# The contribution of voicing to coarticulatory nasalization in two varieties of English

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**Introduction.** American English VN sequences preceding voiceless consonants (e.g., 'sent') typically show more coarticulatory vowel nasalization and a reduced nasal consonant when the preceding consonant is voiced ('send', e.g., Beddor, 2009). Already Malécot (1960) reported an asymmetry in perception when the nasal consonant was extracted from the acoustic signal: American listeners could recover the nasal before voiced stop, but not when the stop was voiceless. In German, Carignan et al., (2021) showed a diminished nasal gesture in size before voiceless in /Vntə/ (Ente, 'duck') than before voiced stops as in /Vndə/ (Ende, 'end'). Busà (2003, 2007) obtained comparable results for an Italian variety. Historically, the development of contrastive vowel nasalization is more likely to take place before voiceless than voiced consonants (Busà 2007; Hajek 1997), but it is not clear what in speech physiology leads to these asymmetries.

Beddor has developed a model linking synchronic coarticulatory nasalization with the sound change known as vowel nasalization, arguing that the nasal gesture (velum) has a similar size across VNC contexts, but varies its alignment relative to the oral gesture (Beddor, 2009: 789). In this model, coarticulatory nasalization results from earlier alignment of the velum. In addition, after analyzing the onset of velum lowering relative to the vowel onset and the proportion of vowel nasalization, Beddor (et al, 2018) showed that the onset of nasalization is earlier in the voiceless context when compared with voiced. Cunha and al. (submitted) tested Beddor's model with voiced /n, nd, nz/ contexts only by comparing American (USE) and Standard Southern British English (BRE). Overall, coarticulatory nasalization was greater in USE than in BRE. Vowels were indeed more nasalized, the nasal consonant less nasalized and the oral togue tip gesture for nasal /n/ was strongly lenited in USE when compared to BRE. The velum was stable in both varieties and not earlier in USE. Instead, the time of tongue tip raising peak velocity was close to the tongue tip maximum for USE, causing a shift in the acoustic boundary towards N (and lengthening the vowel), causing a greater overlap of the velum with the vowel and giving the illusion that the velum gesture aligns earlier in USE. For these voiced contexts, the suggestion is that the reduction of the tongue tip gesture causing coda reduction is the most important factor responsible for the increase of the vowel nasalization in USE.
In the light of the results from Cunha et al. (*in press*), the main aim of the current paper is to extend their analyses to the voiceless context, by comparing /nt/ and /nd/ contexts in the same varieties of English. Two main predictions follow from this model, on the assumption that /nd/ shows less coarticulatory nasalization then /nt/. **i.** /nt/ has greater nasalization in the vowel and shorter nasal coda then /nd/, at least for USE; **ii.** The velum gesture has the same magnitude and temporal extent in both contexts, if vowel nasalization develops as a consequence of an earlier rephasing of a stable velum gesture.

**Methods.** Real-time magnetic resonance imaging (rt-MRI) data were acquired from 27 native speakers of standard Southern British English (SBE13 female) and 16 native speakers of US English (7 female). The US speakers were approximately equally distributed between Midland, Northeast, Southern, and West regions. The recording took place at the Max Planck Institute for Multidisciplinary Sciences in Göttingen, Germany. A 3-Tesla MRI system was used for image acquisition (Magnetom Prisma Fit, Siemens Healthineers, Erlangen, Germany) and an Optoacoustics FOMRI III fiber-optic dual-channel microphone (Optoacoustics Ltd) recorded audio simultaneously. The images were processed in Matlab. Every image in the dataset was first aligned to a reference image. After registration, a semi-polar grid consisting of 28 lines was applied semi-manually to the vocal tract, reaching from the glottis up to the alveolar ridge (see Carignan et al., 2021 for further details). For kinematic analysis of velum lowering, a ROI (region of interest) was manually defined around the spatial range encompassing the velum movements, which was then used as dimensions in principal component analysis (PCA). For the acoustics we have calculated the energy below 1kHz based on the YIN algorithm (de Cheveigne & Kawahara, 2002). The materials analyzed here consisted of 14 lexical words selected from a larger corpus (/nt/: bent, pent up, sent, bint, Pinter, sinter, bunt, punt, shunt; /nd/: band, feigned, fund, bend, binned). The words were spoken in the carrier phrase "saw <targetword> about two/four/five/six/ten", with narrow focus on the target word without repetitions.

**Results.** Fig. 1 (left panel) showing the displacement averaged between the peak velocities of velum movement. The main differences between /nt, nd/ trajectories were: (a) the magnitude of /nt/ is less (green usually less than gold) and (b) the lowering gesture for /nt/ is faster (steeper rise in the trajectory for green to the left of the peak) and (c) the /nt/ gesture is shorter. When testing the magnitude of velum, there was no effect of dialect and the displacement was found to be greater for /nd/ than for /nt/ only for the short vowels, not when the preceding vowel is /æ, eɪ/. These preliminary results so far (Fig. 1 left panel) show that the velum vesture is similarly aligned at acoustic vowel onset.

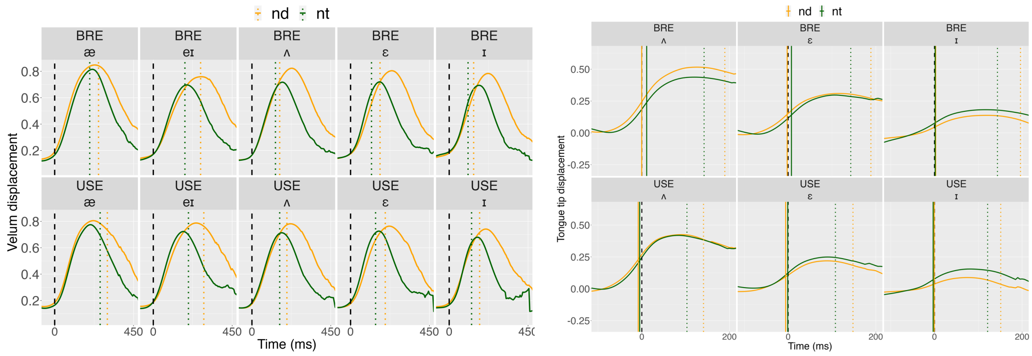


Figure 1: Left: *Displacement of the velum averaged aggregated by dialect, vowel, and /nd, nt/ context after alignment at the acoustic vowel onset (vertical dashed line at t = 0 ms). The green/gold vertical dashed lines for /nd, nt/ are at the times of the acoustic vowel offset. Right: Tongue tip displacement in three of these vowel contexts after aligned at the time of the peak tongue tip raising velocity.*

Fig. 1 (right panel) shows the tongue tip synchronised at peak tongue tip raising velocity (*t* = 0 ms, vertical dashed) with mean time of peak velum opening (solid) and mean time of peak tongue tip displacement (coloured, dotted). The tongue displacements are quite similar in both contexts and there is no evidence for a greater tongue tip undershoot in the /nt/ than in the /nd/ context. We then further analysed the data acoustically in order to determine whether the information for voicing in /n/ was diminished in /nt/ than in /nd/ which could mean that nasalization in the /nt/ coda is more difficult to identify than in /nd/. One of the cues for identifying nasalization acoustically is the presence of energy in the lower part (< 1 kHz) of the spectrum (e.g., Fujimura, 1962; House & Stevens, 1956). Fig 2 shows the dB-SPL level below 1kHz between the onset of /n/ (left vertical dashed line) and the time of the peak velocity of velum raising (dotted green/gold lines for voiced/voiceless). In all contexts and for both dialects, the energy is higher in the /n/ of /nd/ than in the /n/ of /nt/. This suggests that one of the driving forces for nasalization to diminish in the coda in /nC/ clusters where C is voiceless could be that there is a greater drop of the energy under 1 kHz for /nt/ in USE.

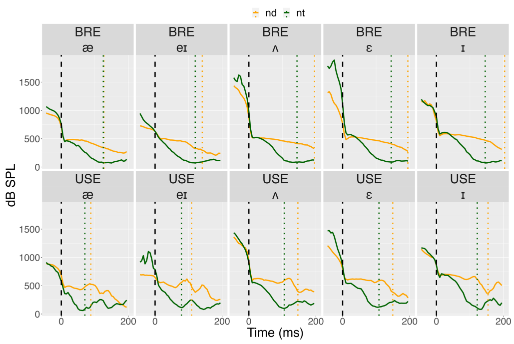


Figure 2: *Energy below 1kHz between the onset of /n/ (left vertical dashed line) and the time of the peak velocity of velum raising (dotted green/gold lines for voiced/voiceless)*

**Discussion.** So far there is little evidence for a leftwards shift of the velum gesture in /nt/ comparing with /nd/, but these analyses are still on progress. On the other hand, the acoustic analysis suggests that one of the driving forces for the diachronic waning of nasalization in a voiceless /nC/ context could be that /n/ is just more difficult to perceive when followed by a voiceless than voiced consonant (Ohala & Busà, 1995; Ohala & Ohala, 1991).

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