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Language, Volume 101, Number 4, December 2025, pp. 660-699 (Article)

Published by Linguistic Society of America
DOI: https://doi.org/10.1353/lan.2025.a978272

VOWEL NASALIZATION AND THE PATH TO SOUND CHANGE: AN MRI STUDY OF AMERICAN AND SOUTHERN BRITISH ENGLISH /nt, nd/

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A central task in sound change research is to account for the emergence of new phonological categories from patterns of synchronic phonetic variation. To this end, a comparison was made of two English dialects differing in their phonologization of coarticulatory vowel nasalization using real-time magnetic resonance imaging of the velum and tongue and their synchronization with the glottal signal. This was done for coda vowel-nasal (VN) sequences preceding voiced and voiceless stops. The results showed that a later phasing of N's oral gesture and an earlier onset of aperiodicity in the nasal consonant were two of the main physiological factors likely to lead to sound change in voiceless VNC̥ clusters. They were also consistent with models of compensatory lengthening by which the vowel is lengthened and the oral gesture of the nasal consonant is shortened as sound change progresses.*

Keywords: vowel nasalization, compensatory lengthening, sound change, English dialects, coda voicing, real-time MRI

1. Introduction.

1.1. Phonologization, vowel nasalization, and sound change.

The present study is concerned with understanding the phonetic origin of phonologization: that is, with shedding light on the factors that cause coarticulatory phonetic variation to advance along a so-called PATH OF SOUND CHANGE (Beddor 2009, Gao & Kirby 2024, Yu 2021) such that usually over several generations it becomes categorical—that is, contrastive. The well-known phonologization-based sound changes include metaphony (Greca et al. 2024, Maiden 1991) and umlaut (Iverson & Salmons 2003, Penzl 1949, Twaddell 1938) with a phonetic origin of anticipatory vowel-to-vowel coarticulation that can span several intermediate consonants; tonogenesis (Brunelle et al. 2016, Brunelle et al. 2020, Coetzee et al. 2018, Hagège & Haudricourt 1978, Hombert et al. 1979) in which the development of a tonal contrast in vowels in nonaspirating languages derives phonetically from differences in fundamental frequency at vowel onset caused by different degrees of laryngeal tension in preceding voiced and voiceless stops; and—the subject of this study—the development of contrastive nasalization in vowels (Beddor 2012, 2023, Busà 2007, Carignan et al. 2021, Coetzee et al. 2022, Cunha et al. 2024, Hajek 1997, Solé 1995, 2009), whose phonetic origin is anticipatory nasal coarticulation due to a following nasal consonant (e.g. Latin SONUS 'sound'> /sɔ̃|sõ/, French *son*, Portuguese *som*).

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* We thank co-editor Shelome Gooden, associate editor Erez Levon, Pam Beddor, and an anonymous referee for their insightful and constructive comments. We are also grateful to Esther Kunay for her assistance in subject recruitment and support with the MRI recordings. The research was funded by the European Union (ERC, SoundAct, project number 101053194). Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. Data and scripts can be downloaded from https://doi.org/10.5282/ubm/data.711.

All of these sound changes have in common that there is a coarticulatory source that prior to the sound change taking hold has a coarticulatory effect. With the progression of the sound change, the coarticulatory effect not only becomes contrastive but is also enhanced well beyond its extent before the sound change occurred (Hyman 1976, 2013, Kirby 2013, Solé 2007).

The puzzle in the last few decades has been to explain how such sound changes are possible: that is, to explain how coarticulation becomes contrastive and enhanced as the source that gives rise to it diminishes and very often disappears completely. In some so-called 'life-cycle' models of phonological change (Bermúdez-Otero 2007, 2015, Kiparsky 2015, Ramsammy 2015, 2018), phonologization is the enhancement of the phonetic characteristics of a contrast that takes place when the sound change is postlexical and under phonetic control (Bermúdez-Otero 2015:383). As the sound change penetrates the lexicon, the variants in some phonological models become auditorily distinct, but noncontrastive quasi-phonemes (Kiparsky 2015). This stage that follows phonologization is sometimes referred to as STABILIZATION, in which the enhanced phonetic variants are the output of categorical phonological rules (Bermúdez-Otero 2015, Bermúdez-Otero & Trousdale 2012).

In phonetic models of sound change, the path to phonologization is often considered from the perspective of variable speech dynamics in production and perception. One of the most influential models of this kind is due to Ohala 1981, 1993. This model emphasizes how listeners process the phonological categories communicated by the speaker through the parsing or occasional misparsing of temporally overlapping speech gestures. Applied to the phonologization of nasalization in the vowel of VN sequences, a listener perceives V as oral in VN if the anticipatory coarticulatory nasalization in the vowel is parsed with the following nasal consonant. But if the listener erroneously parses the coarticulatory nasalization with the vowel, then the condition exists for the vowel to become contrastively nasalized following the loss of the N. The development of contrastive nasalization in the vowel depends on whether this erroneous perceptual parsing of nasalization is carried over into the same listener's speech production and also copied by others in the community. Since the probability of all these events occurring is remote, Ohala's model correctly predicts that the conversion of coarticulation-based variation into sound change is mostly unlikely to occur. Another prediction of this model is that the development of contrastive nasalization in the vowel is contingent upon N-deletion (Ohala 1981:186, 1992). However, such an association fails to explain the existence of numerous dialects with a phonological oral-nasal contrast in the vowel, but in which the N is nevertheless at least partially present (Hajek 1997:20, 75–77). Moreover, this categorical development of an oral-nasal contrast following N-deletion is not consistent with the evidence from other sound changes in which phonological contrasts emerge gradually rather than abruptly (Bukmaier et al. 2014, Coetzee et al. 2018, Kuang & Cui 2018) nor with some studies from first language acquisition showing that the contrast between phonological categories is not binary but is progressively sharpened over a number of years in children without language disorders (Beckman et al. 2007).

The perceptual parsing of coarticulation also has a primary role in the model of sound change developed by Beddor (2009, 2012, 2023, Beddor et al. 2013, Beddor et al. 2018). But whereas in Ohala 1993 sound change is an abrupt transition from VN to Ṽ caused by a categorical parsing error, sound change is gradual in Beddor's model and a consequence of differences between individuals both in their production of coarticulation (Grosvald 2009) and in the attention they pay to coarticulatory information in speech perception. Beddor (2009) shows that there is variation between speakers of American English ranging from those who produce a fully nasalized Ṽ to those who have a near oral V in VN sequences. Compatibly, listeners vary in their sensitivity to such coarticulation (Beddor 2012, Beddor et al. 2013), with some perceiving nasalization in VN sequences very close to vowel onset, while for others, nasalization is timed to occur much later during the N. There is also extensive independent evidence from speech perception (Clayards 2018, Francis et al. 2000, Schertz & Clare 2020, Yu 2022) that listeners vary in the weight that they assign to different cues to a given phonological contrast. According to Beddor, progression along the VN > Ṽ sound change path comes about because of a gradual perceptual reweighting of nasalization cues in the direction of those innovative individuals who give maximum weight to vowel nasalization cues in perception and who often show extensive vowel nasalization in production.

1.2. Syllable-final N weakening, voicing, and sound change. The present study is also concerned with the relationship between weakening of the N and the progression of the VN > Ṽ sound change. The extent of vowel nasalization and N-loss are known to be affected by syllable position. Anticipatory nasal coarticulation in syllable-final VN exceeds perseverative coarticulation in syllable-initial NV, as shown through experimental analyses for many acoustic measurements (Bell-Berti 1993, Cho et al. 2017, Moll 1962, Moll & Daniloff 1971, Ohala 1971, Solé 1992), but not for all languages (e.g. French, Greek, Italian, and Japanese: see Delvaux et al. 2008 for a review).

In many languages, consonants are more likely to undergo weakening and sound change in syllable-final than initial position (Bybee & Easterday 2019, Hock 1992, Lawson & Stuart-Smith 2021, Recasens 2002; see Solé 2010 for domain-final fricative weakening and its association with sound change). One of the reasons why final consonants are prone to weakening or increased hypoarticulation (Lindblom et al. 1995) may be because they are semantically less informative: that is, their reduction results in a minimal loss of information (Cohen Priva 2015, 2017).

Vowel nasalization and N-loss are also more likely for syllable-final VN than syllable-initial NV (e.g. Latin > French: panem ‘bread’ > /pɛ̃/, tempus ‘time’ > /tɔ̃/, but luna ‘moon’ > /lyn/; see Sampson 1999 for further details). The greater anticipatory coarticulation in syllable-final VN is consistent with physiological studies (e.g. Byrd et al. 2009, Krakow 1993) showing an asynchrony between the velum and oral gestures in syllable-final N (such that the velum overlaps substantially with the vowel), whereas the oral-nasal gestures are nearly synchronous (with correspondingly less overlap with a following V) in syllable-initial N (e.g. Byrd et al. 2009, Krakow 1993; see also Krakow 1999 for analogous findings for liquids, and Byrd et al. 2009, Goldstein et al. 2006, Goldstein et al. 2009 for an interpretation in terms of anti-phase coupling for syllable-final consonants as opposed to in-phase coupling for syllable-initial consonants). The greater overlap between velum lowering and the vowel in syllable-final contexts can lead to a perceptual blurring between V and N (e.g. Manuel 1991), whereas the division between the N and V for syllable-initial NV is likely to be sharper: this perceptual smearing is one of the factors that, according to Ohala 1990, makes sound change more likely in VC than in CV sequences in nasals and other consonants.

Obstruent voicing influences vowel nasalization and N-loss, which are more likely preceding a voiceless VNC̥ than preceding a voiced VNC̬ obstruent (e.g. Hindi [dã:ta] ‘tooth’ < Sanskrit *danta*, but Hindi [tʃã:nda] ‘moon’ < Sanskrit *candra*; Ohala & Ohala 1991). N-deletion is common before voiceless fricatives (e.g. Latin insula 'island' > Italian *isola*; Proto-Germanic *wunsk > English 'wish'; cf. German *Wunsch*). In general, voiceless NC̥ sequences are less likely to occur in the world's languages than are voiced NC̬ (Itô & Mester 1986, Pater 1999). The relative scarcity of NC̥ has an aerodynamic origin (Solé 2007, 2009): in an N, intra-oral pressure must be low due to nasal venting, a strategy that is not compatible with the requirement of high intra-oral pressure for the production of most voiceless obstruents. There is extensive evidence based on acoustic and airflow studies that the duration of N is much less in American English voiceless VNC̥ than in voiced VNC̬ (Beddor 2009, Beddor et al. 2007, Beddor et al. 2018, Busà 2007, Malécot 1960, Raphael et al. 1975). In addition, the acoustic study of six speakers of American English in /ɛNt/ (*bent*), /ɛNs/ (*sense*), and /ɛNd/ (*bend*) words, combined with an airflow analysis from forty-two speakers of American English in Beddor et al. 2018 producing quadruplets such as 'bet–bed–bent–bend', showed that longer N durations cooccurred with temporally less extensive vowel nasalization across both voicing contexts together (Beddor 2009) and to a lesser extent within voiceless contexts (Beddor et al. 2018).

In an analysis of thirty-five speakers' production of German /Vnt/ (e.g. *Bunte*) and /Vnd/ (e.g. *Bunde*) sequences using real-time magnetic resonance imaging, Carignan et al. (2021) showed that /Vnt/ was characterized by a reduction in amplitude of the velum gesture in the voiceless compared with voiced sequence, combined with a slightly earlier alignment of the velum in the vowel of /Vnt/. However, the magnitude of nasalization in the vowel, based on a combination of duration and amplitude (specifically the area under the velum trajectory within the vowel), was no different in /Vnt/ and /Vnd/ contexts.

Contextual devoicing in VNC̥—that is, when the N-offset becomes voiceless because of the influence of the following C̥—may contribute to N-attrition and N-loss, as in Sardinian [pessare] derived from Latin pensare 'think' and with a presumed intermediate stage of [pen̥sare] (Hajek 1997:190). Although voiceless nasals have never been analyzed perceptually (Ford et al. 2023), auditory factors are likely to be one of the main causes of voiceless N-attrition and/or loss: voiceless nasals, which are rare in the world's languages (Ladefoged & Maddieson 2004), are auditorily suboptimal, because the frication created by turbulence at the nostrils is of low intensity and lacks a downstream resonator to shape and amplify the noise (Ohala 1975, Ohala & Ohala 1993).

1.3. (Compensatory) vowel length and nasalization. The influence of increasing vowel nasalization and N-loss on vowel length is a further area to which the present study is relevant. With regard to vowel length, Beddor 2007 finds that American English tense (long) vowels (e.g. *seen*) have more nasalization during the vowel and a shorter following nasal consonant compared with lax vowels (*sin*). The same study reports a similar relationship between nasalization, vowel length, and nasal consonant shortening in Thai, a language with contrastive vowel length. According to Hajek and Maeda (2000), the diachronic development of contrastive vowel nasalization in long vowels (V:N > Ṽ:N > Ṽ:) precedes the corresponding sound change in short vowels (VN > ṼN > Ṽ). The same authors also suggest that the well-known association between increasing vowel openness and greater vowel nasalization (Bell-Berti 1973, 1976, Moll & Shriner 1967) may be an artefact of length: building on numerous studies showing that nasalization is more readily perceived in long than in short vowels (e.g. Whalen & Beddor 1989; see also Hajek 1997:88 for evidence from other languages), contrastive nasalization may, according to Hajek and Maeda (2000), develop preferentially in open vowels not because they are phonetically low, but because they are intrinsically long. The findings by Kunay et al. (2022) suggest that CONSTRICTION LOCATION—that is, the point of greatest narrowing in the vocal tract in vowel production (Fant 1960, Iskarous 2010, Lindblom & Sundberg 1971, Stevens & House 1961, Wood 1979)—is nevertheless an important predictor of vowel nasalization. They showed that, although mid-high front tense (and predorsal) /øː/ was at least as long as, and often longer than, low tense (radical) /aː/, the extent of nasalization in /øː/ was nevertheless much less than in /aː/.

A related, unresolved issue that is addressed in this study is whether, with the progression of the VN > Ṽ sound change, there is COMPENSATORY VOWEL LENGTHENING as the final N is lost. In compensatory lengthening, a segment *X* lengthens to compensate for the loss of another segment *Y* such that the total duration of *XY* is maintained after the sound change (Hayes 1989, Hock 1986, Kavitskaya 2002). Applied to the VN > Ṽ sound change, there is an adjustment to the internal syllable structure such that N deletes but not the mora (or X slot: Hayes 1989) with which it is linked, which then comes to be associated with the previous vowel, making it long. Although lengthening of the vowel associated with N-loss is extensively documented (de Chene & Andersen 1979, Gess 2011, Hajek 1997:184, Hayes 1986:338, Sampson 1999:94), modeling the VN > Ṽ sound change in terms of compensatory lengthening is, according to Hajek 1997, in many cases unwarranted, because oral vowel lengthening in VN can often be shown to precede chronologically vowel nasalization and N-deletion.

1.4. PHONOLOGIZATION AND VARIATION BETWEEN DIALECTS.

As observed by Schuchardt (1885), sound change does not necessarily progress at a uniform rate or advance to the same extent across different dialects. For this reason, a comparison between dialects that have been affected by the same sound change to different degrees can provide valuable information for explaining the factors that cause the sound change to advance. The approach is the same as in apparent-time (Bailey et al. 1991, Sankoff 2005) investigations: in both cases, the analysis compares a state *A* with another, *B*, in which sound change has advanced further than in *A*. In an apparent-time analysis, *A* and *B* are older and younger age groups, respectively, of the same community as opposed to two different dialects. Using dialects to investigate sound change has the advantage that, if the same age groups are chosen, there is no confound—unlike in apparent-time studies—between phonetic changes and those resulting from biological age (Reubold et al. 2010). Moreover, apparent-time analyses presuppose that the sound change is in progress, whereas changes involving phonologization have often been completed over several generations.

Comparisons between dialects have been used to model the phonologization of sound change. In one such study, Greca et al. (2024) showed a trade-off between coarticulatory enhancement of a stem vowel and attrition of a final inflectional suffix in which metaphony has advanced to different stages in three Italo-Romance dialects of Southern Italy. The analysis in Cronenberg et al. 2020 of two Andalusian Spanish dialects that have participated in an ongoing sound change of aspiration metathesis ([^{h}t] > [t^{h}]) showed that the progressive phonologization of aspiration in Andalusian Spanish (Gilbert 2024) can be associated with an earlier phasing of the stop closure also resulting in the extinction of preaspiration (see also Parrell 2012). In an investigation of tonogenesis using two dialects of Kmhmu, of which one maintains a voicing contrast while the other is tonal, Kirby et al. (2022) showed that the transphonologization from voicing into f0 contrasts is possible without an intermediary stage based on phonation or vowel quality.

Regarding the progression of the sound change that causes vowel nasalization, Bongiovanni's 2020, 2021 acoustic and physiological analysis of two dialects showed that the extent of coarticulatory vowel nasalization was greater in Santo Domingo than in Buenos Aires Spanish, even though these varieties did not differ in the extent of weakening of the N. Spanish has a well-known distinction between dialects that maintain /n/ after vowels as opposed to those in which the nasal has an /ŋ/-like quality, with the latter showing an earlier onset of nasalization in the vowel (Bongiovanni 2020, Lederer 2003). Whereas in Cuban Spanish, anticipatory coarticulatory nasalization in the vowel is extensive (Lederer 2003), the vowel before N in standard European Spanish is predominantly oral, with the onset of velum lowering being timed relative to the following nasal consonant across different speech rates (Solé 1995). In a study by Coetzee et al. (2022) of Afrikaans, more extensive nasalization was found in the vowel for the White than for the Kleurling variety. In French, in which vowel nasalization is contrastive, Delvaux et al. (2008) showed a later timing of vowel nasalization in Southern than in Northern French. In a comparison of coarticulatory vowel nasalization in American English, Tamminga and Zellou (2015) found greater coarticulatory vowel nasalization in the variety spoken in Philadelphia than in that in Columbus, but also that women might be leading a change in which there is progressively less nasalization in both varieties. Joo et al. (2019) report more extensive coarticulatory nasalization in Australian compared with American English in CVN sequences. A study by Liao et al. (2022) using magnetic resonance imaging showed a greater loss of nasalization together with vowel raising of open vowels in an underlying nasal context in the Chengdu variety of Chinese (thus [æ̃] > [ẽ] > [ɛ]) compared with Standard Mandarin. That vowels in VN sequences which became nasalized through coarticulation can then become oral is also shown for a Bolognese variety of Italian in Hajek 1991, following so-called glide hardening resulting in the insertion of [ŋ]: thus, for example, Latin VINU 'wine' > vĩn > vĩ: > vẽ: > vẽŋ > ven.

The present study is an extension of Cunha et al. 2024 designed to investigate further the physiological basis of the VN > Ṽ sound change through comparisons of American with Southern British English VN sequences. The evidence that vowels in VN are more nasalized in American than in British English has been mostly anecdotal (Hosseinzadeh et al. 2015). More recent empirical evidence is from an acoustic study by Gwizdzinski et al. (2023), which showed greater vowel nasalization in American than in British English VN. According to Gwizdzinski et al. (2023), the greater vowel nasalization, which is also known to provide cues to the presence of a following nasal consonant (e.g. Beddor et al. 2013), explains why there were fewer listener errors in identifying the presence of the nasal consonant for American compared with equivalent British English words.

Nasalization of /æ/ before nasal consonants is especially marked both in a 'broad' Australian English variety (Cox & Palethorpe 2014) and in many American English varieties where it is also associated with extensive tongue-dorsum raising (Cunha et al. 2024, Mielke et al. 2017). The complete deletion of nasal consonants—leaving only a strongly nasalized vowel—in words like *can't* has been reported in American English for several decades (Malécot 1960). By contrast, apart from the London variety of Cockney English (Mott 2012), which is also historically one of the main varieties influencing the early development of Australian English (Mitchell 1965, Yallop 2001), there are no reports of this high degree of vowel nasalization and N-deletion for any other British English varieties. For all of these reasons, the progression along the VN > Ṽ sound change path is likely to be more advanced in American compared with British English varieties.

1.5. Gestural models of the VN > Ṽ sound change. A central aim of the current study is to shed further light on the physiological origin of the VN > Ṽ sound change. In Beddor's 2009, 2023 model of sound change, the temporal extent of nasalization in the vowel and duration of the N are yoked together in a trade-off as a consequence of a variable alignment of the velum gesture that is stable, meaning of presumed constant articulatory duration[1] (Figure 1). Because the velum gesture is stable, the alignment of the velum in the vowel is necessarily inversely related to the duration of N, such that when the velum gesture overlaps completely with the vowel causing its nasalization, then N is lost.

from BEDDOR, PATRICE. 2009. A coarticulatory path to sound change. *Language* 85.785–821.

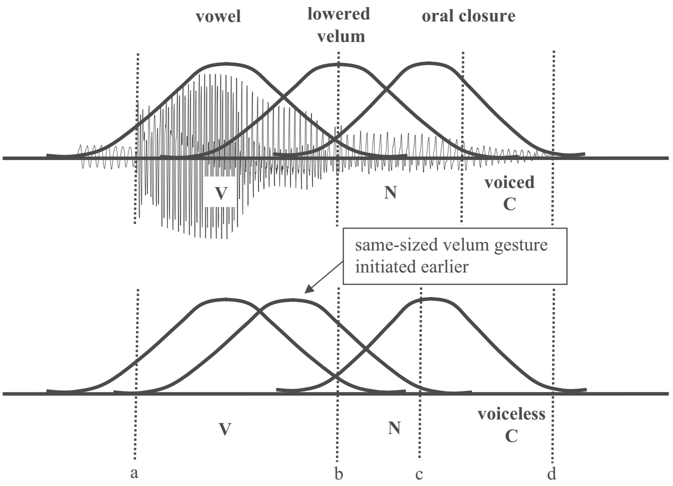

Figure 1. Schematic representation for American English of the different phasing of the velum-lowering gesture in voiced (top) and voiceless (bottom) contexts, resulting in a trading relation in Beddor's model: the earlier the phasing, the longer the duration of Ṽ and the shorter the N. (Dashed lines indicate acoustic segmentation.) Adapted from Beddor 2009:789, figure 1.

The early alignment of the velum gesture is predicted in Beddor's model to be more advanced in contexts like voiceless VnÇ̥ (e.g. *sent*) that have been shown in other studies to lead the VN > Ṽ sound change. Innovative individuals who are the most advanced along the path of sound change in a context-favoring sound change like VnÇ̥ may then extend this innovation to other contexts like voiced VNÇ̬ (Beddor 2009, 2023).

There are few studies that have tested the physiological basis of the trade-off between increased vowel nasalization and temporal reduction of N, partly because direct observation of the velum movement is technically difficult, although increasingly possible with recent advances in image quality from real-time magnetic resonance imaging

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[1] However, as Beddor (2009:795) notes, the idea in her model that 'gestural durations but not their alignment remain absolutely constant across voicing contexts, is an oversimplification'. That is, 'across contexts, the temporal magnitude of the velum gesture appears to stretch or shrink very roughly in proportion to the magnitude of the other gestures in the syllable'. Nevertheless, because the 20–30% increase in gestural durations from voiceless to voiced contexts found in Beddor 2009 was small in relation to the much larger increase in N duration from VNÇ̥ to VNÇ̬, then the substantial segmental difference between these contexts can, according to Beddor 2009, be considered to be largely the result of the different temporal alignments of the velum and oral consonant constriction gestures.

(MRI) recordings of speech (Ruthven et al. 2023). In a real-time MRI analysis of /Vn, Vnd, Vnz/ sequences in monosyllabic words (e.g. *ban*, *band*, *bans*), Cunha et al. (2024) found more extensive nasalization in V and less in N in American (US English; USE) compared with Standard Southern British (British Received English; BRE) speakers, consistent with the idea that American English is further advanced along the path of sound change VN > Ṽ (§1.4). They also found within both varieties a trade-off between the extent of nasalization in the V and lenition of the tongue-tip gesture of N. Although the velum gesture between the varieties was stable, there was no evidence that the greater nasalization in the vowel and diminished nasalization in the N were associated with an earlier alignment of the velum gesture in USE.

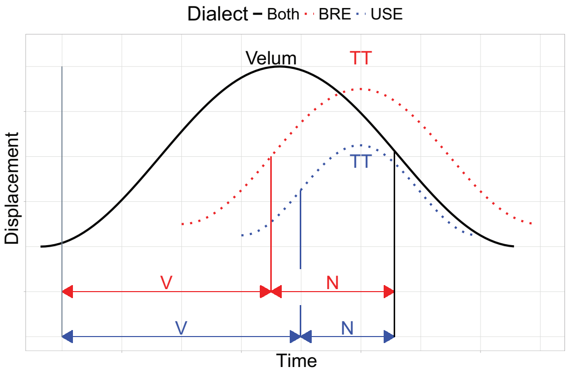

Figure 2. A schematic outline showing the velum (black) and tongue-tip (TT) trajectory (BRE: red dashed, USE: blue dashed) in the production of a voiced VN(Ç) sequence (the tongue-dorsum trajectory for the vowel is not shown). The four vertical lines from left to right are at the following times, respectively: (i) the acoustic vowel onset (gray and unaligned with any displayed trajectory); (ii) /n/'s peak velocity of tongue-tip raising, which coincides with the acoustic boundary between V and N for BRE (red) and (iii) for USE (blue); and (iv) the articulatory offset of N (black). The horizontal arrows show the acoustic duration of the V and the duration of N in the two dialects. Adapted from Cunha et al. 2024:12, figure 13.

Figure 2 shows a model of sound change in voiced VN(Ç) sequences in Cunha et al. 2024 that is based on the differences between the two English dialects and, more specifically, on the idea that USE has advanced further along the VN > Ṽ path of sound change than BRE. As Fig. 2 shows, the velum gesture (black) is stable and hence modeled as the same in the two varieties. The differences are instead in the tongue-tip gesture of N, which was found to be reduced in USE (blue dashed) compared with BRE (red dashed). Moreover, this reduction was associated with a delay in the time of the peak velocity of the tongue-tip gesture in USE, which was also closely aligned with the acoustic boundary between V and N. Because of tongue-tip reduction, the internal VN acoustic boundary was phased later relative to the velum signal in USE than in BRE. As a result, the extent to which the velum overlaps with the vowel (the extent of the black signal for the velum that is to the left of the red or blue vertical boundaries in Fig. 2) was greater in USE than in BRE.

In both Beddor 2009, 2023 and in Cunha et al. 2024, the time of the peak velum opening is phased earlier relative to the internal acoustic VN boundary with a progression of the VN > Ṽ sound change. The central difference between the models is that, whereas in Beddor 2009 this comes about because of an early alignment of the velum, in

Cunha et al. 2024 it is due to a later alignment of the tongue-tip peak velocity (and therefore of the internal acoustic VN boundary). In Beddor 2009, there is, as observed earlier, necessarily a trade-off between the extent of nasalization in the vowel and in N, and this is also so in Cunha et al. 2024.

The early alignment of the velum gesture has no consequences for the acoustic vowel duration in Beddor's 2009, 2023 model, because there is no rephasing of the V and oral closure gesture, as Fig. 1 clearly shows. By contrast, a later phasing of the tongue-tip peak velocity relative to a fixed velum gesture in Cunha et al. 2024 predicts that the acoustic duration of the entire V should lengthen as the duration of N shortens—precisely because the time of the tongue-tip peak velocity is more or less coincident with the internal acoustic VN boundary. Thus, in contrast to Beddor 2009, 2023, the duration of the ENTIRE V and the duration of N are predicted in Cunha et al. 2024 to stand in an inverse relationship to each other for different points of progression along the path of sound change, VN > Ṽ, whereas in Beddor 2009, 2023, only the NASALIZED parts of the V and N exhibit this kind of inverse relationship.

1.6. AIMS OF THE INVESTIGATION. The main aim of the present study is to advance our understanding of the physiological origin of the VN > Ṽ sound change by analyzing the gestural dynamics in the production of VNC sequences for voiced and voiceless C in two varieties of English. The questions of the investigation were inspired by comparing the two physiological models sketched in §1.5 on velum and tongue-tip dynamics from five (§§2.2–2.7) different perspectives. Section 3 extends these models based only on velum-tongue dynamics to include the glottal signal in order to explain why voiceless VNC̥ has often been shown to lead the VN > Ṽ sound change ahead of voiced VNC̬.

2. TESTING THE PHYSIOLOGICAL ORIGIN OF VN > Ṽ.

2.1. THE MODELS' PREDICTIONS. The analyses were designed to test whether the physiological origin of the VN > Ṽ sound change is more likely to derive from an early alignment of the velum (Beddor 2009, 2023) or a late phasing of N's oral gesture (Cunha et al. 2024) or some combination of both. This was done by analyzing velum and tongue-tip movements in word-final /nt, nd/ contexts produced by American and Standard Southern British English speakers. The predictions that were tested are summarized in Table 1. In Beddor 2009, 2023, the predictions apply to coda voicing /nt, nd/ (and not to dialect) differences; in Cunha et al. 2024, the predictions apply to dialect (and not to /nt, nd/) differences.

		MODEL	
		BEDDOR 2009, 2023	CUNHA ET AL. 2024
SECTION	PHYSIOLOGICAL ATTRIBUTE	In /nt/ compared with /nd/:	In USE compared with BRE:
§2.3	Stable velum gesture	Yes	Yes
§2.4	Greater asynchrony between velum and tongue tip	Yes	Yes (relative tongue-tip to peak velocity)
§2.5	Greater nasalization in vowel	Yes	Yes
	Less nasalization in N	Yes	Yes
§2.6	Tongue-tip reduction in N	No	Yes
§2.7	Stable VN duration	No	Yes
	Stable V duration	Yes	No

TABLE 1. Predictions for /nt, nd/ differences in the model of Beddor 2009, 2023 and for dialect differences between American (USE) and Standard Southern British English (BRE) in the model of Cunha et al. 2024. The section column refers to the relevant section in the present study in which these differences were analyzed.

As far as /nt, nd/ differences are concerned, Beddor's model predicts a stable velum gesture that does not vary substantially between /nt/ and /nd/ contexts (§2.3). The earlier alignment of the velum gesture in Beddor's model for /nt/ also predicts a greater asynchrony between the velum and tongue-tip gestures (§2.4), greater nasalization in the vowel, and correspondingly less nasalization in the following N (§2.5) compared with /nd/. The tongue tip is not expected to be more reduced in /nt/ than in /nd/ (§2.6). The total duration of the VN interval is, according to Beddor's model, predicted to be shorter in /nt/ (because of N shortening), but the increased nasalization of the vowel in /nt/ is not expected to cause any change to vowel length (§2.7) (/nt, nd/ have the same acoustic V boundaries in Fig. 1).

Cunha et al.'s (2024) model predicts a stable gesture between USE and BRE (§2.3), meaning that the velum gesture should be of similar duration and magnitude in both varieties. The late phasing of the peak velocity of the tongue-tip gesture (which is closely aligned in their model with the internal acoustic VN boundary) predicts greater nasalization in the vowel and correspondingly less nasalization in N (§2.5). It also predicts a later phasing of the peak velocity of the tongue tip relative to the velum in USE compared with BRE (§2.4) and a greater tongue-tip reduction of N in USE than in BRE (§2.6). According to this model, the VN > Ṽ sound change depends only on a later phasing of the time of the peak velocity of tongue-tip raising (and the internal VN boundary). For this reason, the duration of V is predicted to be greater (and N correspondingly shorter) in USE compared with BRE, whereas the duration of VN is expected to be the same across the dialects.

2.2. Method.

Speakers and stimuli. The data was acquired at the Max Planck Institute for Multidisciplinary Sciences, Göttingen, over two years from 2018 to 2019, from twenty-seven native speakers of Standard Southern British English (thirteen female, median age twenty years, range eighteen to forty-six years) and sixteen native speakers of US English (seven female, median age twenty-six years, range twenty to thirty-seven years) from Midland, Northeast, Southern, and West regions, who were also analyzed in Cunha et al. 2024. No American participants were recruited who had formerly been resident in the UK (and vice versa).

The twenty-seven target words analyzed in this study are shown in Table 2 and form part of a larger corpus collected from the same speakers, which was also analyzed in Cunha et al. 2024. They have the form CVn(d|t), with V = /æ, eɪ, ʌ, ɛ, ɪ/. The initial consonants were chosen to have clear velum raising and included the labial occlusives /p, b, f/ and, less frequently, the fricatives /s, ʃ/.

	vowel				
coda	æ	eɪ	ʌ	ɛ	ɪ
nt (*n* = 10)			bunt	bent	bint
	pant	paint	punt		
		faint			
		saint	shunt	sent	
nd (*n* = 17)	band			bend	binned
	panned	pained	punned	penned	pinned
	fanned	feigned	fund	fend	finned
	sand		shunned	send	sinned

Table 2. The word types analyzed in the present study shown separately by vowel, coda, and initial consonant.

The words were produced in the phrase 'saw <targetword> about two/four/five/six/ten', with nuclear accent on the target word. Each word was typically spoken once per speaker. The combination of twenty-seven word types and forty-three speakers gives a total of 1,161 possible productions. The actual number of analyzed tokens (*n* = 1,156; Table 3) deviated slightly from this total due to the exclusion of a few mispronounced tokens and/or productions in which the MRI data were not reliable and the inclusion of some that were produced twice by the same speaker.

	CODA		
DIALECT	nt	nd	Σ
BRE	269	456	*725*
USE	159	272	*431*
Σ	*428*	*728*	*1,156*

TABLE 3. Number of tokens analyzed by coda and dialect.

DATA COLLECTION. Real-time magnetic resonance imaging (rt-MRI) data were acquired using a 3-Tesla MRI system and with participants measured in supine position via a 64-channel head coil with the radiofrequency (RF)-spoiled FLASH sequence. This method is based on highly undersampled radial gradient echo acquisitions and is combined with serial image reconstruction by regularized nonlinear inversion (Uecker et al. 2010). Individual images were obtained from a single set of nine spokes, resulting in a reconstructed frame rate of 50.05 frames per second (fps). An in-plane pixel size of 1.41 × 1.41 mm and a slice thickness of 8 mm was applied, which yielded images of 136 × 136 voxels (i.e. three-dimensional (3D) volume elements) in a field of view of 192 × 192 mm. Synchronized, noise-suppressed audio was also collected during the scanning session using an Optoacoustics FOMRI III fiber-optic dual-channel microphone (Optoacoustics Ltd.) and was further processed in MATLAB (The Mathworks Inc. 2017) for additional reduction of scanner noise.

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 fifteen items and presented as a slide show, with slides advancing automatically after four seconds (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 twenty-three blocks, giving about 70,000 images per participant. Total time in the scanner including localizer scans amounted to about 1 hour.

DERIVING VELUM AND TONGUE-TIP MOVEMENT. For each speaker's data set, the images were registered by precreating a region of interest (ROI) that covered the upper portion of the head (i.e. covering only structures that do not exhibit speech-related movement). 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 during the recording session (see Carignan et al. 2020, Carignan et al. 2021, Kunay et al. 2022 for further details).

A second ROI was manually defined for each speaker around the spatial range encompassing the velum movements: that is, the region contained all pixels that could be occupied by any part of the velum tissue from 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 (Kunay et al. 2022, figure 1). 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. The velum signal was created from the PC scores obtained from each image. The scores were then rescaled between 0 and 1, corresponding to maximum velum raising and lowering, respectively (see Kunay et al. 2022, figures 1–2, 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).

For the tongue-tip movement patterns in the postvocalic coronal consonants in the target words, a semipolar grid consisting of twenty-eight lines was applied semi-manually to the vocal tract, extending between the glottis and the alveolar ridge (Carignan et al. 2020). The signal for the alveolar region 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 (see Kunay et al. 2022, figure 3).

Both the derived velum and tongue-tip signals were upsampled 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 three-point central-difference method.

The tongue-tip movement was analyzed only in /ʌ, e, ɪ/ vowel contexts in §2.4 and §2.6. The vowel /eɪ/ was excluded 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 due to the particularly salient differences between British and American English in the vowel (widespread prenasal raising in American English: Mielke et al. 2017), which would have distorted any comparison of movement amplitude or duration from vowel to coda.

Statistical analysis. The statistical analysis made use of the mixed model function lmer() from the lmerTest package (Kuznetsova et al. 2022) in the R programming environment (version 4.3.1) and was of the form in 1:

(1) model = lmer(param ~ dialect * coda + (dialect | CV) + (coda | speaker)),

in which *param* is an articulatory parameter, and with fixed factors for dialect (USE, BRE) and coda (/nd, nt/) and with random factors for CV, which included the consonant and vowel (e.g. *be*- for *bent*, *bend*), and for speaker (the forty-three speakers of the study). The model 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 (1 | CV), (1 | speaker), or both). Any interactions between the two fixed factors were tested with the emmeans() function in the package of the same name (Lenth et al. 2023). The glmmTMB() function in the package of the same name (McGillycuddy et al. 2025) was used for testing the significance of proportions limited to between 0 and 1. The syntax was exactly the same as in 1, and emmeans() was used to test for the significance of the levels of the fixed factors.

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 some significant results.

2.3. STABILITY OF THE VELUM GESTURE. As explained in §2.1 (see also Table 1), the principal aim was to test whether the velum gesture was stable between /nt/ and /nd/ (Beddor 2009) and/or between the dialects (Cunha et al. 2024).

METHOD. The comparison between coda context and dialect was made for the four parameters shown in Figure 3: the peak displacement of velum lowering averaged between plateau onset and offset, the duration of the velum gesture, defined as the interval between peak lowering and raising velocities of the velum, and the peak velocities of the velum-lowering and velum-raising gestures. Plateau onset and offset were detected using a 20% velocity criterion: that is, the onset was defined to occur when the velocity fell below 20% of peak velocity. This approach was used in order to obtain a measure of peak displacement location that was less sensitive to unsystematic fluctuations around zero velocity over the plateau phase. In addition, all algorithmically determined kinematic landmarks used in the analysis were visually checked (for example, for occasional items with very small movement amplitude, the peak velocity might be detected completely outside the segment of interest).

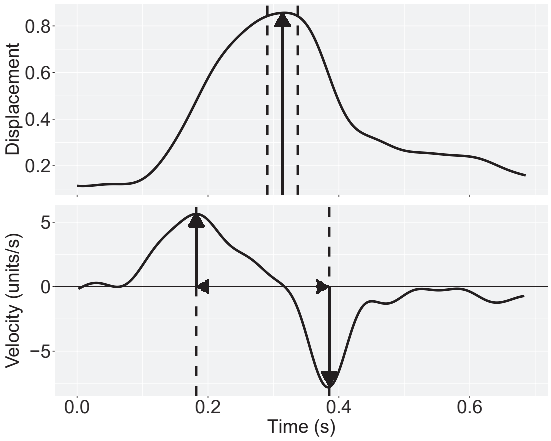

FIGURE 3. Velum displacement and velocity in VN. The four parameters shown are: (i) magnitude of peak velum lowering (vertical solid line, top), averaged between the plateau onset and offset (vertical dashed lines, top); (ii) the peak lowering velocity of the velum (vertical solid upward black line, bottom); (iii) the articulatory duration of the velum gesture (horizontal double arrow, bottom) extending between the times of the velum’s peak lowering and raising velocities; and (iv) the peak raising velocity of the velum (vertical solid downward gray line, bottom).

RESULTS. The trajectories of aggregated velum displacement (Figure 4) show a mostly smaller and shorter displacement for /nt/ than /nd/. A comparison between the rows suggests, however, no marked differences on either of these parameters between dialects.[2]

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[2] The jitter visible in Figs. 4 and 5 (most apparent at the left edges) is a consequence of extracting the data for analysis from the full utterances at 100 ms before vowel onset. However, there might not be any data toward the left edge of the plot for those utterances with shorter-than-average vowel duration. As a result, the aggregation may operate over fewer and fewer items the closer it is performed to the edge of the plot window.

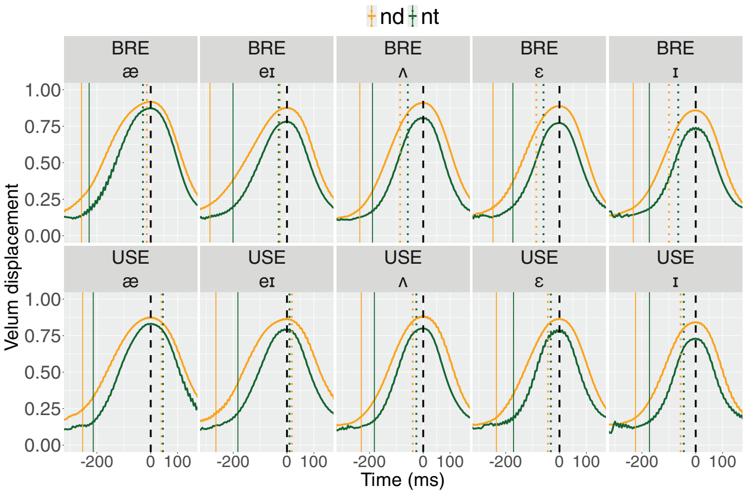

Figure 4. Velum displacement trajectories aggregated by dialect, vowel, and coda after alignment at the time of peak velum lowering (*t* = 0 ms, vertical dashed line). The solid, colored, vertical lines to the left are the aggregated times of the acoustic vowel onset. The dotted, colored vertical lines are the aggregated times at the acoustic VN boundary (acoustic offset of the vowel/acoustic onset of N).

The trajectories of the aggregated velum velocity show (Figure 5) higher peak velocities of velum lowering for /nt/ (compare the peaks between /nt/ and /nd/ for each dialect around −100 ms in Fig. 5). By contrast, there are no discernible /nt, nd/ differences for the peak velocity of velum raising (compare the size of the negative peaks around 100 ms in Fig. 5). Once again, there are no obvious dialect differences as far as the velum velocity trajectories are concerned (compare top and bottom in Fig. 5).

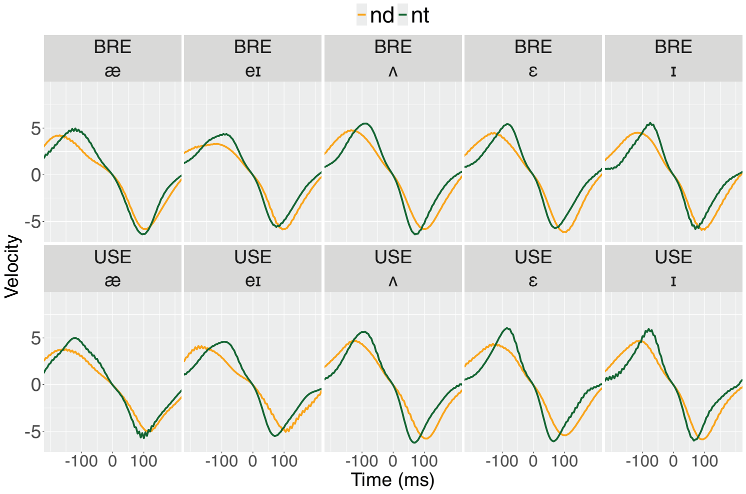

Figure 5. Velum velocity trajectories aggregated by dialect, vowel, and coda after alignment at the time of peak velum lowering (*t* = 0 ms).

The results of the statistical tests on the four parameters (i–iv) in Fig. 3 were generally compatible with these observations and are as follows.

For peak velum displacement (parameter (i)), there was a significant effect of coda ($F_{1,50.764} = 43.696$, $p < 0.001$: /nd/: $\hat{m} = 0.703$, /nt/: $\hat{m} = 0.632$) but not of dialect. For peak velocity of velum lowering (parameter (ii)), there was a significant effect of coda ($F_{1,991.8} = 37.166$, $p < 0.001$: /nt/: $\hat{m} = 6.63$, /nd/: $\hat{m} = 6.17$) and no effect of dialect. For peak velocity of velum raising (parameter (iv)), there was no effect of coda or of dialect. For articulatory duration (parameter (iii)), there was a significant effect of coda ($F_{1,47.929} = 76.692$, $p < 0.001$: /nd/: $\hat{m} = 260$ ms, /nt/: $\hat{m} = 192$ ms) but not of dialect.

DISCUSSION. The results show that, compared with /nd/, the velum gesture in /nt/ is shorter and produced with a faster velum-lowering gesture. In addition, the velum displacement is less for /nt/ than for /nd/. The evidence is, therefore, not consistent with Beddor's 2009 model in Fig. 1 of a stable velum gesture across /nd, nt/ contexts. At the same time, it should be noted that Beddor 2009 never predicted that the absolute duration of the velum gesture (which was measured here) should be constant across /Vnt, Vnd/, but instead that (see n. 1) the temporal magnitude of the velum gesture tends 'to shrink very roughly in proportion to the magnitude of the other gestures in the syllable' (Beddor 2009:795).

The results also showed that the shape and duration of the velum gesture were unaffected by dialect: that is, there were no differences between the dialects in the magnitude, duration, or velocity of the velum gesture either for /nt/ or for /nd/.

Even though there was no stability in the velum gesture between /nt/ and /nd/, it is still possible that there is a greater velum-tongue asynchrony, as predicted in Beddor's model in Fig. 1. This was tested, as described in the following section.

2.4. INTERGESTURAL TIMING BETWEEN THE VELUM AND TONGUE TIP. The main prediction from Beddor's 2009 model to be tested is that an earlier alignment of the velum in /nt/ causes a greater asynchrony with the tongue tip (Fig. 1): that this is possible follows from ideas in articulatory phonology (Browman & Goldstein 1992, Iskarous & Pouplier 2022), and associated findings (Krakow 1993) that the velum and tongue-tip gestures for N can be variably phased with respect to each other.

The prediction to be tested in the model of Cunha et al. (2024) is that the progression along the path VN > Ṽ is associated with a later phasing of the tongue-tip peak velocity (and acoustically of the internal VN boundary with which it tends to coincide) but not of the time of maximum displacement of the tongue tip for N.

METHOD. Two measurements were made from the time of peak velum lowering to the times of (a) the tongue-tip peak velocity (Figure 6: $i_1 = t_1 - t_2$) and (b) the maximum tongue-tip raising (Fig. 6: $i_2 = t_3 - t_2$). On these measures, higher values on both on i_1 and i_2 correspond to a later phasing of the tongue tip relative to the time of peak velum lowering.

RESULTS. The aggregated tongue-tip trajectories synchronized at the time of peak velum lowering suggest that the tongue is phased later relative to the velum for /nt/ than for /nd/: this is shown by the green vertical dashed lines in Figure 7 for /nt/, which are, for both dialects and three vowel contexts, later in time than the gold ones for /nd/. As far as dialect differences are concerned, a comparison between the two rows for the same vowel in Fig. 7 shows that the time of the peak tongue-tip velocity (left vertical dashed lines) was phased later relative to the velum in USE (with values closer to $t = 0$ ms) compared with BRE, whereas there was no evidence of such a phasing difference between the dialects for the time of peak tongue-tip raising (compare the right vertical lines for the same color between top and bottom).

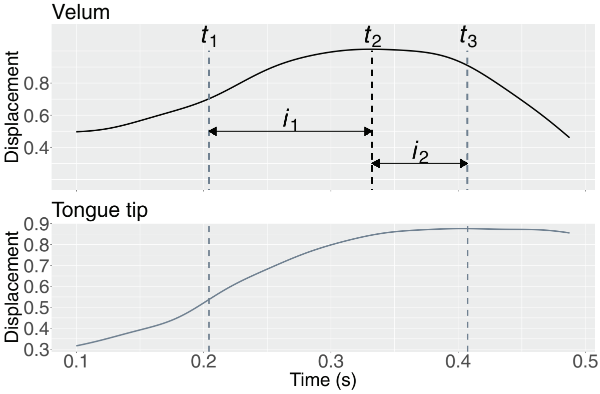

Figure 6. Synchronized velum and tongue-tip trajectories for *band* produced by a BRE speaker. The temporal extent of the trajectories is from the acoustic vowel onset to the time of the peak velocity of velum raising. The times of the vertical dashed lines in the top row are from left to right: t_1, 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 that were analyzed, $i_1 = t_1 - t_2$ and $i_2 = t_3 - t_2$.

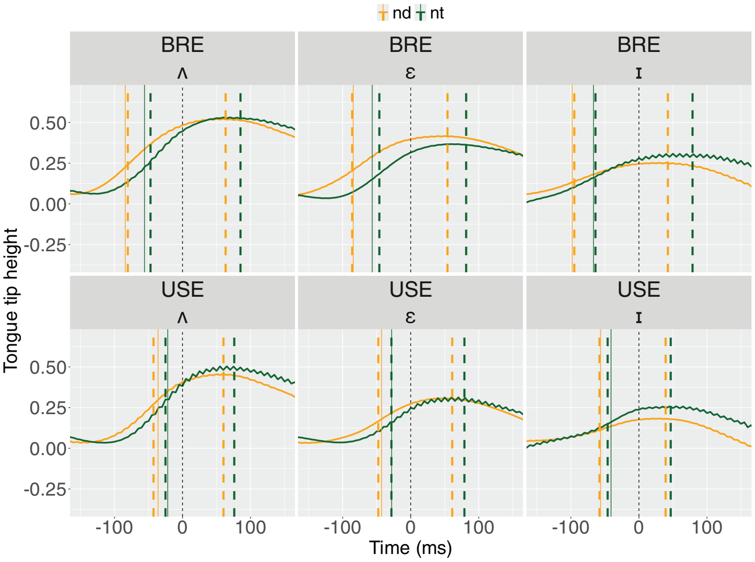

Figure 7. Tongue-tip trajectories aggregated by dialect and coda after alignment at the time of peak velum lowering ($t = 0$ ms). The vertical dashed lines to the left of $t = 0$ ms are the mean times of the peak velocity of tongue-tip raising; those to the right are the mean times of the peak tongue-tip displacement. The vertical thin solid lines to the left of $t = 0$ ms are the mean times of the acoustic offset of the vowel/acoustic onset of the N.

Figure 7 also shows the close correspondence between the mean times of the tongue-tip velocity and those of the internal acoustic VN boundary (dashed and solid thin lines, respectively, at values less than 0 ms), such that earlier/later alignments of the tongue-tip peak velocity correspond quite closely to earlier/later alignments of the internal acoustic VN boundary.

The distributions in Figure 8 of the two durational parameters i_1 and i_2 (Fig. 6) showed greater i_1 values both for /nt/ than for /nd/ and for USE than for BRE. Figure 8 also suggests greater i_2 values for /nt/ than for /nd/, but no effect of dialect. Consistent with these observations, the results of the statistical analysis with dependent variable $i_1 = t_1 - t_2$ (Fig. 6) showed a significant effect for coda ($F_{1,52.296} = 42.2563$, $p < 0.001$) and dialect $F_{1,41.05} = 20.1103$, $p < 0.001$) and a significant ($F_{1,40.904} = 5.4916$, $p < 0.05$) coda × dialect interaction. Post-hoc tests showed a later phasing of the tongue-tip peak velocity in /nt/ than in /nd/ both in BRE ($p < 0.001$: /nt/: $\hat{m} = -51$ ms, /nd/: $\hat{m} = -86$ ms) and in USE ($p < 0.05$: /nt/: $\hat{m} = -32$ ms, /nd/: $\hat{m} = -49$ ms). The post-hoc tests also showed a later phasing of the tongue-tip peak velocity in USE than in BRE both for /nd/ ($p < 0.001$: USE: $\hat{m} = -49$ ms, BRE: $\hat{m} = -86$ ms) and for /nt/ ($p < 0.05$: BRE: $\hat{m} = -51$ ms, USE: $\hat{m} = -32$ ms).

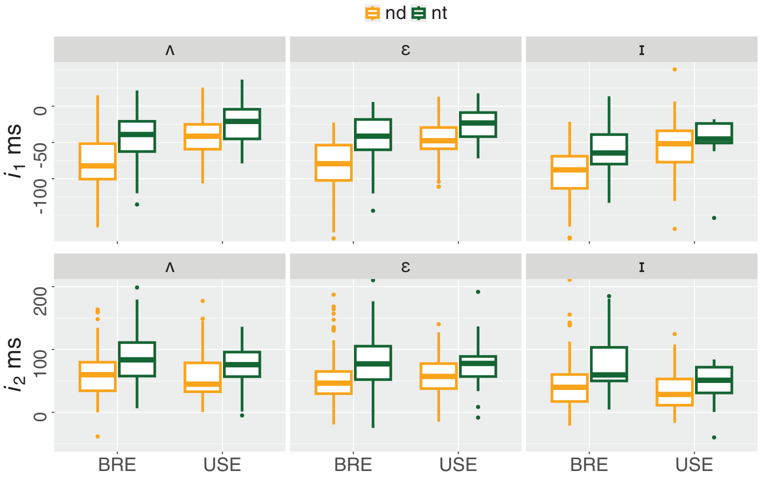

FIGURE 8. Boxplots showing the distribution of the two parameters i_1 and i_2 (Fig. 6) by coda and dialect.

For the dependent variable $i_2 = t_3 - t_2$, the results of the statistical test showed a significant effect for coda ($F_{1,49.454} = 20.26$, $p < 0.001$: /nt/: $\hat{m} = 75$ ms, /nd/: $\hat{m} = 52$ ms) but not for dialect.

DISCUSSION. Consistent with Beddor's 2009 model, the velum-tongue asynchrony was greater for /nt/ than for /nd/ on measures of the times of both the tongue-tip peak velocity and tongue-tip maximum. As far as dialect is concerned, the results were also consistent with the predictions of Cunha et al. (2024), showing a greater velum-tongue asynchrony for USE than for BRE on the time of the tongue-tip peak velocity both in /nt/ and in /nd/.

The observed greater velum-tongue asynchrony could have two origins: either the velum gesture is phased earlier relative to the tongue, or the tongue is phased later relative to the velum (or some combination of both). In Beddor's 2009 model, the difference is clear: the velum is aligned earlier relative to the other articulators in /nt/ than in /nd/. In Cunha et al. 2024, by contrast, the peak velocity of the tongue-tip raising gesture is phased late relative to the velum. Regardless of whether the velum is phased early (Beddor 2009) or the internal acoustic VN boundary is phased late (Cunha et al. 2024), the outcome as far as how nasalization is distributed across VN is the same: in both models, an early velum phasing or a late phasing of the internal VN boundary predicts greater nasalization in V and less nasalization in N. Therefore, the prediction according to Beddor (2009) is that the extent of nasalization should be greater in V and less in N in /nt/ compared with /nd/, and according to Cunha et al. (2024) that the extent of nasalization should be greater in V and less in N in USE compared with BRE. These predictions were tested in §2.5.

2.5. NASALIZATION IN THE V AND IN N. The analysis of how nasalization was distributed in VN was made in two ways: by determining the time of peak velum lowering relative to the acoustic vowel boundaries (predicted to be early for /nt/ and early for USE), and by calculating the extent of nasalization on either side of the VN boundary between the peak velocities of velum lowering and raising (predicted to be greater in the V than in N in /nt/ and in USE).

METHOD. Two parameters were analyzed. The first was t_{prop}, the proportional time of occurrence of peak velum lowering relative to the acoustic onset and offset of the vowel and calculated from 2:

$$(2)\quad t_{prop} = \log((t_3 - t_0) / (t_2 - t_0)),$$

where t_0 and t_2 are, respectively, the acoustic onset and acoustic offset of the vowel, and t_3 is the time of peak velum lowering (Figure 9). When $t_{prop} = 0$, then peak velum lowering is exactly at the acoustic boundary between V and N, and when t_{prop} has negative/positive values, then the peak velum lowering precedes/follows this boundary. The second was N_{prop}, the extent of nasalization in the N relative to the extent of nasalization between the velum's peak lowering and raising velocities. N_{prop} was calculated from 3:

$$(3)\quad N_{prop} = A_N / (A_V + A_N),$$

where A_V and A_N are, respectively, the total areas under the velum trajectory in the vowel (Fig. 9: orange area) and in the N (Fig. 9: blue area).

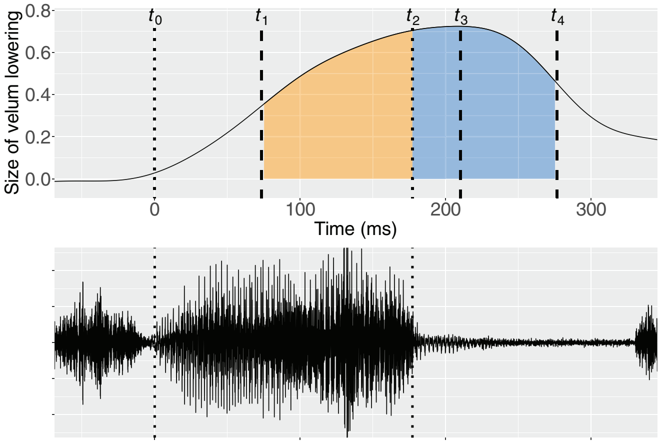

FIGURE 9. Velum lowering as a function of time in VN in the production of *saint* by a BRE speaker. The vertical lines from left to right are at the following times: t_0: acoustic (periodic) onset of the vowel, t_1: peak lowering velocity, t_2: acoustic boundary between V and N, t_3: peak velum lowering, and t_4: peak raising velocity. The two shaded areas are the extent of nasalization in the vowel (orange) and in the nasal coda (blue).

The earlier phasing of the velum in Beddor's 2009 model predicts that both t_{prop} and N_{prop} should be less for /nt/: the first because peak velum lowering occurs earlier in the vowel, and the second because the earlier alignment of the velum causes nasalization to decrease in N. The later phasing of the internal acoustic VN boundary (t_2 in Fig. 9) in Cunha et al.'s (2024) model predicts that t_{prop} and N_{prop} should be less for USE: the first because, if the acoustic vowel offset/N onset is phased later, then the time of peak velum lowering is necessarily phased earlier relative to the acoustic onset and offset of the vowel; the second because the later phasing of the internal acoustic VN boundary causes a reduction in the extent of nasalization in the N, if the velum gesture is stable between the varieties.

Results. The top of Figure 10 shows the results of t_{prop}, the proportional time of peak velum lowering relative to the acoustic onset and offset of the vowel. A comparison of the gold and green boxes in the top row shows little evidence of any systematic difference between /nt/ and /nd/ on this measure. By contrast, for both /nt/ and /nd/, t_{prop} is less for USE than for BRE (compare the boxes within any panel of the same color in the top row).

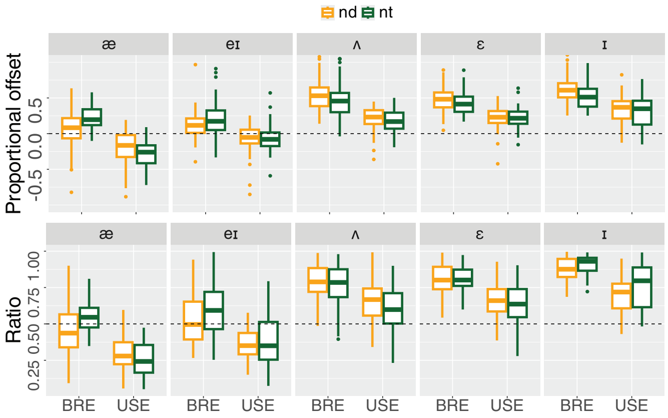

Figure 10. Top: t_{prop}, the proportional time of the peak velum lowering relative to the acoustic onset and offset of the vowel. The horizontal dashed line at $t_{prop} = 0$ is when the time of the peak velum lowering coincides with the acoustic boundary between V and N. Bottom: N_{prop}, the proportion 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.

A similar pattern emerges for N_{prop}, the extent of velum lowering in the nasal consonant as a proportion of nasalization in the entire velum gesture. There are few indications of /nt, nd/ differences, but once again the proportional area and hence extent of nasalization in the N are less for USE than for BRE.

The results of the statistical analyses were generally consistent with these observations.

- For t_{prop} (Fig. 10, top), there was a significant effect of dialect ($F_{1,47.563} = 46.254$, $p < 0.001$: BRE: $\hat{m} = 0.3571$, USE: $\hat{m} = 0.0978$) but not of coda.
- For N_{prop} (Fig. 10, bottom), there was a significant effect of dialect both within /nd/ ($z = 6.004$, $p < 0.001$) and within /nt/ ($z = 6.509$, $p < 0.001$) but not of coda and no interaction between these factors.

DISCUSSION. The results have provided no support for the idea that the velum was phased earlier in the vowel for /nt/-words than for /nd/-words, nor that /nt/-words were produced with less nasalization in the nasal consonant. They are therefore not consistent with Beddor's 2009 model of early velum phasing in /nt/ as presented in Fig. 1.

However, Beddor 2009 and Beddor et al. 2018 provide strong evidence for an earlier alignment of the velum in /Vnt/ than in /Vnd/ sequences based on a combination of airflow and acoustic and perceptual data. Quite why our results and those of Beddor are divergent in this regard requires further investigation. Given the various findings from the past literature (see §1.4) showing that the timing of nasal and oral gestures in VN sequences is dialect-specific, then it is possible that the discrepant findings between this study and those of Beddor have come about because most of the participants in Beddor's studies (in contrast to our US speakers) were speakers of a Midwestern, especially Michigan, variety. It is clear that further data from participants of different English dialects (both in the US and elsewhere) are required to shed further light on the issue of whether our findings are specific to our present speakers or generalize to a wider range of speakers and dialects.

As far as dialect is concerned, the results are generally consistent with the findings in Cunha et al. 2024 that USE is characterized by a later phasing of the internal acoustic VN boundary and reduced nasalization in the nasal consonant: these dialect differences were observed for both /nt/ and for /nd/.

A potential difficulty for Cunha et al.'s (2024) model is the finding in the preceding section, on the one hand, of a later phasing of the tongue-tip gesture relative to the velum in /nt/ compared with /nd/ (especially so for BRE: see Fig. 7 and associated results); in the analysis of this section, on the other hand, /nt, nd/ were shown not to differ in the distribution of nasalization across the vowel and nasal consonant (Fig. 10). The difficulty is that if the time of the peak velocity of tongue-tip raising (Fig. 7) and the time of the internal acoustic VN boundary (Fig. 10) are supposed to be the same, then these two sets of results should not diverge. However, the association between a change in the phasing of the tongue-tip raising gesture (Fig. 7) and the distribution of nasalization across V and N (Fig. 10) is conditional in Cunha et al. 2024 on the velum gesture being stable in time and space (Fig. 2). But this was shown not to be so across coda voicing (§2.3). Thus, any change in the distribution of nasalization across VN brought about by a late phasing of the tongue-tip raising gesture could be offset by differences between /nt/ and /nd/ in the shape and timing of the velum gesture.

In Cunha et al.'s 2024 model, the shrinkage of N is manifested by an oral gesture that becomes smaller and shorter but not slower (Fig. 2) during the progression of the VN > Ṽ sound change. If this is so (and again based on the idea that USE is further along this sound change path), then USE should have a smaller tongue-tip displacement and duration but the same tongue-tip peak raising velocity compared with BRE. These predictions were tested in the next section.

2.6. TONGUE-TIP REDUCTION IN N.

METHOD. Four parameters (Figure 11) were measured in order to assess the extent and nature of tongue-tip reduction. These were (i) the magnitude of the tongue-tip displacement averaged between the plateau onset and offset, (ii) the peak velocity of tongue-tip raising, (iii) the articulatory duration of the tongue-tip gesture, defined as the duration between the tongue-tip peak raising and lowering velocities, and (iv) the duration between the times of the tongue-tip peak raising velocity and tongue-tip peak displacement. The procedures for obtaining kinematic landmarks were applied to the tongue analogously to those in Fig. 3 for the velum.

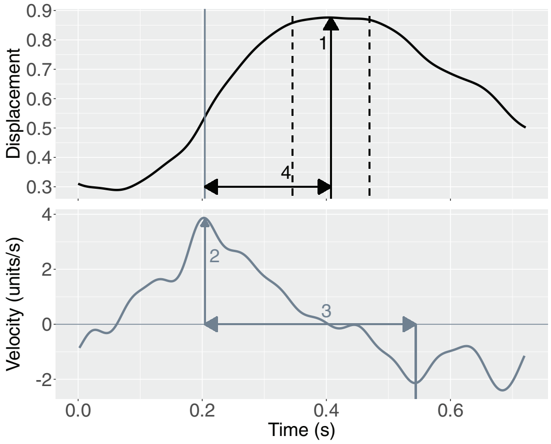

FIGURE 11. Tongue displacement and velocity in the production of *bend* by a USE speaker. The four parameters shown are: (i) the magnitude of peak tongue-tip raising (vertical solid line, top) averaged between the plateau onset and offset (vertical dashed lines, top); (ii) the peak raising velocity of the velum (vertical solid upward gray line, bottom); (iii) the articulatory duration of the tongue-tip gesture (horizontal double arrow, bottom), extending between the times of the tongue tip's peak lowering and raising velocities; and (iv) the duration between the time of the tongue-tip peak velocity and the time of the temporal midpoint between tongue-tip plateau onset and offset.

RESULTS. There is little evidence from Figure 12 that the peak tongue-tip displacement or raising velocity is influenced either by dialect or by coda consonant. The results of the statistical analyses were as follows.

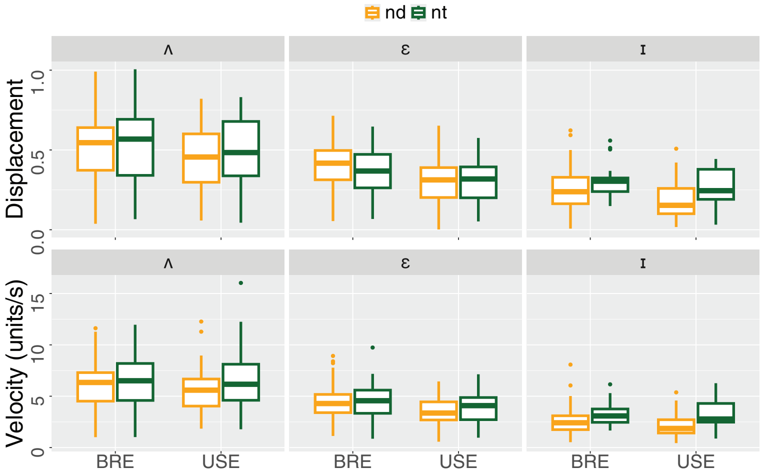

FIGURE 12. Boxplots of the peak displacement and peak raising velocity of the tongue tip (parameters (i) and (ii) in Fig. 11) by dialect and coda consonant.

For tongue-tip displacement (Fig. 12, top), there was an effect of dialect ($F_{1,45.29}$ = 4.2346, $p < 0.05$) and a significant ($F_{1,211.0} = 7.5995$, $p < 0.05$) coda × dialect interaction. Post-hoc tests showed only a greater tongue-tip displacement in BRE /nd/ compared with USE /nd/ ($p < 0.05$: BRE: $\hat{m} = 0.399$, USE: $\hat{m} = 0.385$).

For the peak velocity of tongue-tip raising (Fig. 12, bottom), there was a significant effect for coda ($F_{1,646.33} = 15.6853$, $p < 0.001$) and a significant ($F_{1,640.38} = 6.2638$, $p < 0.05$) coda × dialect interaction. Post-hoc tests showed only a greater tongue-tip peak velocity in USE /nt/ than in USE /nd/ ($p < 0.001$: /nt/: $\hat{m} = 4.58$, /nd/: $\hat{m} = 0.383$).

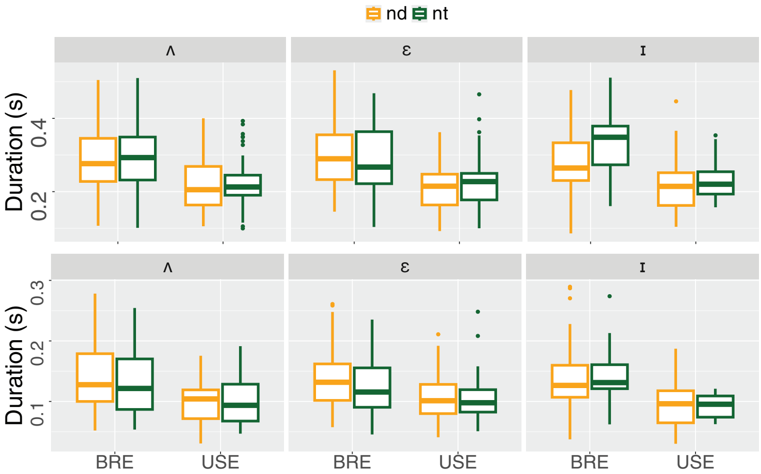

Figure 13. Boxplots of the durations of the tongue-tip gesture (top; see also parameter (iii) in Fig. 11) and of the tongue tip's raising gesture (bottom; see also parameter (iv) in Fig. 11).

As far as the coda consonant is concerned, Figure 13 shows few differences between /nt/ and /nd/ on either of the two articulation parameters that were investigated. The two parameters are, by contrast, clearly influenced by dialect: the articulatory durations both of the tongue-tip gesture (top) and of the tongue-tip raising gesture (bottom) are generally greater for BRE compared with USE.

For the articulatory duration of the tongue-tip gesture (parameter (iii), Fig. 11), the results showed no significant effect of coda consonant but a significant ($F_{1,41.108}$ = 17.197, $p < 0.001$) influence of dialect (USE: $\hat{m}$ = 223 ms, BRE: $\hat{m}$ = 296 ms). For the articulatory duration of the tongue-tip raising gesture (parameter (iv), Fig. 11), the results showed no effect of coda consonant but a significant ($F_{1,40.968} = 12.902$, $p < 0.001$) influence of dialect (USE: $\hat{m}$ = 101 ms, BRE: $\hat{m}$ = 135 ms).

Discussion. The main purpose of the analysis in this section was to test the prediction that USE has a smaller tongue-tip displacement and duration but the same tongue-tip peak raising velocity compared with BRE. The results have shown, contrary to the prediction, that peak tongue displacement is not less in USE. Consistently with the prediction, there were no differences in the peak velocity of the tongue-tip raising gesture between the dialects, and the duration of the tongue-tip gesture was less in USE than in BRE on both of the duration parameters that were measured. The main revision that needs to be made to Cunha et al.'s (2024) VN > Ṽ sound change model is that the shortening of the tongue-tip gesture with the progression of sound change is not necessarily associated with its spatial reduction. With this modification, Cunha et al.'s (2024) model—in which, with the progression of sound change, the acoustic VN boundary is phased later as a consequence of the later phasing of the tongue-tip raising gesture—is applicable to both voiced /Vnd/ and voiceless /Vnt/ coda clusters in American English.

Beddor's 2009 schematic model does not show any tongue-tip gesture differences in the oral gesture of voiceless /NC̥/ and voiced /NC̬/, and this corresponds closely to most of the findings, which show no /nt, nd/ differences in peak displacement or duration of the tongue-tip gesture and only one difference for USE, which was shown to have a faster tongue-tip raising gesture in /nt/ than in /nd/.

2.7. Compensatory lengthening between V and N. In the Cunha et al. 2024 model, the VN > Ṽ sound change is associated with a later phasing of the tongue-tip peak velocity (and internal VN boundary) that causes a lengthening of the V but no overall change to the duration of VN. The prediction with regard to dialect is that, in USE, the duration of V should be greater than in BRE but that the two dialects should not differ in VN duration.

Method. Two measures of duration were made: of VN, defined as the interval from the acoustic onset of V to the time of peak velum-raising velocity ($t_4 - t_0$ in Fig. 9, §2.5), and of V, defined as the interval between the acoustic vowel onset and acoustic vowel offset ($t_2 - t_0$ in Fig. 9).

Results. Figure 14 suggests that the dialects do not differ in the overall VN duration but that there is lengthening of the vowel in both /Vnd/ and /Vnt/ in USE compared with BRE. The same figure also shows overall shortening of both V and VN in the /nt/ compared with the /nd/ context. Consistent with these observations, the results of the statistical analysis with the total duration of VN as the dependent variable showed no effect of dialect and a significant effect of coda consonant ($F_{1,45.274} = 101.48$, $p < 0.001$: /nd/: $\hat{m} = 358$ ms, /nt/: $\hat{m} = 275$ ms). For V duration, there was a significant effect both of dialect ($F_{1,45.846} = 7.4708$, $p < 0.01$: USE: $\hat{m} = 195$ ms, BRE: $\hat{m} = 169$ ms) and of coda ($F_{1,55.041} = 201.0808$, $p < 0.001$: /nd/: $\hat{m} = 207$ ms, /nt/: $\hat{m} = 157$ ms).

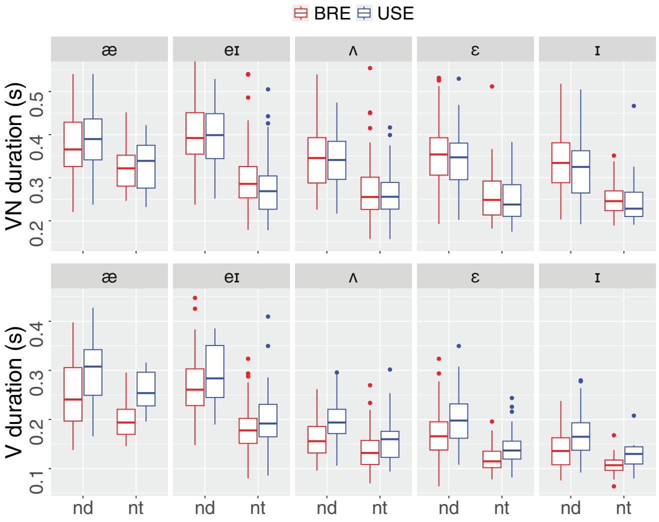

Figure 14. Boxplots of the duration of VN (top) and of V (bottom) by coda and dialect.

DISCUSSION. Consistent with the results of the preceding section, the results show that the dialects differ in the timing of the internal acoustic VN boundary, which is phased later in USE than in BRE. For USE, this later phasing is associated with an increase in vowel duration and, given the finding that the duration of VN is the same between the dialects, a decrease in N duration compared with BRE. These results are further supportive of the model in Cunha et al. 2024, in which the VN > Ṽ sound change is associated with an increasingly delayed phasing of the internal acoustic VN boundary, such that V lengthens and becomes increasingly nasalized as N shortens. The results in this section have shown that this conclusion generalizes across coda voicing, given that similar timing differences between the dialects were shown to occur in both /nd/ and /nt/.

Superficially, the findings of a shorter VN in /nt/ than in /nd/ are consistent with Beddor's 2009 model of sound change. According to this model, the cause of VN shortening in /nt/ is the earlier alignment of the velum, which leaves V duration unaffected and shortens the duration of N. However, if N shortening were due to the early alignment of the velum, then the proportion of VN duration taken up by V, corresponding to $(b - a / c - a)$ in Beddor's model in Fig. 1, should be greater in /nt/. But this is not consistent with the present results. Thus, based on the estimated marginal means reported above, the proportion of VN taken up by V in /nt/ = V duration / VN duration = 157 ms / 275 ms ≈ 0.571, and the corresponding proportion for /nd/ is almost the same at 207 ms / 358 ms ≈ 0.578. Thus, whatever the cause of VN shortening in /nt/ compared with /nd/, it is not due to the earlier alignment of the velum.

3. ALIGNMENT WITH THE GLOTTAL GESTURE. The results so far have provided no evidence that the intragestural characteristics of the velum are stable in either time or space across /nt, nd/. Nor was there any evidence of greater nasalization in the vowel and less nasalization in the nasal consonant in /nt/ compared with /nd/ clusters. Although the results showed a greater intergestural asynchrony between the velum and tongue tip in /nt/ compared with /nd/ clusters, as predicted by Beddor's 2009 model, this was considered to come about, not because the velum gesture is left-aligned, that is, phased earlier, but because the tongue-tip gesture for the N is right-aligned, that is, phased later, in /nt/ than in /nd/ (also Fig. 10).

Consistent with Cunha et al. 2024, the comparison between the two dialects has shown that the VN > Ṽ sound change is associated with a later phasing of the oral gesture of N in relation to a velum gesture that is stable across the dialects in space and time. This later phasing of the oral gesture of N and hence of the internal acoustic VN boundary causes greater nasalization in V and less nasalization in N with the progression of sound change: just these differences were found for USE compared with BRE in both /nt/ and /nd/.

By contrast, the supralaryngeal analyses of how the velum is coordinated with the tongue tip (§2.4) have uncovered few, if any, differences between /nt/ and /nd/ that might be relevant for explaining why the VN > Ṽ sound change has been reported to occur preferentially in /nt/ (Beddor et al. 2018, Busà 2007, Hajek 1997, Malécot 1960, Raphael et al. 1975). However, an obvious coda difference not considered so far is that /nt/ and /nd/ also differ in voicing. Moreover, as discussed in §1, it has been suggested that an earlier onset of glottal opening, that is, of voicelessness in /nt/, may contribute to the diminished perceptibility of nasalization in the nasal consonant (Ohala 1975). Accordingly, the main aim in the following analysis was to determine whether the onset of voicelessness begins earlier during the nasal consonant for /nt/ than for /nd/: that is, whether in comparison with /nd/, voicelessness is phased earlier relative to the velum in /nt/.

3.1. Method. The YIN algorithm (de Cheveigné & Kawahara 2002) was used to provide a measure of the periodicity of the acoustic signal from which an estimate of the onset of voicelessness during the N was derived. The YIN algorithm is a modified autocorrelation method for estimating f0 in music (including singing) and speech signals. As part of the estimation procedure, it also provides a measure of the amount of aperiodic energy in the signal. For the purposes of this analysis, the complement of this measure was used such that 1 corresponds to a completely periodic signal (and 0 to completely aperiodic). The threshold of 0.5 used in further calculations below corresponds to a signal in which the total power divides equally into periodic and aperiodic contributions.

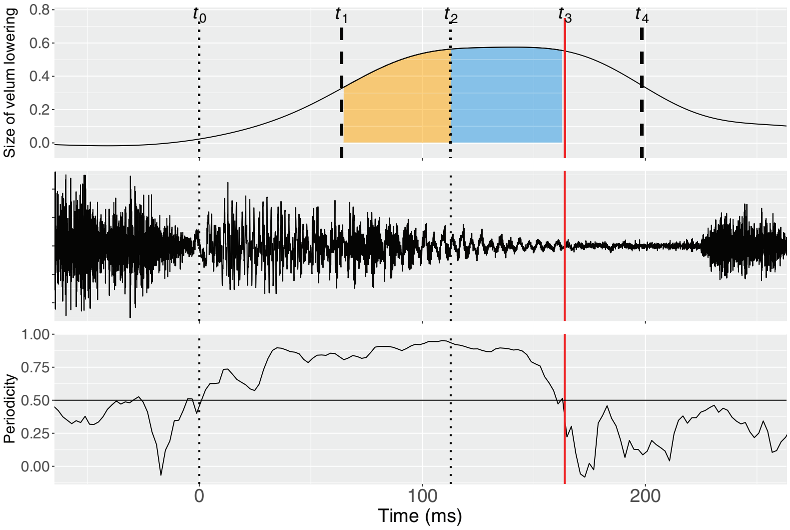

Figure 15. A production of *saint* produced by a BRE speaker showing the synchronized velum signal, acoustic waveform, and periodicity calculated with the YIN algorithm. The vertical boundaries from left to right are: t_0: the acoustic onset of the vowel; t_1: the time of the peak velum-lowering velocity; t_2: the acoustic offset of V/acoustic onset of N; t_3 (red vertical line): the time between t_2 and t_4, at which the periodicity first falls to 0.5; and t_4: the time of the peak velum-raising velocity. The orange and blue shaded areas denote the extent of nasalization in the V and voiced N, respectively.

Two quantifications were made in order to test whether /nt/ and /nd/ were differently affected by voicing during the N. The first was the mean periodicity during the N, calculated by averaging all periodicity values between the acoustic vowel offset and the time of the peak velocity of velum raising (between time points t_2 and t_4 in Fig. 15). The second was the average energy in the signal between these same time points after low-pass filtering the signal between 0 and 1000 Hz. The basis for this second calculation is the evidence that voiced nasal stops are characterized by a nasal murmur that causes a high level of energy in this low-frequency region (Fujimura 1962, Ohala & Ohala 1993, Pruthi & Espy-Wilson 2004). The prediction was that /nt/ should be less than /nd/ on both parameters, if a greater interval of the signal during N in which the velum is lowered is voiceless.

A third parameter, $N_{prop.voice}$, was calculated from equation 4 of the extent of nasalization in the voiced part of the N relative to the entire velum gesture (the latter defined as extending between t_2 and t_4 in Fig. 15):

$$(4)\ N_{prop.voice} = A_{N.voice} / (A_V + A_{N.voice}),$$

where A_V and $A_{N.voice}$ are, respectively, the total areas under the velum trajectory in the vowel (Fig. 15: orange area) and in the VOICED part of the N (Fig. 15: blue area). This quantification is exactly the same as that of Fig. 9, except that the right boundary for N was often earlier, at the transition between the voiced and voiceless part of the signal. This boundary (Fig. 15: t_3) defining the transition between the voiced and voiceless parts of the signal was estimated from the time at which periodicity first dropped to 0.5 in the interval from the acoustic onset of N (Fig. 15: t_2) to the time point of peak velum-raising velocity (Fig. 15: t_4). The prediction was that $N_{prop.voice}$ should be less for /nt/ if the right boundary at which voicing ends is phased earlier than in /nd/. In addition, and based on the findings is §2, $N_{prop.voice}$ was also expected to be less for USE, if (as the results of §2 suggest) the left boundary at the transition between V and N is phased later than in BRE.

3.2. RESULTS. Figure 16 shows that the periodicity in the interval from the acoustic vowel offset (acoustic onset of N) to the time of the peak velocity of velum raising is less for /nt/ than for /nd/. The results of the statistical analysis applied to the mean periodicity over this interval showed a significant effect of coda consonant ($F_{1,45.139} = 272.74$, $p < 0.001$: /nt/: $\hat{m} = 0.568$, /nd/: $\hat{m} = 0.820$) and no effect of dialect.

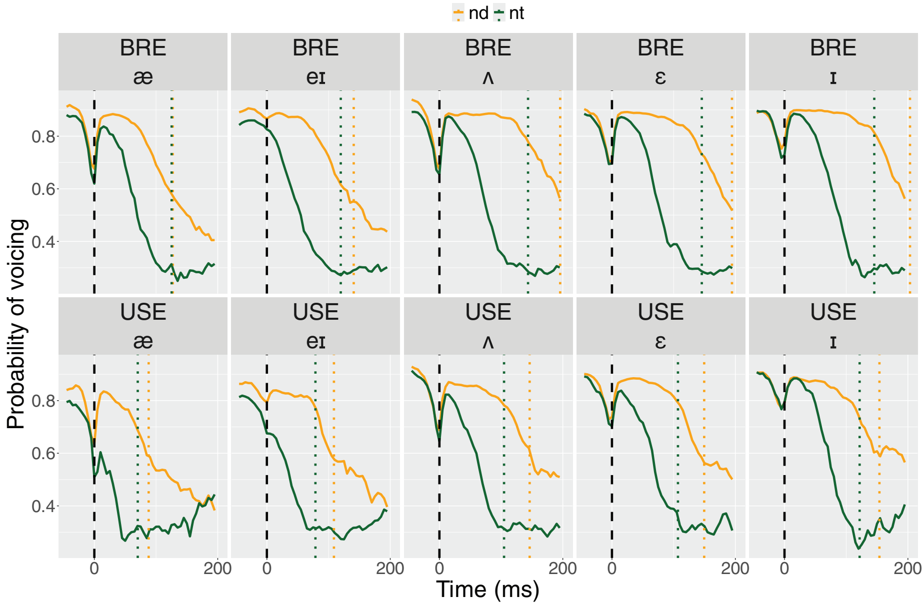

FIGURE 16. Periodicity trajectories aggregated by dialect, vowel, and coda after alignment at the acoustic vowel offset ($t = 0$ ms; Fig. 15: t_2) and showing the mean times of the peak velocity of velum raising (colored vertical lines: Fig. 15: t_4).

Figure 17 shows less energy below 1000 Hz for /nt/ than for /nd/ over the same time intervals that were measured for periodicity (Fig. 16). The statistical analysis showed a significant effect of coda consonant ($F_{1,46.539} = 69.287$, $p < 0.001$: /nt/: $\hat{m} = 48.3$ dB, /nd/: $\hat{m} = 51.2$ dB) and no effect for dialect.

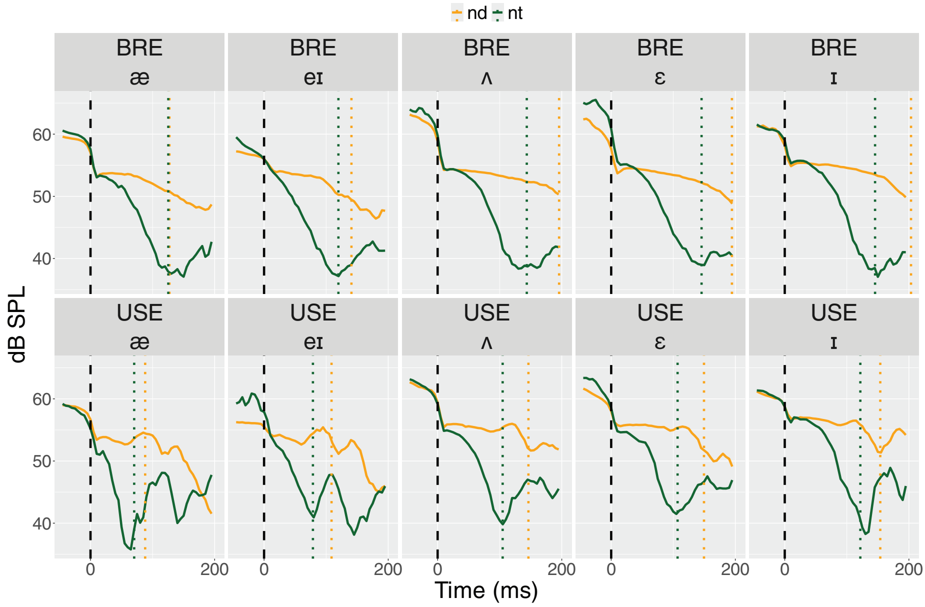

FIGURE 17. Energy below 1000 Hz aggregated by dialect, vowel, and coda after alignment at the acoustic vowel offset ($t = 0$ ms; Fig. 15: t_2) and showing the mean times of the peak velocity of velum raising (colored vertical lines: Fig. 15: t_4).

Figure 18 shows the proportional times between the onset and offset of N at which the periodicity first falls below 0.5. These data show that the N is typically voiced over its entire interval for /nd/ (because most of the values for /nd/ are above 1.0 in Fig. 18), whereas for /nt/, the signal is fully voiced for typically around 50–75% of the interval into the N: that is, the final 25% or so of the N is voiceless (if the onset of voicelessness is taken to be when the periodicity falls below 0.5).

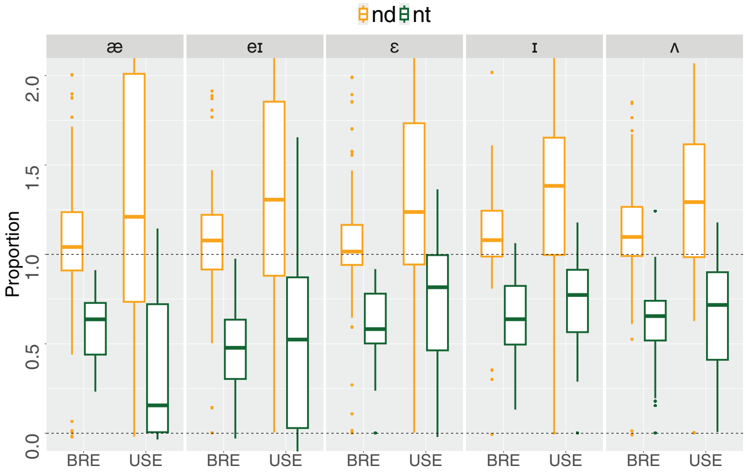

FIGURE 18. The boxplots show the times at which the periodicity first falls to below 0.5 (Fig. 15: t_3) as a proportion of the interval between the acoustic N onset (Fig. 15: t_2) and the N offset (Fig. 15: t_4). (Thus, a y-axis value of 1.0 denotes that the periodicity first fell below 0.5 at the N offset.)

Figure 19 shows the distribution of $N_{prop.voice}$: that is, the ratio of nasalization in the voiced part of the N (Fig. 15: orange area) to the nasalization in the VN sequence (Figure 15: blue and orange areas together). These data show that $N_{prop.voice}$ is less both for /nt/ compared with /nd/ and for USE compared with BRE. Compatibly, the statistical analysis showed a significant effect of coda consonant both within USE ($z = 4.662$, $p < 0.001$) and within BRE ($z = 8.216$, $p < 0.001$), as well as a significant effect of dialect both within /nd/ ($z = 3.45$, $p < 0.01$) and within /nt/ ($z = 2.77$, $p < 0.05$), and no interaction between these factors.

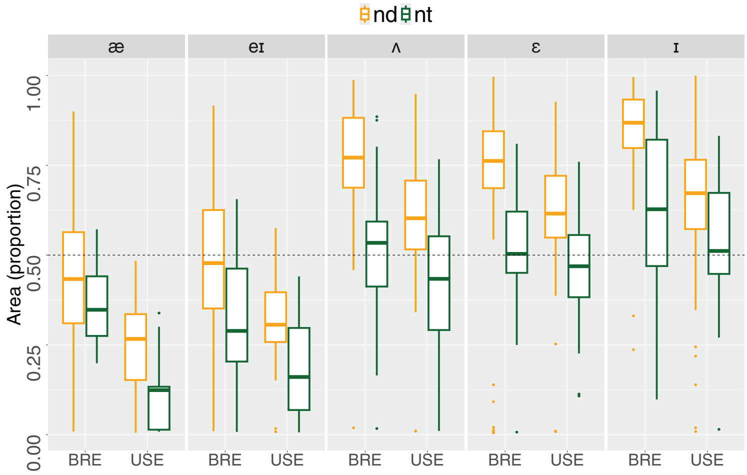

FIGURE 19. Boxplots of $N_{prop.voice}$ (eq. 4), the proportion of the area under the velum curve in the voiced interval of N relative to VN. The horizontal dashed line is the value for which the areas under the curve in V and N are equal.

3.3. DISCUSSION. The results have shown that the periodicity during the N—where N is defined here as extending between the acoustic vowel offset and time of the peak velocity of velum raising—is weaker in /nt/ than in /nd/. A consequence of this attrition of voicing during the N for /nt/ is that the energy below 1 kHz, which is typically high for a fully voiced N due to the presence of a nasal murmur, is also less in the N of /nt/. Listeners' ability to perceive the N may well be compromised to a greater extent in /nt/ than in /nd/, given that a voiced murmur (Kurowski & Blumstein 1984) or at least the predominance of low amplitude voicing (Ohala & Ohala 1991) is itself one of the salient cues to the presence of a nasal consonant. The finding that voicing extends throughout /nd/ is to be expected. From an aerodynamic perspective, nasal venting results in a sufficiently high transglottal pressure difference, which sustains vocal-fold vibration into the following voiced stop (Ohala & Ohala 1991, Solé 2009). From an acoustic perspective, the presence of vocal-fold vibration throughout /nd/ produces high-amplitude, low-frequency energy that is a cue for both nasals and fully voiced stops (Ohala & Ohala 1991, 1993, Solé 2009).

The reason why the VN > Ṽ sound change is likely to be advanced in a voiceless VNÇ̥ compared with a voiced VNÇ context is because voicelessness, or at least an irregularly voiced signal, is phased earlier in VNÇ̥. According to the results from §2, the late phasing of the oral gesture of N causes a decrease in the extent of nasalization of the N and a corresponding increase in nasalization in the V (Fig. 10). From a physiological perspective, the degree of N shortening and attrition is no different between /nt/ and /nd/. However, the results in this section show that the extent of nasalization in the voiced part of N is less in /nt/ than in /nd/. Consequently, the progression of the VN > Ṽ sound change by which the oral gesture is phased later is likely to cause the attrition and loss of the voiced part of N earlier in VNC̥: that is, the voiced part of the N is squeezed to the right by the much earlier onset of aperiodicity and/or voicelessness and simultaneously to the left with the progression of the VN > Ṽ sound change and later phasing of the oral component of N. These combined effects from the left and the right cause USE /nt/ to have the most diminished voiced N of all four possible dialect × coda combinations (Fig. 19).

4. General discussion. The principal synchronic basis of the VN > Ṽ sound change is a shrinkage of N's oral gesture in which the time of the raising gesture's peak velocity is phased closer to the time of peak displacement. The acoustic correlate of this articulatory change is a delay in the internal acoustic VN boundary as the sound change progresses. Because the velum gesture is stable in space and duration with the progression of sound change, a delay in the internal acoustic VN boundary causes the extent of nasalization in the V and N to increase and decrease, respectively. Since the VN duration is constant with the progression of sound change (§2.7), then, as the internal acoustic VN boundary is delayed, V lengthens as N shortens. Since all of these considerations have been shown to apply equally to /nd/ and /nt/ in the present study, the model in Cunha et al. 2024 (their figure 2; henceforth the CR or coda reduction model) is appropriate for relating synchronic variation to VN > Ṽ change, irrespective of the voicing status of the final consonant.

By contrast, the types of models shown in Fig. 1 (Beddor 2009) and Fig. 2 (the CR model), which are exclusively based on velum and tongue gestures, cannot explain the evidence from some experimental (Busà 2007, Malécot 1960) and philological (Hajek 1997) studies suggesting that the VN > Ṽ sound change progresses faster in voiceless VNC̥ than in voiced VNC̬. This greater likelihood that VNC̥ leads the sound change can be accounted for by augmenting the CR model in Fig. 2 (which is a model of voiced VN(C̬) > Ṽ(C̬)) with a glottal signal that divides the N into predominantly voiced and voiceless sections (Figure 20). On the assumption that an aperiodic or voiceless N provides only very weak cues to the presence of a nasal consonant (Ohala 1975, Ohala & Ohala 1993)—that is, listeners predominantly rely on a periodic signal with low-frequency energy for identifying nasality—then, even without any sound change in progress, the acoustic information signaling the presence of nasality in the N is likely to be weaker in voiceless VNC̥ for which the duration of the fully periodic N is much less than in voiced VNC̬ (Fig. 20; compare with Fig. 2).

Moreover, the prediction of the CR model is that, as the internal acoustic VN boundary is phased progressively later with the progression of the sound change, then N will eventually disappear. However, the voiced part of the N, which is likely to be essential to its identification, will disappear first in VNC̥ because of the proportionately earlier onset of glottal opening, thereby leaving only a weakly voiced or voiceless section of N, which may not provide sufficiently strong cues to signal the presence of a nasal consonant. An important consideration in this model is that the velum and the glottal signal

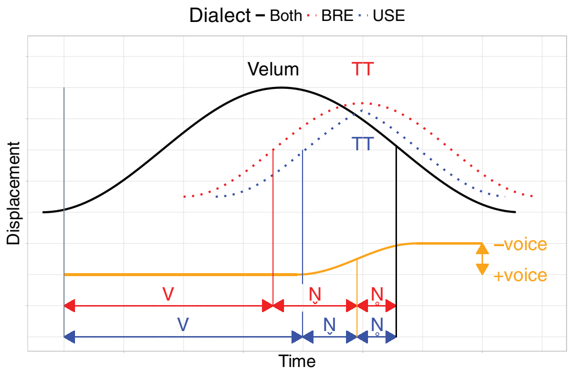

Figure 20. A schematic outline showing the velum (black), tongue tip (TT: red/blue dashed for BRE/USE), and variation in the glottal signal (gold) between voiced and voiceless in the production of a voiceless VNC̥ sequence. The five vertical lines from left to right are at the following times, respectively: (i) the acoustic vowel onset (gray and unaligned with any displayed trajectory), (ii) /n/'s peak velocity of tongue-tip raising, which coincides with the acoustic boundary between V and N for BRE (red) and (iii) for USE (blue), (iv) the boundary between voiced N̬ and voiceless N̥ (gold), and (v) the articulatory offset of N (black). The three horizontal arrows from left to right show, respectively, the acoustic duration of the V, the duration of the voiced N̬, and the duration of the voiceless N̥ in BRE (red) and USE (blue).

are stable during the sound change in progress: the only change due to sound change is in the time of the peak velocity of the oral raising gesture (and associated internal VN acoustic boundary), which is phased later as the sound change progresses. This phase change alone, against stable velum and stable glottal signals, explains the redistribution of nasalization toward V and away from N, the inverse durational relationship between V and N, the disappearance of N in the later stages of the sound change, and why the voiced part of the N is likely to disappear first in voiceless VNC̥.

The two English dialects that have been analyzed differed not only in the extent of vowel nasalization but also in the length of the entire (oral and nasal part) of the vowel. This is predicted from the CR model in which the VN > Ṽ sound change involves a progressively later phasing of the internal acoustic VN boundary as a consequence of temporal compression (and sometimes lenition) of the oral gesture of the N (the result is, however, not predicted by Beddor's model of sound change, in which the velum gesture is phased earlier in time without any vowel lengthening). These results are also consistent with a model of VN > Ṽ sound change involving some form of compensatory vowel lengthening (Gess 2011, Hock 1986, Kavitskaya 2002, Topintzi 2006) in view of the present findings in which the two dialects were shown not to differ in the total duration of the VN but in the reciprocal relationship between the length of the vowel and following nasal consonant. Thus, these findings show that vowel lengthening is the inevitable diachronic outcome of a progressively later phasing of the oral raising gesture of N combined with no change to the velum gesture in either magnitude or duration. From this perspective, the CR model makes the prediction that a VN > Ṽ sound change should never be possible without at least some phonetic vowel lengthening. This position is therefore quite close to that of Hajek 1997 and Hajek and Maeda (2000), who consider vowel length as the primary conditioning factor in the phonologization of vowel nasalization. The evidence against this view might be that the development of contrastive nasalization is also possible in short vowels (e.g. de Chene & Anderson 1979:529). However, based on Hajek’s 1997 detailed analysis of Northern Italian dialects, showing that vowels always seem to lengthen chronologically prior to the development of phonological nasalization, it cannot be ruled out that these short vowels became phonetically longer (but not as long as the long vowels with which they contrast) with the diachronic progression of vowel nasalization.

A commonality between the CR model and that of Beddor 2009 is that both predict an inverse relationship between the extent of nasalization in the V and in the N. In both cases, this inverse relationship derives from an increasing asynchrony between peak velum lowering and the tongue, such that with the progression of the VN > Ṽ sound change, velum lowering comes to be increasingly in-phase with the vowel and antiphase with N’s oral gesture. The single difference between the models is how these supralaryngeal phase changes are achieved: by an earlier alignment of the velum in Beddor, as opposed to a later alignment of the peak velocity of N’s oral raising gesture in the CR model. Despite these underlying physiological differences, the outcome as far as the trade-off between the extent of nasalization in the V and N is concerned is the same: in both models, as nasalization in the V increases with the progression of sound change, it decreases in N. For this reason, the various findings by Beddor and colleagues on how listeners parse nasalization from VN sequences (e.g. Beddor et al. 2013) are equally well predicted by either model: that is, both models predict that listeners should perceive nasalization by assigning greater weight to the V and less to the N with the progression of sound change, and that listeners might pay equal attention to the nasalization in the V and N (perhaps parsing nasalization with the entire VN rhyme) in earlier stages of the sound change in which the nasalization tends to be distributed variably and/or roughly equally between the V and N (as demonstrated for the perception of nasalization in American English *send* in Beddor 2012). They also both predict that cues should be weighted toward the vowel to a greater extent in /nt/ than in /nd/, provided that the increased weighting is determined with respect to the VOICED part of the N in /nt/ (as opposed to the entire N gesture). Thus, the insight from Beddor’s 2009, 2023 model that applies equally to the CR model is that a phase change in the association between the velum and tongue predicts a perceptual trade-off in cue weighting of the nasalization between V and N (or voiced N for /nt/), as long as the velum gesture remains stable (in space in Beddor 2009, 2023, in space and length in the CR model) as the sound change progresses.

The CR model of sound change predicts that the weakening and later phasing of the raising gesture of the oral component of N causes nasalization to occur proportionately earlier in the vowel. This is for two reasons. First, the rephasing of N’s oral gesture also results in a later phasing of the internal acoustic VN boundary that brings about vowel lengthening. Second, the velum gesture remains stable in space and time as the sound change progresses. If the vowel lengthens against a fixed velum gesture, then the proportion of the vowel that is nasalized also increases. For example, at the earlier stage of sound change in the schematic outline of Figure 21, the peak velocity of velum lowering occurs at around 40% of the duration into the vowel but at around 35% at the later stage of sound change. Thus, the proportion of the vowel that is overlaid with nasalization increases as the sound change progresses, since, according to the CR model, the proportionally more extensive V nasalization is an inevitable consequence of N reduction.

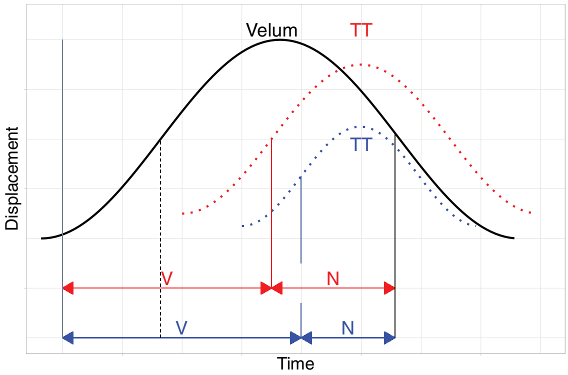

FIGURE 21. A schematic outline of the CR model showing the velum (black) and tongue-tip (TT) trajectories at earlier (red) and later (blue) stages of sound change (see also Fig. 2). The vertical black dashed line shows the time of peak velocity of velum lowering relative to the acoustic boundaries of V.

For both Ohala 1993 and Beddor 2009, 2023, coarticulation is the phonetic origin of VN > Ṽ, either through misparsing (Ohala 1993) or because cues to nasalization are progressively reweighted from the nasal consonant to the vowel in both perception and production (Beddor 2009, Beddor et al. 2018, Zellou & Cohn 2024). In the CR model, by contrast, the phonetic origin of this sound change is not in coarticulation but in coda reduction and in particular in the temporal compression of N's oral gesture from which the extent of anticipatory nasalization in the vowel is predictable. This idea finds resonance in some comments made by Browman and Goldstein (1995) in considering coda laterals: they note that the tongue tip in coda /l/ is often timed very late relative to the tongue-body gesture, indeed so late in final laterals that it may occur during the following silence (if coda /l/ is utterance-final). From this observation, they speculate that a substantial delay in the tongue-tip gesture of /Vn/ might similarly become inaudible (see also Lawson et al. 2021 for similar observations regarding a delayed tongue-tip gesture in weakly articulated rhotics of a working-class Scots English variety). The important point, as Browman and Goldstein (1995) note, and one that is entirely consistent with the findings and model of the present study, is that in such a scenario, 'NO ADDITIONAL PROCESSING WOULD NEED TO BE INVOKED TO NASALIZE THE VOWEL' (p. 25, emphasis added). Instead, with the progression of the VN > Ṽ sound change, coda reduction causes the raising gesture of the oral part of N to be phased late: it is this later phasing (and ultimate deletion) that produces increasing nasal coarticulation in the vowel. One of the factors that is likely to cause coda reduction is high semantic predictability or low informativity (Cohen Priva 2015, 2017) or lower communicative load (Scarborough & Zellou 2022), which have been shown to shorten word duration (Seyfarth 2014, Tang & Shaw 2021). This raises the possibility that a loss or reduction of information that causes coda reduction and that in turn produces greater coarticulatory vowel nasalization is at the origin of the VN > Ṽ sound change.

5. CONCLUSIONS.

American English (USE) is further along the path of the VN > Ṽ sound change than Standard Southern British (BRE). The evidence for this exists not just in the findings of this study showing greater vowel nasalization and a more attenuated N in USE, but also independently of it: USE in comparison with BRE has substantially more prenasal vowel raising in /æ/ (Mielke et al. 2017; see also Cunha et al. 2024, appendix C) and a much greater attrition of the nasal coda in words like *pant* and *can't* (Malécot 1960). For this reason, a comparison between these dialects can be used to infer the physiological changes that have taken place in the progression along this sound change path. The findings in this study suggest that the most likely synchronic basis for the VN > Ṽ change is a delay in the raising gesture of N's oral constriction and associated acoustic boundary within VN, while the velum gesture remains stable in space and time as the sound change progresses. This phase change in N's oral raising gesture applies in equal measure both to voiced /nd/ and to voiceless /nt/. The attainment of the point at which VN is phonologized as Ṽ is nevertheless likely to be reached sooner in /nt/. This is based first on the finding in this study that the VOICED part of the N gesture is shorter and therefore likely to be extinguished earlier in /nt/ with the progressive delay in the internal VN boundary and oral raising gesture, and second taking into account the evidence that listeners are likely to rely on a voiced signal in order to identify the presence of nasalization. The overall conclusion is that, while speakers and listeners who are positioned at different stages of the sound change are certainly likely to process coarticulation differently, as various studies (Beddor 2009, 2012) have shown, coda reduction and specifically the reduction of N's oral gesture in time and sometimes in space is the primary factor in the VN > Ṽ sound change from which variation in coarticulatory processing is derivative and predictable. Nevertheless, the possibility remains that this theory may be an oversimplification, if subsequent research shows evidence of dialects that nasalize the vowel to the same degree but differ in the extent to which the oral gesture of the nasal is reduced in time (and possibly in space).

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[Received 31 August 2024;
revision invited 23 April 2025;
revision received 18 May 2025;
accepted pending revisions 7 July 2025;
revision received 22 July 2025;
accepted 25 July 2025]