between i_1/i_2 and TT_{pd} in both BRE (slope = 0.328, standard error = 0.075) and USE (slope = 0.443, standard error = 0.0859).

The reconstructed slopes between these variables in the two dialects are shown in Fig. 10.

As Fig. 10 shows, the slope is slightly greater for USE than for BRE (but not significantly so). The lower value of the predicted regression line on the *y*-axis for USE comes about because, as the results from section 3 (Fig. 3, row 1) showed, the proportional time of peak velum lowering was earlier for USE than for BRE.

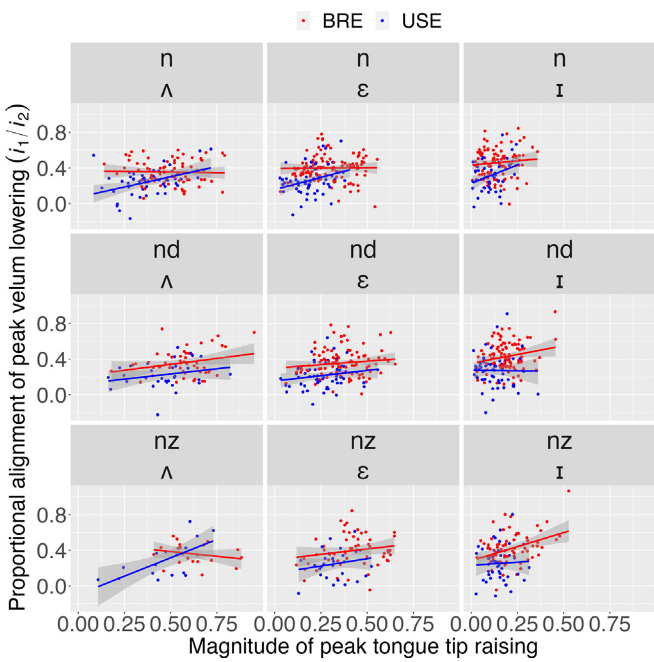

Fig. 9. A scatter plot with superimposed regression lines of the proportional alignment of peak velum lowering as a function of the magnitude of peak tongue tip raising separately by dialect, vowel, and nasal coda.

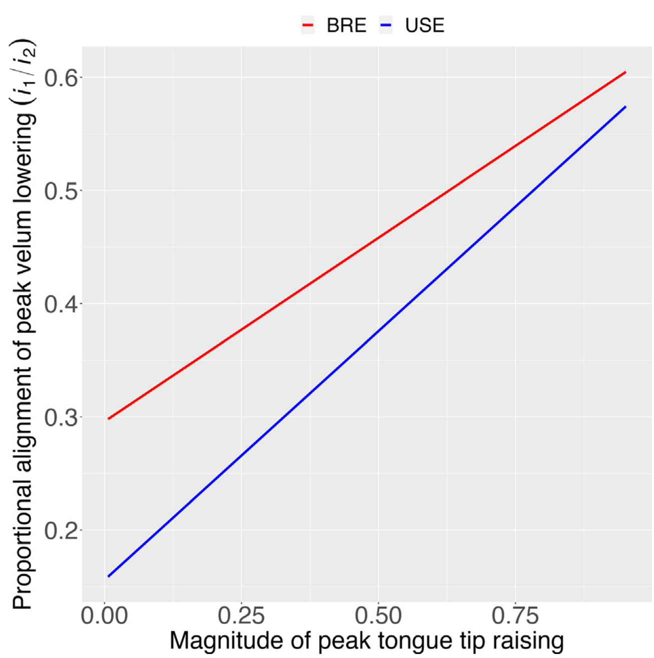

Fig. 10. The slope and intercept estimated from the mixed model in the plane of proportional alignment of peak velum lowering and magnitude of peak tongue tip raising. The estimates were derived post-hoc from (3).

6.3. Discussion

The results showed that an earlier alignment of the peak velum lowering was associated with greater tongue tip lenition. This finding was found for both dialects that did not differ significantly from each other on this relationship. These results therefore lend support to the idea that the sound change VN > Ṽ involves a reciprocal relationship between the coarticulatory effect and source: as the effect (i.e., vowel nasalization) increases, then the source (the nasal coda) is weakened.

So far, it remains unclear how the temporal relationship between the velum and tongue tip changes with an earlier peak velum lowering relative either to the acoustic VN boundary (section 3) or relative to the time of the peak tongue tip raising velocity (section 6.1). If the sound change VN > Ṽ involves a realignment of the velum but not the oral gesture of the nasal coda, then the peak velum lowering and peak tongue tip raising are predicted to be more asynchronous in USE than in BRE. This prediction was tested in the following section.

7. Inter-gestural analysis of tongue tip and velum

The main objective was to test the prediction that the asynchrony between the velum and tongue tip is greater in USE than in BRE as a consequence of the earlier alignment of a stable velum gesture.

7.1. Method

For the purposes of measuring the coordination between the tongue tip and velum, two intervals (Fig. 11) were measured as follows:

- $i_1 = t_2 - t_1$, between the time of the peak velum lowering (t_2) and the time of peak tongue tip raising velocity (t_1).
- $i_2 = t_3 - t_2$, between the time of the peak tongue tip raising (t_3) and the time of the peak velum lowering (t_2).

7.2. Results

Contrary to the prediction, there is little evidence from Fig. 12 that the tongue tip peak is aligned later with respect to the peak velum lowering in USE than in BRE. Consistently with section 5.2 (Fig. 6), however, Fig. 12 shows a greater lenition of the tongue tip in USE. Fig. 12 also shows that the time of the peak tongue tip velocity (vertical solid blue and red lines) is later in USE than in BRE. Moreover, these tongue tip peak velocity times shown in the same figure are very close to those of the aggregated times of the acoustic boundary (dotted ver-

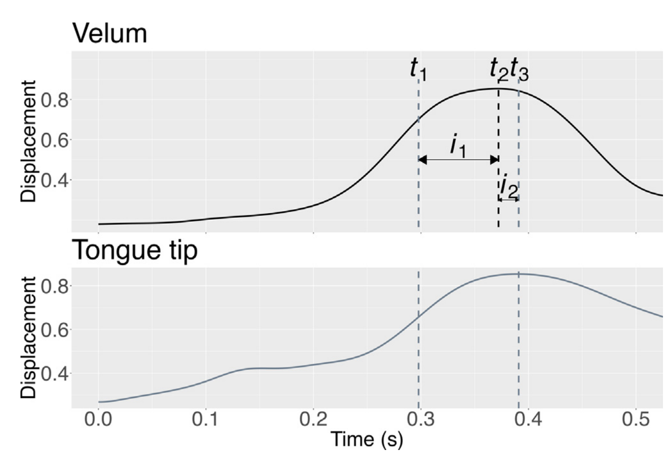

Fig. 11. Synchronized velum and tongue tip trajectories over a VN(C) interval. The times of the vertical dashed lines in row 1 are from left to right: (t_1) peak velocity of tongue tip raising (t_2) peak displacement of velum lowering (t_3) peak displacement of tongue tip raising. The horizontal double arrows show the two parameters, i_1 and i_2, that were analysed.

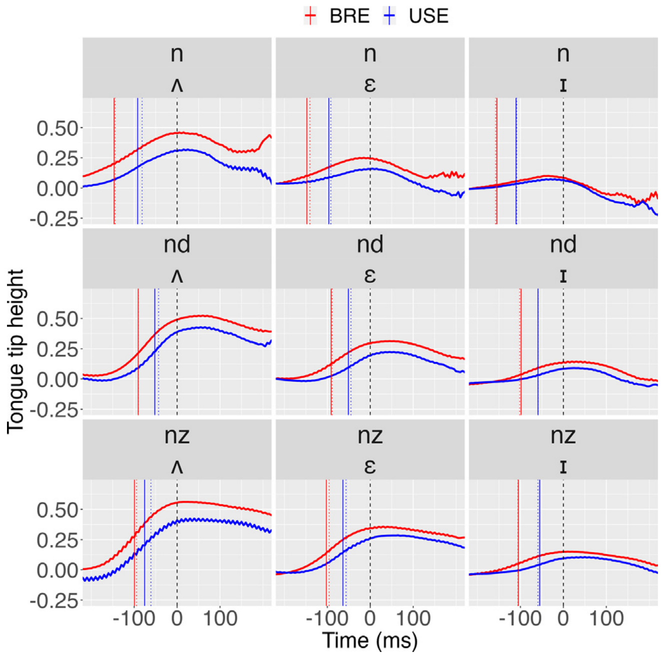

Fig. 12. Tongue tip trajectories synchronised at the time of peak velum lowering (t = 0 ms, dashed vertical black line) and aggregated without time normalization separately by dialect, vowel, and nasal coda. The red and blue solid vertical lines are the mean times of peak tongue tip velocity in BRE and USE. The red and blue dotted vertical lines are the mean times of the acoustic boundary between the vowel and nasal in VN(C) in BRE and USE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tical lines) between the vowel and nasal consonant (and that these are always later for USE).

The results of the statistical analysis for the two intervals i_1 and i_2 (Fig. 11) are as follows.

- For i_1, the interval between the times peak velum lowering and peak tongue tip raising velocity, there was a significant influence of dialect (F(1,40.63) = 12.86, p < 0.001. BRE: $\hat{m}$ = 114 ms; USE: $\hat{m}$ = 69 ms) and of nasal coda (F (2,762.18) = 126.70, p < 0.001. /n/: $\hat{m}$ = 122 ms; /nd/: $\hat{m}$ = 72 ms; /nz/: $\hat{m}$ = 80 ms), no influence of vowel, and no interaction between the fixed factors.
- For i_2, the interval between the time of the peak tongue tip raising and the time of the peak velum lowering, there was no influence of dialect, a significant influence of vowel (F(2,971.93) = 47.801, p < 0.001. /ʌ/: $\hat{m}$ = −36 ms; /ɛ/: $\hat{m}$ = −25 ms; /ɪ/: $\hat{m}$ = −1 ms) and a significant influence of the nasal coda (F(2,41.75) = 41.480, p < 0.001. /n/: $\hat{m}$ = 29 ms; /nd/: $\hat{m}$ = −45 ms; /nz/: $\hat{m}$ = −46 ms) and no significant interaction between the fixed factors.

7.3. Discussion

The results for interval i_2 (Fig. 11) have shown no greater asynchrony between peak velum lowering and peak tongue tip raising for the nasal coda for USE compared with BRE. But on the other hand, the interval i_1 (Fig. 11), between the time of the peak velum lowering and peak tongue tip velocity, is less in USE. In addition, the analysis in section 5.2 showed that the tongue tip gesture in the nasal coda was smaller and shorter but not slower in USE while those in section 4.2 showed that the velum gesture between the dialects was stable.

Taken together, these findings imply that the greater nasalization in the vowel and associated diminished nasalization in the nasal coda for USE can be explained by a rightwards shift

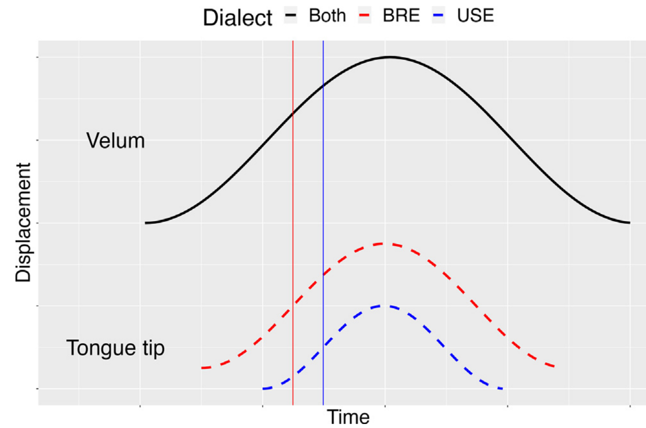

Fig. 13. A schematic outline of the displacement of the velum (black, for both dialects) and of the tongue tip (BRE: red dashed; USE: blue dashed) as a function of time. The vertical lines are the times of the peak velocity of tongue tip raising for BRE (red) and USE (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the time of the peak tongue tip velocity (t_1 in Fig. 11) which, as Fig. 12 suggests, corresponds quite closely to the acoustic boundary between the vowel and nasal consonant in VN. Thus, the shorter interval that was found in section 3.2 for USE between the times of the peak velum lowering and the internal acoustic VN boundary does not come about because of a leftwards shift (earlier alignment) of the velum: the velum gesture between the varieties is stable not only in magnitude, but also in time. The closer interval between the time of peak velum lowering and the internal VN boundary in USE derives instead from a greater rightwards shift in USE compared with BRE of the time of peak tongue tip velocity (and hence of the internal VN acoustic boundary). Thus, the tongue tip reduction in USE is associated with a later timing of peak tongue tip velocity and it is the rightward shift of this articulatory landmark (that is also closely associated with the acoustic boundary between the vowel and nasal consonant) that leads to a greater temporal extent of nasalization in the vowel and proportionately less nasalization in the nasal coda (see Fig. 13).

8. General discussion

The starting point for this investigation was that American English (USE) was further along the path of sound change VN > ṼN > Ṽ than Standard Southern British English (BRE). The link between these dialect differences and the progression of sound change is that both are hypothesized to involve a realignment of a stable velum gesture with respect to oral, lingual gestures. The model used to test this synchronic-diachronic connection was that of Beddor (e.g., Beddor, 2023 for a recent summary) whose analyses were primarily informed by within-USE comparisons between VNÇ (e.g., *sent*) that is predicted to be further along the V > VN > Ṽ path of sound change than VNÇ (e.g., *send*).

The results in the present study have shown that for most vowel × coda contexts investigated here, USE had greater nasalization in the vowel and less nasalization in the coda nasal consonant (section 3) than BRE. Moreover, as predicted by Beddor's model, the velum gesture was stable: that is, the size, peak lowering velocity, and articulatory duration of the velum gesture were no different in comparing USE with BRE (section 4).

There were some vowel and coda-specific findings. Thus, across both dialects, peak alignment was affected by vowel length given that the proportional alignment was earlier for /æ, eɪ/ than for /ʌ, ε, ɪ/ and for /ʌ, ε/ than for /ɪ/. The pattern was similar regarding the extent of nasalisation in the coda nasal i.e., the extent of nasalization in the nasal consonant was less when it was preceded by /æ/ than by /eɪ/ than by /ʌ, ε, ɪ/. Given that /eɪ/ is a long vowel and taking into account that nasalized /æ/ for these American English speakers is [−low] (see Appendix C), then duration and not vowel height is the likely cause of the vowel-specific influences of anticipatory nasal coarticulation. The interaction between length and vowel nasalization in German VN rhymes was recently analysed in Kunay et al (2022). They showed (see in particular their Fig. 6) that peak velum displacement was attained proportionately earlier in German (tense i.e., long) vs. German lax (i.e., short) vowels and also that this effect was greatest in tense /a:/. These findings from German pattern quite well with those from the present study regarding the earlier proportional timing of peak velum displacement in long /æ, eɪ/. The explanation in Kunay et al (2022) for this length effect is the perseverative effect of the levator palatini (a primary muscle for velum closure) from the initial oral consonant in CVN combined with the diminished time available for velum lowering in lax vowels. Given that the initial C in the present data was also oral, this also seems to be a plausible explanation for the earlier attainment of peak velum lowering in long vowels /æ, eɪ/ compared with the short vowels /ʌ, ε, ɪ/ in the present data.

In the present study, the target words were always produced under narrow focus. A study by Cho et al (2017) of the effects of prosodic focus and boundary on coarticulatory vowel nasalization is relevant to understanding how the findings might be extended to other prosodic contexts. In their study, Cho et al, (2017) found that when target words were prosodically unfocused, then anticipatory vowel nasalization increased and the duration of the N murmur in CVN sequences decreased. Since these findings from focused to unfocused are in the same direction as found in the present study between British and American English speakers respectively, then our two groups of dialect speakers would likely show similar (or possibly greater) differences if the target words in our study had been prosodically unfocused.

As far as the effects of a prosodic phrase boundary are concerned, the same study by Cho et al (2017) found nasal murmur lengthening and greater anticipatory coarticulatory vowel nasalization in CVN sequences. In accordance with other models and findings (Browman & Goldstein, 1992, 1995; Fougeron, 1999; Keating, Wright, & Zhang, 1999), Cho et al (2017) suggest that in phrase-final position, the final N is subject to weakening (even though it is lengthened). This could lead both to a reduction in the force that elevates the velum and increased nasalization, also in the vowel. Their further interpretation is that these effects can be best understood as caused by a weakening of the degree of consonantality of the final N together with an anti-phase velic-oral coupling association between the vowel and coda consonant (Byrd,et al., 2009; Goldstein et al., 2009). Assuming that the reduction of the oral constriction found in our study is commensurate with Cho et al's (2017) interpretation of a weakening of N consonantality, then their findings from phrase-medial to phrase-final are generally also in the same direction as found between British and American English speakers respectively. It is therefore possible that the two groups of dialect speakers would likely show similar differences if the target words had been produced in phrase final position. Nevertheless, whether there really is an interaction between the dialects analysed here and prosodic focus or prosodic boundaries requires further testing.

The path of the sound change VN > ṼN > Ṽ predicts not only that the nasalization in the coda N is transferred to the vowel, but also that the size of the N's oral gesture should be diminished and then disappear completely as the vowel is fully nasalized. Consistently with this prediction, it was shown (section 5) that the tongue tip reduction of /n/ was greater in USE than in BRE. The tongue tip reduction manifested itself as a decrease in gestural magnitude and duration but not velocity in USE: that is, the tongue tip gesture was found to be smaller and shorter in USE but not slower than in BRE.

The path to sound change is also predicted to involve a trade-off between coarticulatory effect and source such that, as the former is enhanced, the latter is diminished (Raphael et al., 1975, Busà 2007, Beddor, 2009). Just such an effect was found for these data (section 6). That is, in both USE and BRE, the greater degree of vowel nasalization was found to predict increasing tongue tip lenition. This is consistent with recent findings from a nasometric study by Bongiovanni (2021a) showing that a shorter and/or weaker N was associated with an earlier onset of nasalization in both Spanish dialects that were investigated.

Finally, we tested whether the velum gesture was left shifted i.e., aligned earlier in time for USE than for BRE. That this should be so follows from Beddor's model (2009) in which the increase in vowel nasalization and concomitant decrease in nasalization in the coda is a consequence of a velum gesture that is stable i.e., unchanging as it slides into the preceding vowel. This prediction was also found to be consistent with the findings in the present study of (i) greater and less nasalization in the vowel and coda nasal respectively for USE combined with (ii) a velum gesture that does not differ in magnitude nor duration between the two varieties. Nevertheless, there was no evidence (section 7) of a greater left alignment of the velum gesture in USE than in BRE. The analysis by contrast showed that the velum gesture across the varieties was stable not just in space but also in time. What did differ between the varieties was the time of the tongue tip peak raising velocity which was closer to the (reduced) tongue tip peak in USE. An acoustic consequence of this rightwards shift of the time of peak tongue tip raising velocity was also a rightwards shift in the internal acoustic VN boundary that typically occurs close to this time point. Given that the velum gesture between the varieties was found to be stable, then a rightward shift in the acoustic boundary between V and N has the consequence of nasalization that is greater in V and less in N for USE compared with BRE.

The comparison between these two dialects suggests that coda weakening is likely to be one of the main contributory factors in the progression along the path of sound change VN > ṼN > Ṽ. Coda weakening is common synchronically (Bauer, 2008; Browman and Goldstein, 1995; Fougeron, 1999; Gurevich, 2004; Ohala & Kawasaki, 1984; Recasens, 2014) and is one of the principal sources of variation in different types of sound change (Bybee & Easterday, 2019; Cohen

Priva, 2017; Hock, 1992; Lin et al., 2014; Lawson and Stuart-Smith, 2021; Ohala, 2012; Solé, 2010). Extrapolating from the results of the present physiological analysis, the oral gesture of N in VN > ṼN > Ṽ sound changes is likely to be weakened in two ways: 'vertically' as a result of lenition causing the N to become more vowel-like; and 'horizontally' as the internal VN boundary is pushed increasingly closer towards the maximum point of N's oral constriction. The progressive lenition of the N's oral constriction combined with an increasingly rightwards shift of the internal VN boundary provide the physiological conditions for nasalization to be phonologized in the vowel with complete loss of the coda N. More generally, the physiological comparison between these two varieties suggests that the increase in the anticipatory coarticulatory nasalization potentially leading to its phonologization in the vowel comes about because coda weakening targets N's oral but not nasal gesture (which was found to be stable across both varieties).

There is, in fact, scant evidence from our studies (both the present results and those in Carignan et al., 2021) and from other production analyses that the velum gesture becomes left-aligned in contexts in which vowel nasalization increases and the coda nasal shrinks. The shift of a velum gesture earlier in time has instead been one of the possible (and entirely plausible) interpretations based upon the ample evidence showing a trade-off in production (Beddor, 2009; Beddor et al., 2007; Busà, 2007) and perception (Beddor et al., 2018) between coarticulatory nasalization in V and the duration of N. Moreover, with the exception of recent analyses by Bongiovanni (2021a, 2021b), previous studies proposing a leftwards shift of the velum gesture have been silent with regard to the impact of such an earlier alignment on its coordination with the oral constriction of the N. Following the model of articulatory phonology in which gestures from different tiers are autonomous (Browman & Goldstein, 1991, 1992; Pouplier and Goldstein, 2010), the sliding of the velum gesture earlier in time should cause it to become increasingly asynchronous with the oral gesture for N. However, there was no evidence that this was so in the present study and moreover this would predict an increasing oralization of the N as the velum gesture is aligned earlier in time. However, while an acoustic analysis in Beddor (2009) shows that shorter nasal consonants (and longer nasalized vowel portions) co-occur with longer oral stop closure duration in /ɛnt/ (*sent*) than in /ɛnd/ (*send*) words, sound changes in which ṼN > Ṽ passes through an intermediary stage of ṼC in which the final consonant is oral are to our knowledge undocumented (as are synchronic fast speech processes showing a variation between ṼN and ṼC). It could instead be argued, as implied by Fig. 1a (section 1) that the oral constriction of N shifts synchronously with the leftwards alignment of the velum gesture. However, there are likely to be biomechanical restrictions on the extent to which a tongue tip raising gesture could be early-aligned relative to the dorsal component for a preceding V and in any case this explanation could never be extended to other places of articulation: for example, an earlier jaw raising for N = /m/ would conflict with the required jaw lowering for most kinds of preceding V (especially for open vowels in which the sound change has been reported to most advanced). Moreover, while an earlier alignment of the velum gesture can be phonetically and typologically motivated for voiceless VNÇ clusters (*sent*), there is no synchronic phonetic motivation for an earlier alignment of the velum gesture in most of the other VN contexts. Consequently, the increasingly early alignment in VNÇ as the sound change progresses would have to extend in some not yet well-defined way – presumably by analogy – to all these other VN contexts, if the leftwards shift of the velum gesture in VNÇ is argued to constitute the synchronic basis for the sound change VN > ṼN > Ṽ.

There are by contrast no such obstacles to the alternative explanation that increased nasalization in the vowel is a by-product of the shrinkage of the N (and more specifically as shown in this study of a shift in the time of tongue tip peak velocity towards the tongue tip maximum) combined with a stable velum gesture. This is firstly because a shrinkage of N can indirectly cause increased nasalization in the vowel without any change in the alignment between the velum and N's point of maximum oral constriction: therefore, explanations concerning the impact of an earlier alignment of the velum gesture on its synchronization with the oral gesture of N are not necessary. Secondly, the main force that drives the shrinkage of the N, i.e., coda reduction, could apply to wider nasal coda contexts and not just to VNÇ. In fact, just such an interpretation that is compatible with the present results in which speakers might shorten N without realigning the velum gesture has already been suggested by Beddor (2009:797) in noting that speakers might target a stable velum gesture in order to maintain the information about nasality even if N shortens. We agree with this premise, but would propose the following modification: speakers target a reduction of coda consonants which has a greater detrimental effect on the oral than on the nasal component of N. Under this interpretation, increased anticipatory nasal coarticulation in V is an inevitable, mechanical consequence of the shrinkage in time and space of the oral component of N.

The model by which variable coarticulatory vowel nasalization as a path to sound change derives from the combination of a stable velum gesture and N reduction rests on numerous assumptions that warrant further investigation. One of the main shortcomings of the present study is that the proposed model linking synchronic variation to diachronic change has been founded on a comparison of just two dialects that have been argued to be at different stages along the sound change path. Other similar types of dialect pairs also from other languages may well show different patterns of phonetic variation. For example, Bongiovanni's (2021a, 2021b) comparison between two Spanish dialects (Santo Domingo which was presumed to be further along the path of sound change than Buenos Aires Spanish) showed that they differed in the extent of anticipatory coarticulatory nasalization, even though the dialects showed a similar degree of N weakening. Further investigations are needed to extend the present study to other contexts such as final labials (*stem*, *stems*, *stemmed*), as well as to other speaking styles in order to determine whether, as predicted by various analyses (Beddor et al., 2013; Coetzee et al., 2022), those American English individuals that we have argued to be at a more advanced stage of sound change in production are also more sensitive to anticipatory coarticulatory nasalization than their Southern British English counterparts in perception.

Finally, it is quite possible that the proposed model in which increased vowel nasalization is driven by lenition of the oral component of N does not carry over to NÇ with a final voiceless obstruent in which the vowel has been shown to be more nasalized than in similar voiced NC̬ contexts (Cohn, 1990; Beddor, 2009). Indeed, it seems unlikely that the model proposed in the present study is easily extendible to NC̥ in words like *sent* because there is so far no independent evidence that the alveolar closure is more lenited than in NC̬ (*send*). Moreover, Beddor (pers. comm.) has provided additional acoustic and aerodynamic data for the speakers in Beddor (2009) and Beddor et al (2018) to show that the onset of nasalization and/or onset of nasal airflow is earlier in CVNC̥ than in CVNC̬ sequences. In addition, the velum gesture could become left-aligned in VNC̥ words because of so-called NC̥ repulsion by which nasals in the languages of the world are less likely to be followed by voiceless than by voiced consonants (Pater, 1999; Itô & Mester, 1986; see also Carignan et al., 2021; Ohala & Ohala, 1993, Ohala & Busà 1995, Ohala et al., 1998, Shosted, 2006, and Solé 2007 for physiological, acoustic, and perceptual explanations for why NC̥ should repel each other). Thus, the findings in the present study by no means exclude the possibility that the path to sound change in VNC̥ is due to an earlier alignment of the velum gesture and therefore different from C lenition in VNC̬ that is proposed as the principal mechanism of sound change in the present study.

CRediT authorship contribution statement

Conceição Cunha: Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Phil Hoole:** Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Dirk Voit:** Visualization, Software, Resources, Methodology, Formal analysis. **Jens Frahm:** Supervision, Software, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jonathan Harrington:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Appendix A

(See Table A1).

Table A1
The vowel and coda combinations and corresponding words that formed part of the read materials in this study.

Rhyme		n	nd	nz
Vowel	**Onset**			
æ	b	ban	band	bans
	p	pan	panned	pans
	f	fan	fanned	
	other		sand	
ɛ	b	Ben	bend	Ben's
	p	pen	penned	pens
	f	fen	fend	
	other	Zen	send	
ɪ	b	bin	binned	bins
	p	pin	pinned	pins
	f	fin	finned	
	other	sin	sinned	sins
ʌ	b	bun		
	p	pun	punned	puns
	f	fun	fund	
	other	shun	shunned	shuns
eɪ	b	bane		
	p	pain	pained	pains
	f	feign	feigned	feigns
	other	sane		

Appendix B

(See Table B1).

Table B1
Details of the speakers that participated in the recordings by age, sex and for the American English (USE) speakers by state and by region.

Dialect	Speaker	Age (years)	Sex	State	Region
USE	S02	25	f	Georgia	South
	S03	26	f	Alabama	
	S28	30	m	Georgia	
	S04	28	m	Washington	West
	S05	28	m	Washington	
	S07	29	f	California	
	S25	26	m	Oregon	
	S27	29	m	Oregon	
	S42	42	m	Washington	
	S14	20	f	Pennylvania	Atlantic
	S34	26	f	Pennylvania	
	S41(excluded)	20	f	Pennylvania	
	S30	24	f	Pennylvania	
	S06	27	m	Wisconsin	Midland
	S24	22	f	Indiana	
	S31	37	m	Columbus	
	S35	22	m	Indiana	
BRE	S01	24	f		
	S08	21	m		
	S09	23	m		
	S10	46	m		
	S11	21	f		
	S12	19	f		
	S13	19	f		
	S15	23	m		
	S16	19	f		
	S17	19	m		
	S18	24	m		
	S20	20	m		
	S21	20	m		
	S22	25	m		
	S23	21	m		
	S26	19	f		
	S29	20	m		
	S32	18	m		
	S33	18	f		
	S36	20	m		
	S37	19	f		
	S38	19	f		
	S39	23	f		
	S40	20	f		
	S43	20	f		
	S44	21	f		
	S45	24	m		

Appendix C

The aggregated trajectories for the 16 USE speakers in Fig. C1 show a higher tongue dorsum position for /æ/ before /n, nd, nz/ than for /ɛ/ before (oral) /d/. The plot therefore suggests that the vowel height of /æ/ preceding these nasal consonants was at least mid for all 16 speakers and for most considerably higher than that of /ɛ/.

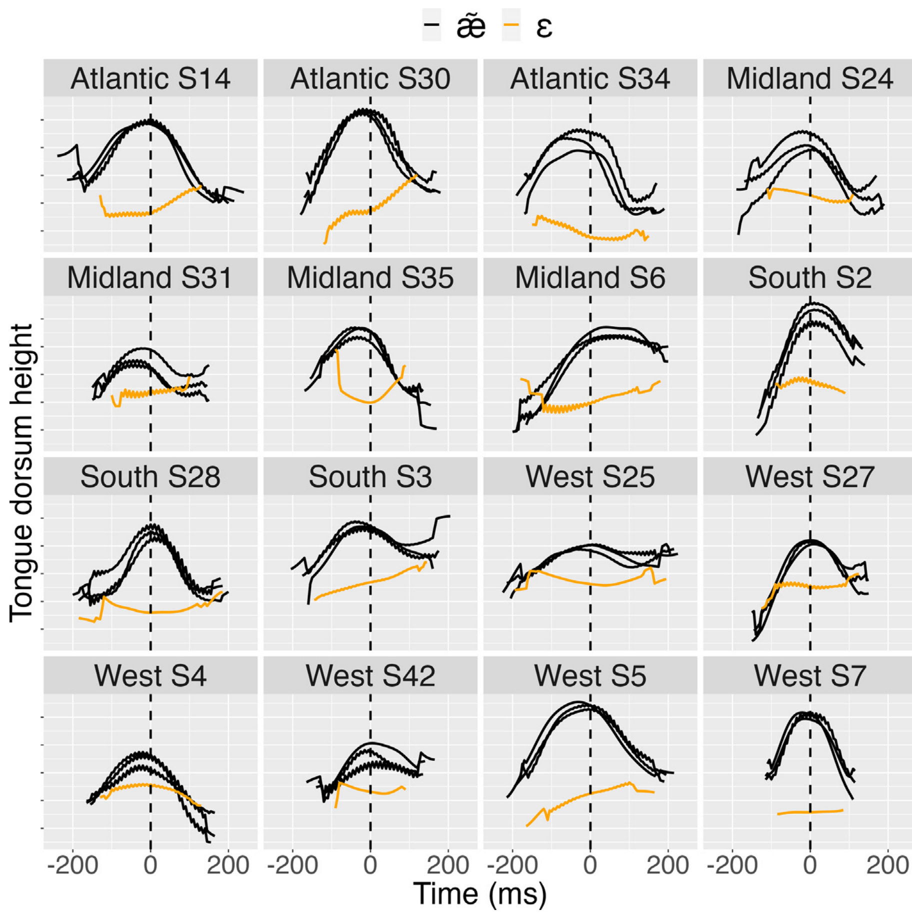

Fig. C1. Tongue dorsum trajectories aggregated for each of the 16 USE speakers separately for /æ/ before /n, nd, nz/ (black: three trajectories per speaker) and for /ɛ/ before /d/ (gold). The trajectories are based on the gridlines from the palatal region, with processing and normalization carried out as detailed in 2.5.2. Accordingly, all panels are scaled from 0 to 1 (1 corresponding to each speaker's most constricted dorsal tongue position). The regional affiliation (Appendix B) for each speaker is shown above each plot. The trajectories extend between the acoustic vowel onset and offset and were aggregated after alignment at the acoustic vowel midpoint (vertical dashed line).

Appendix D

As Fig. D1 shows, there was no evidence of differences between the two dialects in velum height at the acoustic onset of vowel.

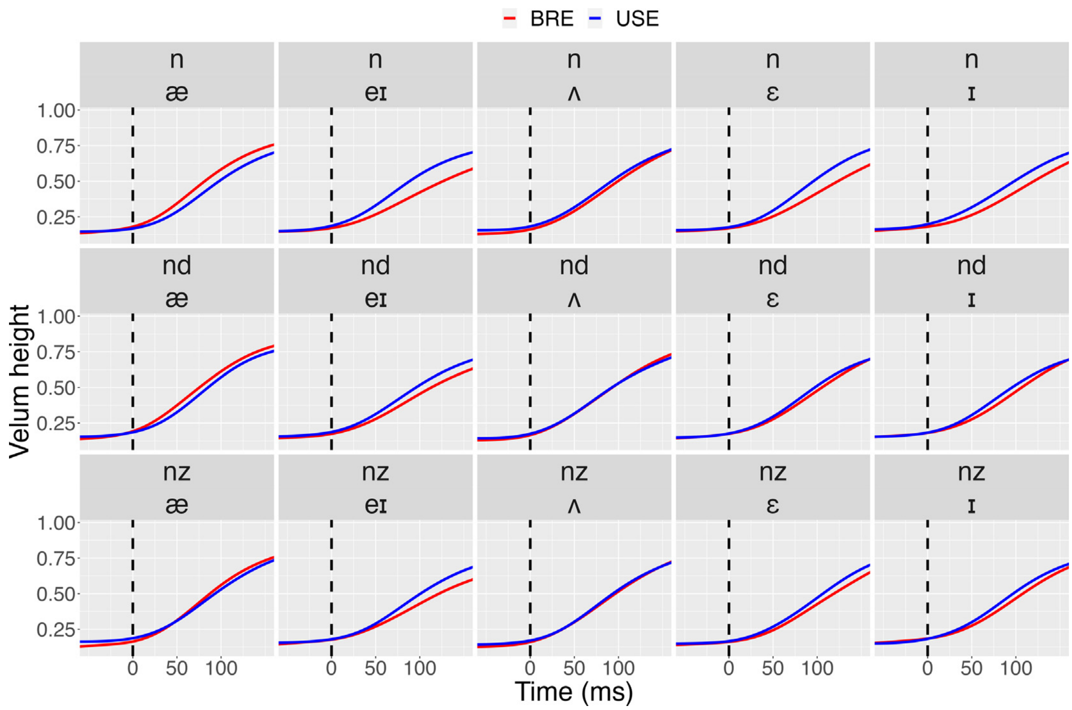

Fig. D1. Trajectories of velum height aggregated by vowel, coda and dialect and aligned at the acoustic onset of the vowel (t = 0 ms).

Appendix E

An overall prediction from these results is that the vowel duration before N should be greater and the N duration less in American compared with British English CVN sequences. This is so for these data where V is measured between the acoustic onset and offset of the vowel and N from the acoustic offset of the vowel to the time of peak velocity of velum raising. (See Fig. E1).

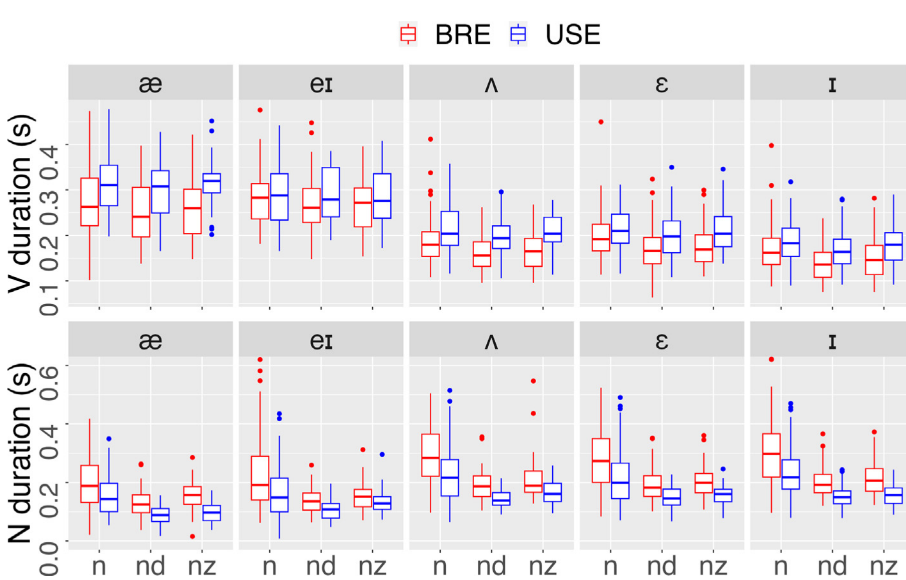

Fig. E1. Above: Duration in seconds of the vowel between the acoustic onset and offset. Below: Duration in seconds of the interval between the acoustic vowel offset and time of the peak velocity of velum raising. The measures were calculated for the same data analysed in Fig. 3.

Appendix F

The aggregated trajectories in Fig. F1 show that the time of the tongue tip peak raising (solid vertical lines) precedes the time of the peak velocity of velum raising at t = 0 ms, i.e., occurs predominantly within an interval in which the velum is lowered. Fig. F2 provides further evidence that the time of the tongue tip peak raising is typically earlier than the time of peak velocity of velum raising in both varieties.

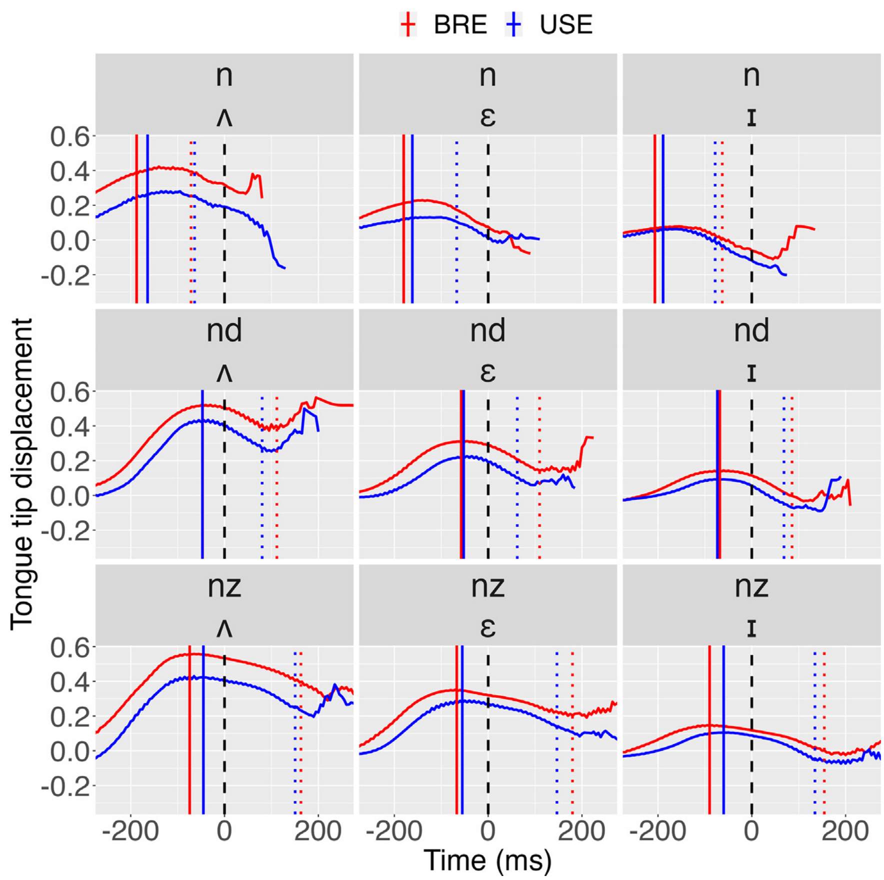

Fig. F1. Tongue tip trajectories aggregated without time normalisation by dialect, vowel, and coda after alignment at the time of the peak velocity of velum raising (t = 0 ms). The solid vertical lines (that precede t = 0 ms) are the times of peak tongue tip raising. The dotted vertical lines (preceding t = 0 for /n/ and following t = 0 ms for /nd, nz/) are the times of the peak velocity of tongue tip lowering.

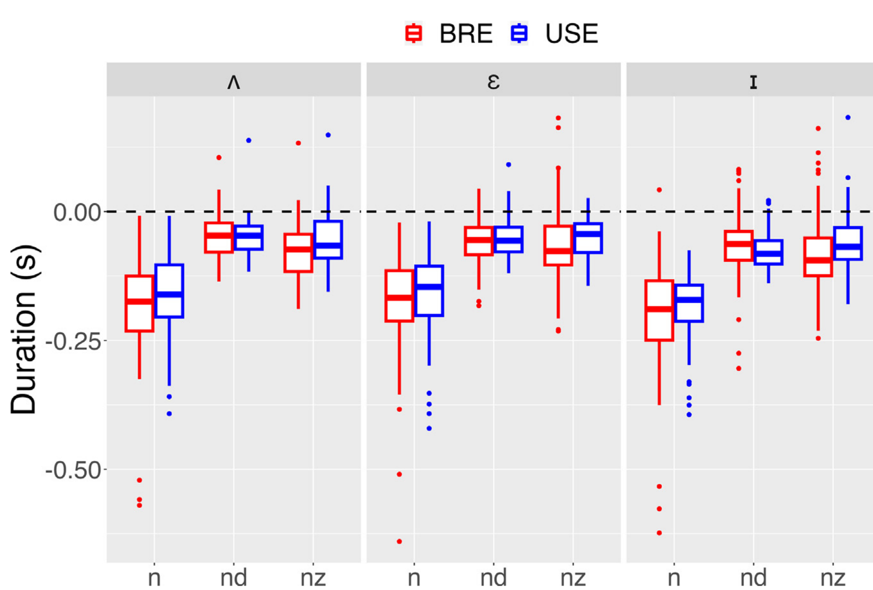

Fig. F2. Boxplots of the duration of $t_1 - t_2$ where t_1 is the time of peak tongue tip raising (the solid lines preceding t = 0 ms in) and where t_2 is the time of the peak velocity of velum raising. The horizontal dashed line at 0 ms corresponds, therefore, to the times at which the peak tongue tip raising and peak velocity of velum raising are the same.

Appendix G. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wocn.2024.101329.

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