Journal of Phonetics 107 (2024) 101365

Contents lists available at ScienceDirect

Journal of Phonetics

journal homepage: www.elsevier.com/locate/Phonetics

Language-specific and individual variation in anticipatory nasal coarticulation: A comparative study of American English, French, and German

Marianne Pouplier [a,*], Francesco Rodriquez [a], Justin J.H. Lo [b,d], Roy Alderton [a,c], Bronwen G. Evans [d], Eva Reinisch [e], Christopher Carignan [d]

[a] Institute of Phonetics and Speech Processing, LMU Munich, Germany
[b] Linguistics and English Language, Lancaster University, UK
[c] Department of Language and Communication Science, City, University of London, UK
[d] Department of Speech, Hearing and Phonetic Sciences, University College London, UK
[e] Acoustics Research Institute, Austrian Academy of Sciences, Vienna, Austria

ARTICLE INFO

Article history:
Received 10 November 2023
Received in revised form 2 September 2024
Accepted 15 September 2024

Keywords:
Coarticulation
Nasality
French
English
German
Individual variability

ABSTRACT

Anticipatory contextual nasalization, whereby an oral segment (usually a vowel) preceding a nasal consonant becomes partially or fully nasalized, has received considerable attention in research that seeks to uncover predictive factors for the temporal domain of coarticulation. Within this research, it has been claimed that the phonological status of vowel nasality in a language can determine the temporal extent of phonetic nasal coarticulation. We present a comparative study of anticipatory nasal coarticulation in American English, Northern Metropolitan French, and Standard German. These languages differ in whether nasality is contrastive (French), ostensibly phonologized but not contrastive (American English), or neither (German). We measure nasal intensity during a comparatively large temporal interval preceding a nasal or oral control consonant. In English, coarticulation has the largest temporal domain, whereas in French, anticipatory nasalization is more constrained. German differs from English, but not from French. While these results confirm some of the expected language-specific effects, they underscore that the temporal extent of anticipatory nasal coarticulation can go beyond the preceding vowel if the context does not inhibit velum lowering. For all languages, the onset of coarticulation may considerably precede the pre-nasal vowel in VN sequences, especially so for English. We propose that in English, the pre-nasal vowel has itself become a source of coarticulation, making American English pre-nasal vowel nasality uninformative about coarticulatory nasalization. Degrees of individual variation between the languages align with the phonological or phonologized role of nasalization therein. Overall, our data further add to our understanding of the non-local temporal scope of anticipatory coarticulation and its language-specific expressions.

1. Introduction

It is a fundamental characteristic of speech that successive sounds are coarticulated, meaning that they are produced in an overlapping fashion, giving rise to contextual variability. In part, coarticulation stems from the physiological characteristics of articulator motion, such as muscle response time and inertia. Yet it has long been recognized that coarticulation sits at the interface between cognitive and physical aspects of speaking: It is a hallmark of skilled speech production and requires learning in both first and second language acquisition (Jang, Kim, & Cho, 2023; Noiray, Wieling, Abakarova, Rubertus, & Tiede, 2019; Oh, 2008). In a much cited study, Whalen (1990) revealed that anticipatory coarticulation co-varies positively with increased time to plan an utterance, providing evidence for the "largely planned" nature of coarticulation. It is also known that coarticulation varies as a function of linguistic utterance structure, such as phrase boundaries (Cho, Kim, & Kim, 2017; Jang, Kim, & Cho, 2018; Li, Kim, & Cho, 2020), and is sensitive to phonotactic regularities (Desmeules-Trudel & Brunelle, 2018) as well as the structure of the lexicon (Scarborough, 2013). This sensitivity to linguistic structure also

* Corresponding author at: Institute of Phonetics and Speech Processing, LMU, Schellingstr. 3, 80799 München, Germany.
E-mail address: pouplier@phonetik.uni-muenchen.de (M. Pouplier).

https://doi.org/10.1016/j.wocn.2024.101365
0095-4470/

means that coarticulation is bound to vary by language. There is a long history of coarticulation research that has sought to pin down the specific linguistic factors which may condition coarticulatory idiosyncrasies of particular languages (among others, Beddor, Harnsberger, & Lindemann, 2002; Clumeck, 1976; Cohn, 1990; Manuel, 1990, 1999; Öhman, 1966; Pouplier et al., 2022).

In particular, a variety of coarticulatory phenomena have been investigated in order to understand whether phonological contrast is a predictor for the temporal domain of coarticulation (among others, Beddor et al., 2002; Lubker & Gay, 1982; Manuel, 1990; Mok, 2012; Noiray, Cathiard, Ménard, & Abry, 2011; Steinlen, 2005). The goal of our current study is to contribute to this research in several respects. For one, we seek to deepen our understanding of the temporal extent of anticipatory coarticulation and its cross-linguistic variation. To this end we present a comparative study on anticipatory nasal coarticulation in General American English (henceforth: English), Northern Metropolitan French (French), and Standard German (German). Secondly, we investigate the temporal domain of coarticulation in these three languages by employing stimuli that offer maximal opportunity for anticipatory coarticulation to occur. This should clearly bring out differences between languages, if present, and also allow us to observe the levels of variability within each language and speaker. Both of these factors – temporal extent and variability – have been used in the past to argue for different views on the origins of coarticulation in the speech production process. Furthermore, we include a relatively high number of speakers per language with the aim of gauging levels of individual variability in relation to language-level differences in coarticulation. Finally, our findings will be interpreted against the different functional roles of nasality in these three languages: In French, nasality is a contrastive feature of the vowel system. For American English, it has been hypothesized that anticipatory vowel nasality is phonologized (Solé, 1992, 1995), meaning speakers may target the pre-nasal vowel allophonically as nasal. This opens the possibility that the pre-nasal vowel has itself become a source of coarticulation in English and nasality should spread anticipatorily from the vowel. If so, this should become apparent in our study by virtue of our stimulus design, which allows for anticipatory nasality to spread over several segments. German anticipatory nasality, finally, has rarely been studied (recent exceptions are Carignan et al., 2021; Kunay et al., 2022), and there is to our knowledge no cross-linguistic study which directly compares German to any other language in this respect. In any case, there is no evidence for contextual nasality being phonologized or phonological in the sense that it has been proposed for American English specifically (Carignan et al., 2021).

The role of phonological contrast in constraining coarticulation has often been investigated with respect to contextual nasality and especially so (but by no means exclusively) for French, a language with a nasal-oral vowel contrast (Cohn, 1990; Delvaux, Demolin, Harmegnies, & Soquet, 2008; Dow, 2020). The general premise of the so-called *contrast hypothesis* is that coarticulation may endanger phonemic distinctions by reducing the acoustic distance of two categories – in this case, oral and nasal vowels. Contextually induced nasality during an oral vowel could cause perceptual confusability if a given language has a phonemic oral-nasal contrast; in other words, temporally extensive phonetic nasalization during an oral vowel could be incorrectly interpreted by a listener as a phonemic nasal vowel. Therefore, contextual vowel nasality in VN contexts should be relatively constrained compared to languages without such a contrast, and should only affect a small portion of the pre-nasal vowel. A classic case in point for such a scenario is presented by French in comparison to English. While English is known for its extensive anticipatory nasalization, in French anticipatory contextual nasality is more limited in scope (Cohn, 1990; Delvaux et al., 2008; Dow, 2020). Such a cross-linguistic difference is consistent with the contrast hypothesis: Nasality may spread maximally in the absence of a contrast but be blocked by a phonological oral-nasal vowel contrast. Observations such as these have been used to argue for models of coarticulation as maximal feature spreading (for an overview, see Farnetani & Recasens, 2010), a point which will be taken up again in the Discussion.

Several arguments have been advanced against such a simple predictive role of contrast for coarticulation. French phonotactics allow a phonologically nasal vowel to follow, but not to precede a nasal consonant: *ṼN, but not NṼ, is illicit. This would, from a contrast perspective, predict extensive anticipatory coarticulation for VN but limited carryover coarticulation in NV contexts. However, the opposite is actually the case: Carryover coarticulation in French NV is more extensive than anticipatory coarticulation in VN, meaning extensive contextual nasal spreading is observed in the very context (post-nasal) in which the oral-nasal vowel contrast occurs phonotactically. During an oral vowel *preceding* a nasal consonant on the other hand, anticipatory nasality is relatively more limited (e.g., Delvaux et al., 2008; Dow, 2020), even though phonotactically there is no potential for confusion. This raises the question of how much perceptual confusability contextual nasality actually creates, especially given that other cues to the realization of a phonologically contrastive nasal vowel are known to exist. In observing that the degree of nasal airflow in contextually nasalized oral /ɛ/ in NVN sequences of French was as high as the nasal airflow in phonologically nasal /ɛ̃/, Delvaux et al. (2008) posited that the distinction between /ɛ/ and /ɛ̃/ was nonetheless maintained due to their different oral configurations (see also Carignan, 2014, 2017).

Clumeck (1976), comparing anticipatory nasality in six languages based on 1–3 speakers per language, observed that some of the languages with distinctive nasalization in his sample (French, Hindi, Amoy) were characterized by a comparatively lesser degree of contextual nasality, while a single speaker of Brazilian Portuguese (the only one recorded in that study) produced comparatively more contextual nasality. Scarborough, Zellou, Mirzayan, and Rood (2015) provide evidence for anticipatory vowel nasality in Lakota, a language with an oral-nasal vowel contrast. As in French, carryover coarticulation exceeds anticipatory coarticulation in Lakota.[1] There is nonetheless clear vowel nasalization in VN at least from the

[1] Note that the relative greater extent of carryover coarticulation in Lakota and French should not be deduced from the presence of an oral-nasal vowel contrast in both languages: In a variety of Australian languages that do *not* contain such a contrast, carryover nasalization has likewise been reported to exceed the extent of anticipatory nasalization (Butcher, 1999; Butcher & Loakes, 2008; Stoakes, Fletcher, & Butcher, 2020).

vowel midpoint onwards. It is also apparent in their data that vowel nasality in ṼN contexts is higher compared to VN, overall and especially initially. They thus argue that anticipatory vowel nasalization does not necessarily lead to neutralization, as the nasal-oral vowel contrast is maintained in both the time course and the strength of nasality (although they do observe contrast neutralization for some of their speakers in the carryover context). While the authors see a role for functional, perceptual pressures (sufficient contrast) in shaping the patterns of coarticulation, they call for a more nuanced view by suggesting that the time course of how nasality is realized for a nasal vowel may change depending on coarticulatory context (for arguments on the relevance of the time course of nasality, see also Delvaux et al. (2008) and Huffman (1990)). This would once more support coarticulation being under speaker control in a temporally very fine-grained fashion. Overall, the presence or absence of a contrast does not by itself seem to be sufficient to globally predict the temporal domain of anticipatory coarticulation, either in a given language or across languages.

While contextual nasality is often discussed in the context of language-specific coarticulation, there are relatively few directly comparative studies of languages *with* a nasal-oral contrast. One such study was referred to earlier: Clumeck (1976) noted that a Brazilian Portuguese speaker (the only one recorded) showed a different coarticulation pattern compared to other languages with contrastive vowel nasality. Clumeck's study has very few speakers per language, which means that inevitably individual speakers are taken to be representative for the entirety of a given language community. Another notable exception is Brkan (2018; Brkan, Amelot, & Vassière, 2014), who compared anticipatory nasalization, measured by means of a piezoelectric accelerometer, in American English, French, Bosnian, Norwegian, and Urdu, presenting data from five speakers per language. French and Urdu have contrastive vowel nasalization, while the other languages studied do not. In her data, all languages are characterized by anticipatory nasality spanning 50–80% of the pre-nasal vowel, sometimes even 100%. Unsurprisingly, American English again shows the most extensive vowel nasalization, confirming previous observations. Interestingly, Norwegian and French align in terms of the relatively lowest degree of anticipation while Bosnian and Urdu speakers fall between English and French/Norwegian. This is a remarkable result, since it suggests variability in the scope of anticipatory coarticulation among languages with a phonological contrast (French and Urdu), which is unexpected from a general contrast perspective. Furthermore, Brkan's work highlights that among languages *without* a nasal-oral vowel contrast, anticipatory coarticulation seems to be fine-tuned in language-specific ways. She concludes that contrast fails to predict the temporal domain of anticipatory vowel nasalization across languages. Yet a different argument concerning contrast is put forward by Desmeules-Trudel and Brunelle (2018): The authors studied Québécois French and Brazilian Portuguese, both of which have an oral-nasal vowel contrast. They come to the conclusion that contrast does limit both the extent of coarticulation and its variability, yet only in interaction with phonotactic regularities of the two languages rather than at a global level.

Particularly relevant for our current study is Solé's (1992, 1995) work on anticipatory nasality in American English and Peninsular Spanish. She observed that, under variable speech rate, Spanish anticipatory nasality remains durationally fixed in absolute time irrespective of pre-nasal vowel duration, whereas in English, contextual nasality changes with vowel duration and is proportionally constant. This led her to propose that vowel nasality has become phonologized in English, with speakers targeting a [+nasal] vowel. In Spanish, however, coarticulation is a function of the kinematic characteristics of the velum: Velum opening is timed to "nasal consonant onset" (which she determines from the acoustics) and "reflect[s] the time needed by the velum to open the velar port for the nasal consonant at the optimal articulator velocity." (Solé, 1995, p. 9) Solé also decidedly argued against a predictive role of contrast for coarticulation. Given her own results on Spanish and by reviewing the literature (at that time) on anticipatory nasal coarticulation in a variety of other languages, she concludes that languages generally show a minimal amount of coarticulation, which arises from "a physiological time constraint" (p.30) on velum opening with the only exception being American English. She argues that American English has undergone sound change by which contextual nasalization has become allophonic (see also Beddor, 2009; Beddor, Coetzee, Styler, McGowan, & Boland, 2018), while languages without such a sound change, like Spanish, anticipate nasality only to the degree that is physiologically necessary to ensure a fully open velum at the nasal consonant onset. This minimal anticipation interval will be invariant, no matter the durational variation of the coarticulated segments. This, in her view, makes coarticulation a low-level, physiological phenomenon. A similar state of affairs in Santo-Domingo vs. Buenos Aires Spanish has been used by Bongiovanni (2020, 2021) to support Solé's view of a categorical separation of coarticulatory phenomena into "intended" (Bongiovanni, 2021, p. 7) allophony and low-level, mechanical coarticulatory nasality. Dow (2020) argues for a differentiation between mechanical and controlled coarticulation within French as a function of vowel quality. In his view, contextual nasalization of high pre-nasal vowels arises from a low-level property of speech production since their contextual anticipatory nasalization is more variable compared to mid and low vowels. Since French high vowels are more strongly nasalized than mid and low vowels (previously also reported by Delvaux et al. (2008)), he concludes that coarticulation is planned (actively blocked) for mid and low vowels only. In sum, previous literature has used relative differences in both temporal extent and variability to argue for a distinction between planned and low-level, mechanical coarticulation.

Overall, the literature paints a multi-faceted picture of anticipatory nasal coarticulation and between-language differences. However, few studies directly compare languages with a sufficiently large number of speakers to reliably tease apart individual differences from language-level effects. The informative value of meta-comparisons between studies is limited due to numerous methodological differences, and the problem of low participant numbers cannot be alleviated. Virtually any study on coarticulation, nasal or not, remarks on high levels of inter-speaker variability and the presence of speaker-specific 'strategies' or 'preferences.' The corollary of this is that we cannot be sure to what extent speaker-level effects actually reflect language-level effects. In the context of labial coarticulation, Noiray et al. (2011), in their study of anticipatory lip rounding in Canadian French and American English, came to the conclusion that there are no language-specific differences, but only individual speaker preferences. Moreover, it is currently not well understood how the concept of individual speaker grammars (Beddor, 2009) within a language-community (see below) relates to linguistic structure being a possible shaping factor in coarticulation differences between languages.

Individual variability, while long treated as experimental noise of unclear theoretical relevance, has come to be at the center of attention in recent research. Work on nasality in particular has put this individual variation at the heart of explanations for sound change. Individuals within a language community may differ systematically in how they produce and perceive coarticulation, according to their own speaker-specific grammar (Beddor, 2009; Beddor et al., 2018; Zellou, 2017). Nonetheless, phonological contrast should constrain how variably a given acoustic cue is produced within individuals of a given language community (Hauser, 2021). The implications of this shift in perspective towards intra-language variability for our understanding of between-language variation in coarticulation are yet to be explored. In our current study, we present data from 27 to 30 speakers per language, which allows us to ascertain the robustness of language-specific effects against the range of individual variability within each language.

It is possible that the function of contrast is not necessarily to constrain the temporal extent of coarticulation; rather, the presence of a contrast may lead to a relatively lower degree of both within and between speaker variability in a given language compared to languages without a contrast. Such an argument is presented by Hauser (2021) when she discusses whether phonological contrast is a determinant of the extent of token-wise and/or contextual variability. She proposes contrast-dependent variation according to the weight assigned to a given cue in a given language. For example, in Hindi negative VOT is consistently produced across speakers since it is a primary cue to phonological voicing. In English, as an aspirating language, prevoicing is free to vary by speaker. For our present study, this hypothesis of contrast-dependent variation would predict a low level of variability in French, both within and across speakers. In American English, a final oral-nasal consonant contrast can, at least in specific contexts, be systematically cued by contextual nasalization, as argued by Beddor (2009). This would lead us to expect that American English should align with French in terms of a low level of individual variability compared to German. Solé's view of a phonologized contextual vowel nasalization in English would likewise predict a relatively low level of variability. Beddor et al. (2018), on the other hand, argue for American English that the phonological equivalence relationship between vocalic and consonantal nasality differs by individual, according to an individual's grammar of speech production. This could condition a low within-speaker variability, comparable to French, but a higher between-speaker variability, since some speakers may cue the nasal consonant on the vowel to a greater degree than others. We take note of the fact, however, that Beddor and colleagues investigated a $VNC_{obstruent}$ context (e.g., *bent*) specifically, and that this context is not part of our current study. However, in any scenario, German would be the most variable language, since there are no constraining factors. Yet a further possibility is that velum opening in German is purely mechanical as it was proposed to be for Spanish by Solé (1992). In that case, we expect anticipatory coarticulation to be consistently constrained to a narrow time window before the nasal consonant onset. Note that Solé found English and Spanish speakers to be "strikingly consistent in their behavior" (p. 39) within their language group, despite the marked difference in the temporal domain of coarticulation. That is, different origins of coarticulation may not necessarily condition different levels of variability.

In sum, if functional pressure due to the nasal-oral vowel contrast in French is a shaping force in coarticulation, we would expect anticipatory coarticulation in French to be most constrained and to cover only a small part of the vowel. We expect a comparatively low degree of variability within and between speakers. Given that, by virtue of our stimulus material, we allow for anticipation to occur earlier than the pre-nasal vowel, we expect there to be a pronounced difference between French and the other two languages. From previous work on German (Carignan et al., 2021), contextual vowel nasalization should be moderate in this language, but since there is no existing comparative work, it is not clear a priori where German will fall in relation to English and French, in particular when a relatively large window of opportunity for nasal coarticulation is available. In any case, German speakers should be most variable since there is no attested phonological or phonologized function of anticipatory vowel nasality. For English, where vowel nasality has been reported to be a systematic cue to the final consonant contrast (in certain contexts) or a nasal vowel is targeted, we expect the most extensive spread of coarticulation. Phonologization of contextual vowel nasality would predict a relatively lower level of variability for English speakers, yet if the cue trading relations observed by Beddor and colleagues generalize beyond the $VNC_{obstruent}$ context used in their study, a higher level of individual variability would be expected.

2. Methods

2.1. Participants

We present data from 30 native speakers of German and of English, and 27 speakers of French.[2] All participants reported using their native language on a daily basis and being speakers of the respective standard variety. All German speakers were recorded at LMU in Munich. Sixteen of the American and 15 of the French speakers were recorded in Munich; the other speakers were recorded at University College London. The technical recording setup was identical in both labs. Speaker recruit-

[2] We recorded 30 French, 33 German, and 34 American speakers. 9 speakers had to be excluded from analysis entirely due to technical problems with the recording device or because it turned out that they did not fit the recruitment criteria (i.e., they were not speakers of the standard varieties). All of these speakers were excluded prior to data analysis. One German speaker was excluded because they consistently inserted prosodic breaks in their productions immediately before the target word.

Table 1
Carrier phrases by target consonant position and language with example minimal pair set from the nasal and oral conditions, in both orthography and broad transcription, as well as an English gloss for French and German. The interval for analysis (ROI) is underlined, and the target consonant is in bold face in both the orthography and the transcription. The obstruent of *Cleo/Cléo/Kleo* serves as a hard boundary for the anticipatory spreading of coarticulation and thus delimits the ROI. To control for VOT differences between the languages, the ROI onset was defined as the boundary between the lateral and the following vowel of *Cleo/Cléo/Kleo*. In the initial condition, the ROI therefore corresponds to the vowel sequence in *Cleo/Cléo/Kleo*.

Position of target consonant	Language	Nasal condition	Oral condition
Initial	English	He'll tell Cleo ***m**at* soon. /hiːl tɛl kliːoʊ **m**æt suːn/	He'll tell Cleo ***p**at* soon. /hiːl tɛl kliːoʊ **p**æt suːn/
	French	Je dis à Cléo ***m**ot* samedi. /ʒə di a kleo **m**o sam(ə)di/ ‘I say to Cléo________on Saturday.’	Je dis à Cléo ***p**eau* samedi. /ʒə di a kleo **p**o sam(ə)di/
	German	Er las Kleo ***M**acht* zweimal vor. /eːɐ laːs kleːoː **m**axt tsvaɪmaːl foːɐ/ ‘He read________to Kleo twice.’	Er las Kleo ***P**acht* zweimal vor. /eːɐ laːs kleːoː **p**axt tsvaɪmaːl foːɐ/
Non-initial	English	He'll tell Cleo *rhy**m**er* soon. /hiːl tɛl kliːoʊ raɪ**m**ɚ suːn/	He'll tell Cleo *ri**p**er* soon. /hiːl tɛl kliːoʊ raɪ**p**ɚ suːn/
	French	Je dis à Cléo *l'é**m**is* samedi. /ʒə di a kleo le**m**i sam(ə)di/	Je dis à Cléo *lé**p**i* samedi. /ʒə di a kleo le**p**i sam(ə)di/
	German	Er las Kleo *Lei**n**e* zweimal vor. /eːɐ laːs kleːoː laɪ**n**ə tsvaɪmaːl foːɐ/	Er las Kleo *Lei**t**e* zweimal vor. /eːɐ laːs kleːoː laɪ**t**ə tsvaɪmaːl foːɐ/

ment was shared across the labs to be able to enlist enough participants within the foreseen timeframe of the project. Average participant age by language was: English 28.4 (SD 8.2), French 31.1 (SD 7.2), German 26.5 (SD 5.8). For English 21 females and 9 males were included in the analyses, for French 21 females and 6 males, for German 20 females and 10 males. Due to the imbalance in gender sampling across the languages, we include gender as a nuisance variable (additive fixed factor) in the statistics but will not comment on this factor any further since it is of no interest to our main research question.

2.2. Stimuli and recording procedure

Target words were chosen as minimal pairs with a nasal or oral target consonant. The target consonant was either in initial (e.g., English ***m**at* – ***p**at* /**m**æt – **p**æt/) or non-initial position, which comprises word-medial and final (e.g., English *rhy**m**er* – *ri**p**er* /ɹaɪ**m**ɚ – ɹaɪ**p**ɚ/, *ra**n*** – *ra**t*** /ɹæ**n** – ɹæ**t**/). The oral control consonant was a voiceless oral stop, in order to ensure that the velum was in a closed position at the oral target consonant onset (due to the aerodynamic requirement for intra-oral pressure build-up during the stop). For all languages, we chose a set of words with an initial target nasal/oral stop and a set of words with a non-initial target nasal/oral stop. The initial nasals allowed us to observe to what extent nasality would spread anticipatorily across a word boundary in our three languages. For each language, 15 stimulus minimal pairs were constructed, five with the target sounds (nasal/oral stop) in initial and ten in non-initial position. For the non-initial stimulus words, in which the nasal consonant could be in word-medial or final position, the nasal was always the third segment of the target word (with the exception of the English word *own*). For German, due to experimenter error, there are only 8 minimal pairs in the non-initial condition. The full set of minimal pair stimuli for each language is given in the Appendix.

All target words were elicited in a constant carrier phrase. This carrier phrase was constructed to be as similar as possible across the three languages in terms of length, and number of syllables (see Table 1). Note that French is a head/edge prominence language, while English and German are stress-based, head-prominence languages (Jun, 2014). The sentences were constructed in all three languages as phrases with broad focus (‘neutral declarative’ in Jun & Fougeron's (2000) terminology). In French, the target word is its own accentual phrase, and in German and English the target word is its own prosodic word (in principle, allowing for some variation in any given rendition). That is, in all languages the target word is by canonical realization its own phrase with comparable boundary strength at some level lower than the intermediate phrase (ip).

The carrier phrase in all languages contained a voiceless velar obstruent (the /k/ of “Cleo/Cléo/Kleo”, henceforth *Cleo* for simplicity) which served as a landmark to delimit the *region of interest* (ROI) for analysis, i.e., it demarcated the maximal available window for anticipatory nasal coarticulation and hence the time interval of analysis. In practical terms, the beginning of the ROI was, for all conditions, the boundary between /l/ of *Cleo* and the following vowel <e> (instead of the /k/ release due to the VOT differences between our languages)[3]; the end of the ROI was the onset of the nasal/oral target consonant. The onset and offset of the target consonant were defined as the beginning and end of the relevant oral closure in the acoustic signal (see Fig. 1). Nasal consonant duration and average intensity of the nasal consonant as used in the analyses was calculated over this interval. In Table 1 the ROI preceding the (bold face) nasal/oral target consonant of an example stimulus pair is underlined.

The segmental content within the ROI was chosen such that only oral vowels and approximants precede the target consonant, neither of which phonetically control velar opening and thus in principle allow for anticipatory nasal coarticulation to occur. Importantly, the minimal pair method thereby ensures that any segment-intrinsic velum height characteristics of the segments of the ROI can be factored out (Bell-Berti & Krakow, 1991). This is so because any segment-intrinsic

[3] French is generally classified as a true voicing language; German and English both are aspirating languages. In both English and German the lateral can be partially or fully devoiced due to the long VOT (Pouplier et al., 2022).

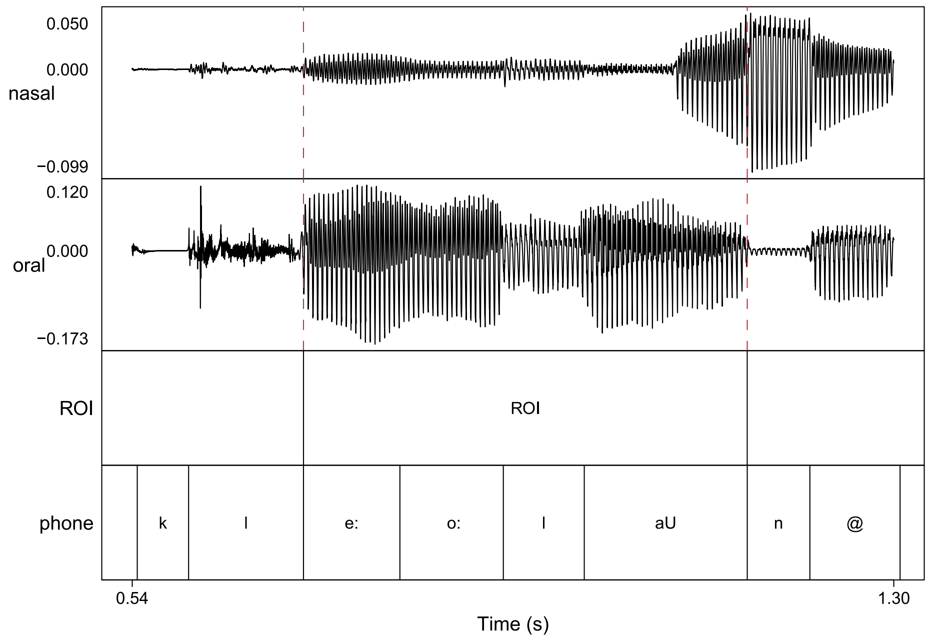

Fig. 1. Illustration of a stereo recording as output from the nasometer, together with our segmentation of the Region of Interest (ROI). The recording is from a trial containing the German target word /laʊnə/. The segmental boundaries other than those of the target consonant and preceding vowel are given for orientation only and were not used in the analyses. Only the nasal channel (top oscillogram) was used for analysis. The ROI is defined as the interval from the beginning of the first vowel of Cleo (here, /eː/ of German /kleːo/) to the acoustic onset of oral closure for the oral/nasal target consonant (here, /n/) and is demarcated by dashed red lines in the graph. Notice how nasal intensity in the top oscillogram begins to rise during the /aʊ/ diphthong preceding the nasal consonant. The obstruent onset /k/ is a hard boundary for nasal anticipation; the ROI thus demarcates the maximal possible window of coarticulatory anticipation. For practical reasons (see main text), the lateral-vowel boundary served as onset of the ROI interval over which coarticulation was determined in our analyses. Any segment-inherent velum opening differences as they are apparent here in the initial parts of the ROI are factored out of our quantification of anticipatory coarticulation by computing a nasal-oral condition difference curve for each minimal pair during data processing (see Section 2.3). The graph was generated using praatpicture (Puggaard-Rode, 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

velum height characteristics should be the same across matched nasal and oral conditions which only differ in the orality/nasality of the target consonant. The degree of nasalization was estimated using a nasometer which comprises acoustically separated oral and nasal microphones. Our measure, as detailed in the Section Data Processing, only considers differences in nasal intensity between a given nasal-oral minimal pair. Fig. 1 gives an example of the acoustic stereo signal as recorded from the nasometer device together with our segmentation of the ROI. The oral channel oscillogram is shown for reference only; only the nasal channel signal was analyzed (see below). Fig. 2 illustrates the nasal channel signal recordings for three repetitions of a given minimal pair.

For any time normalization reported in the analyses, the ROI served as the normalization interval by mapping the samples of a given ROI linearly onto a [−1, 0] interval, with −1 being the beginning of the ROI and zero being the onset of the target consonant. Note that for the initial condition, the ROI comprises only the vowel sequence of the carrier phrase word *Cleo*.

Three repetitions of each token were recorded, and the stimuli were presented in randomized blocks with each target word occurring once per block. The data recording session was part of a larger experiment on the characteristics of coarticulation of multiple articulators across and within multiple languages. Note that each participant only recorded the stimuli in their native language. The Appendix gives the full set of stimuli recorded for each language.

Data were recorded at a sampling rate of 44.1 kHz in a sound attenuated booth, using a nasometer device which consists of two microphones separated by an acoustic baffle. Participants were asked to hold the device so that the acoustic baffle rested on the upper lip, thus allowing the separate acoustic radiations from the nose and mouth to be captured by the respective microphones. This resulted in a stereo recording with the nasal and oral waveforms in separate channels (Fig. 1). *SpeechRecorder* (Draxler & Jänsch, 2004) was used for stimulus presentation and data recording. Participants were familiarized with the stimuli before the recording and then instructed to read the sentence displayed on the computer screen in front of them as naturally as possible as a single phrase. Any renditions that contained a pause and/or a glottal stop in the ROI were excluded from analysis since the acoustic

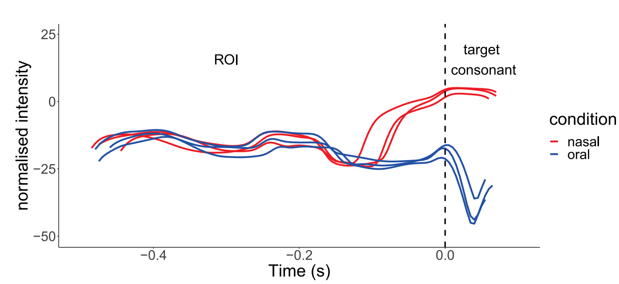

Fig. 2. Example for normalized nasal intensity signals extracted for all three repetitions of the German minimal pair /laʊ**n**ə – laʊ**t**ə/ over the ROI plus the target consonant by one speaker (the same as in Fig. 1). Only the nasal channel signal is shown for both the oral and nasal conditions. Signals were lined up at the onset of the nasal/oral target consonant defined by the acoustic onset of closure. The line-up point is marked by a dashed vertical line on the graph. Positive time points (> 0) occur during the target consonant interval; negative time points occur during the ROI.

signal drops to zero in these cases. This also means that only renditions that were pronounced as a single IP up to the target word were included (renditions with prosodic breaks after the target word were retained since these breaks do not interfere with our analyses).

Post-recording, all sound files were processed in *Praat* (Boersma & Weenink, 2022). Each channel was filtered with a Hann pass-band filter with cut-off frequencies of 80 Hz and 10 kHz prior to intensity computation (in db_{SPL}). Nasal channel intensity of each trial was normalized by subtracting the mean total intensity (oral and nasal) of the given trial. Further analyses used this normalized nasal channel intensity only. It is important to keep in mind for the remainder of the paper that we only refer to the time series of normalized nasal channel intensity during the ROI interval, be it in the oral or nasal conditions.

2.3. Data processing: Operationalizing onset of coarticulation

In the context of our experiment, we define the onset of coarticulation as the timepoint at which a given nasal condition intensity curve diverges from the corresponding oral condition intensity curve within a minimal pair; see Fig. 2 for a visual impression of oral-nasal condition curve divergence. We thereby proceeded as follows: Normalized nasal intensity curves for the oral control tokens were averaged in raw time across the three repetitions. This per word-pair nasal intensity average of the oral condition served as reference against which the onset of coarticulation was determined for the nasal condition. From each individual nasal token, the average oral condition curve was subtracted (cropping on the left edge to whichever was the shorter curve), resulting in a nasal intensity difference curve. This difference curve was then time- and magnitude-normalized and subjected to an iterative sigmoid fitting procedure to determine the onset of coarticulation, as illustrated in Fig. 3.

For the sigmoid fitting procedure we used the sicegar R package (Caglar, Teufel, & Wilke, 2018), which was originally developed to fit time-intensity curves with nonlinear growth and decay dynamics in biology. We used this package to fit several sigmoid versions to each time- and magnitude-normalized difference curve (a single sigmoid, and two versions of a double-sigmoid fit to deal with the variation in the fall-rise patterns in the difference curves). The relative best fit was chosen as the sigmoid model with the lowest Akaike information criterion (AIC). For this chosen sigmoid, a line tangential to the midpoint of the sigmoid rise was computed. The point at which this tangential line intersects with the lower asymptote was translated back into absolute time. This time-point demarcates the *divergence point* for each nasal token and constitutes our working definition for the onset of coarticulation. The divergence point, therefore, is the point at which we can statistically predict a following oral or nasal consonant.

Outliers were removed according to the following criteria. Tokens for which the predicted divergence point was outside the region of interest were excluded from analysis (N = 44). Further, in order to have an absolute measure of the quality of the sigmoid fit, we computed, for each difference curve, the RMS of error from the fitted sigmoid model. On a by-language basis, the 5% of difference curves with the highest

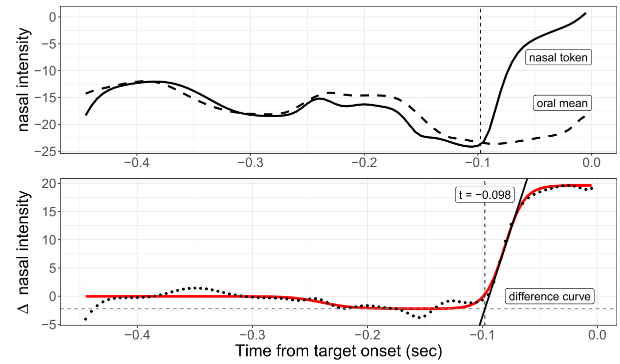

Fig. 3. Illustration of the difference curve and sigmoid fitting method used for divergence point calculation. Zero time on the x-axis is the acoustic onset of the oral closure associated with the target consonant. Top panel: Mean-corrected nasal intensity curves from a single nasal token (solid line) and the mean of the oral condition (dashed line) from a given minimal pair. Lower panel: The dotted line is the difference curve obtained by subtracting the oral mean from the nasal condition curve. The solid red line in the lower panel is the sigmoid fitted to the difference curve. The black solid line in the lower panel is the line tangential to the midpoint of the sigmoid rise. Its intersection with the lower asymptote, here marked as point t, is how we operationalize the onset of nasal-oral divergence, i.e., the onset of coarticulation. The dashed vertical line, across the two panels of the graph, marks the divergence point t calculated for this particular difference token. Note that the sigmoid fitting is done on time- and magnitude-normalized difference curves. The divergence point is then mapped back onto the raw data as plotted here. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Number of difference curves per language and nasal consonant position entering the analyses.

Language	Word-Initial	Non-Word-Initial
English	417	640
French	381	728
German	410	636

RMS values were defined as outliers and removed from analysis (N = 171). Table 2 gives the number of difference curves per language included in the following analyses.

2.4. Inferential statistics

Unless stated otherwise, we ran mixed models using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015). Significance is evaluated by *anova* model comparisons or, for complex models, the *step* function of the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017). Models always included a random intercept for speaker and word pair. Gender was included as a nuisance variable. Initially, recording site (London, Munich) was also entered into the models but proved to be consistently irrelevant and was thus disregarded. The variance accounted for by a selected statistical model was computed using the MuMin package (Bartoń, 2022). Post-hoc tests were conducted using the emmeans package (Lenth, 2022). Significance was assumed at $p < 0.05$.

3. Results

3.1. Initial condition

Recall that the initial condition served to estimate the extent to which nasality spreads anticipatorily beyond a word boundary in our languages, especially given the prosodic differences between French as a head/edge prominence language with the target word being its own accentual phrase, and English and German as stress-based, head-prominence languages (Jun, 2014) in which the target word forms a prosodic word. While the role of prosodic boundary is not the topic of our current investigation, and there are no direct predictions regarding nasal coarticulation across a boundary in these languages, a basic comparison of the effect of word boundary in these three languages is necessary to be able to compare possible longer distance effects in the following sections. Table 3 gives the mean ROI duration and divergence points per language; Fig. 4 gives the divergence point distribution in absolute and normalized time. Recall that the normalization interval is the ROI which begins with the <e> vowel of the carrier phrase word *Cleo/Cléo/Kleo* and ends with the onset of the acoustic closure of the target consonant. In the initial condition the ROI is thus equivalent to the <eo> vowel sequence of the carrier phrase word *Cleo/Cléo/Kleo*.

On average for all languages the divergence point is 65–85 ms before the onset of the target consonant. French shows less anticipation compared to English and German but also has a somewhat shorter mean ROI duration. In proportional time, the peak of the French distribution is closer to zero (the onset of the target consonant) but is skewed to the left. In order to test whether divergence point differs significantly as a function of language, we ran a mixed model with the log-transformed divergence point in absolute time as a dependent variable. Language, ROI Duration, and their interaction were independent variables. The main question is whether we observe an effect of Language, which in the initial condition is mainly informative as to the role of the word boundary in our data. The ROI Duration term in the model here and particularly in the following analysis of the non-initial condition serves to test whether the onset of coarticulation differs as a function of durational variation in the segmental context material preceding the nasal, that is, whether anticipatory nasality varies with duration of the available anticipatory time window.

Table 3
Mean and standard deviation for the divergence point and for ROI duration for the initial condition. For the divergence point, smaller numbers mean earlier onset of coarticulation.

Language	Divergence Point(in seconds)	ROI Duration (in seconds)
English	−0.085, SD 0.04	0.22, SD 0.044
French	−0.065, SD 0.03	0.19, SD 0.043
German	−0.084, SD 0.04	0.20, SD 0.042

The initial model includes an interaction of Language and ROI Duration, since a previous study reported the duration of anticipation as a function of context segment duration to be language specific (Solé (1992), see Introduction). Recall that, as laid out in the Introduction, a mechanistic view on velum opening as expressed by Solé (1992) for Spanish and Dow (2020) for French predicts that in the case of low-level coarticulation, the divergence point should not vary with the available coarticulatory window.

The best model selected by the *step* function included an additive effect of Language and ROI Duration, but no interaction (Language: $F(2, 77.6) = 5.7$, $p = 0.005$; Duration: $F(1, 436.2) = 7.8$, $p = 0.005$). This means that the languages differ significantly in divergence point, but that variation in ROI duration affects anticipation in all languages to an equal degree. Posthoc results were: German – English: $p = 0.81$; German – French: $p = 0.006$, English – French: $p = 0.04$. The variance accounted for by the fixed effects is, however, very low and amounts to only 10% as opposed to 43% accounted for by the model including random effects. This means that the influence of language and ROI duration, although significant, is only weakly present in the initial condition. The results fall along the lines as expected from both a contrast and from a prosodic perspective with French differing from the two other languages. A model on normalized time as the dependent variable, testing for a main effect of Language on the divergence point, gives no significant main effect of Language ($\chi^2(2) = 3.89$, $p = 0.14$). This would suggest that the significant divergence point differences in raw time are at least partially due to vowel sequence duration (ROI) differences between the languages, even though these differences are of moderate magnitude (see Table 3). Proportional ROI nasalization is, in the initial condition, the same across our language sample.

We conclude that anticipatory nasalization occurs in principle across a word boundary in all three languages to a proportionally equal degree, despite the word boundary being prosodically an accentual phrase boundary in French, but a prosodic word boundary in English and German. We will return to the potential influence of prosodic differences between the languages in the Discussion. All languages show variation in anticipatory nasalization as a function of ROI duration (here, vowel sequence duration of *Cleo*), with a greater portion of vowel nasalization the longer the ROI duration. For the remainder of the paper, we will concentrate on the non-initial condition, which is the main focus of our study.

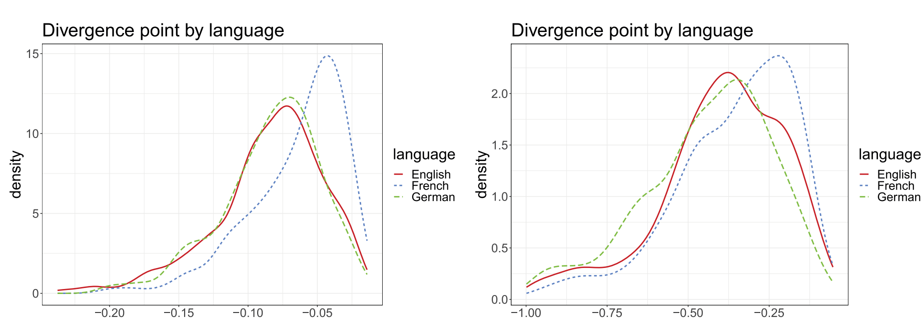

Fig. 4. Divergence point distribution for each language in absolute (left) and proportional (right) time for the initial condition. Zero is the onset of the target consonant; smaller numbers mean earlier onset of coarticulation.

3.2. Non-initial condition

3.2.1. Between-language variation

We begin by comparing ROI duration for the non-initial condition for our languages. Recall again that the ROI is the maximal possible window of coarticulation which we consciously designed to be larger than the preceding vowel in this non-initial condition. Table 4 shows English and German to be fairly similar in terms of ROI duration, while French has, as in the initial condition, a shorter ROI on average. This may be due to variation in inherent vowel duration or to speech rate differences. The size of the standard deviation is comparable in the three languages, meaning that the opportunity to observe variation in divergence point as a function of ROI duration (which was not explicitly manipulated in our experiment) should be comparable.

To give a visual impression of the data, we give in Fig. 5 the smoothed average difference curves by speaker, separately for the three languages, in both absolute and normalized time. A single curve represents a given speaker's nasal-oral difference curve, averaged over all productions by that speaker.

Table 4
Mean and standard deviation for the divergence point and ROI duration by language for the non-initial condition. For the divergence point, smaller numbers mean earlier onset of coarticulation.

Language	Divergence Point (in seconds)	ROI Duration (in seconds)
English	−0.19, SD 0.10	0.453, SD 0.083
French	−0.09, SD 0.05	0.364, SD 0.077
German	−0.13, SD 0.08	0.457, SD 0.084

Fig. 6 gives the distribution of the divergence points (onset of coarticulation) by language in absolute (left) and proportional (right) time. Clearly, the distribution of divergence points in English is considerably wider than the one for French, which has a much tighter distribution. By visual impression, German falls between the two other languages (also evident in the means in Table 4), although in proportional time it is arguably more similar to French.

We built a statistical model with log-transformed, absolute divergence point as the dependent variable. For fixed effects we included Language with ROI Duration, the interaction of Language with Nasal Consonant Duration, plus additive effects of Nasal Intensity of the nasal target consonant (averaged over its duration, see Methods), and Number of Syllables of the target word, since the languages differ in how many mono- and disyllabic stimulus words were recorded (see Appendix). Model comparison using the *step* function resulted in a model with fixed additive effects of Language ($F(2, 52) = 11.6$; $p < 0.001$) and ROI Duration ($F(1, 515.4) = 35.2$, $p < 0.001$) only. In this model, the fixed effects of Language and ROI Duration account for 26% of the variance; the model in total for 55%. A pairwise Tukey post-hoc comparison proved English to differ significantly from both French and German, but the latter two did not differ significantly from each other (English – French: $p < 0.001$; English – German: $p = 0.006$;

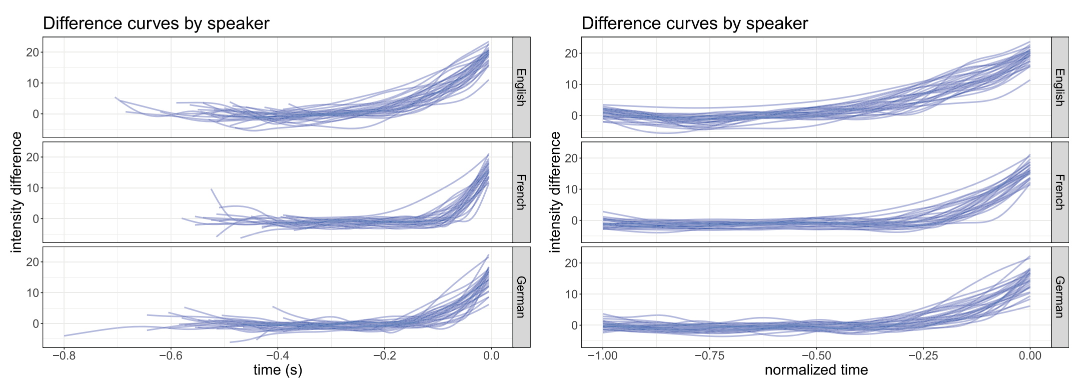

Fig. 5. Smoothed average difference curves by speaker for each language in absolute (left) and proportional (right) time for the non-initial condition. Each line presents a mean nasal-oral difference curve of an individual speaker. Zero corresponds to the acoustic oral closure onset of the target segment. The curves were gam-smoothed in ggplot2 using the formula = y ∼ s(x, bs = “cr”, k = 15).

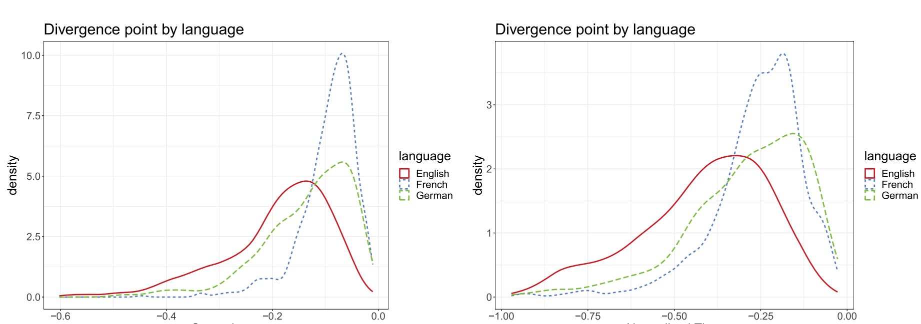

Fig. 6. Divergence point distribution by language in absolute (left) and proportional (right) time, non-initial condition. Zero is the onset of the target consonant; smaller numbers mean earlier onset of coarticulation.

French – German: p = 0.47). We take note of the fact that, as in the initial condition, there is no significant interaction between ROI Duration and Language, but only a significant main effect of each factor. This means that the divergence point varies as a function of ROI duration and, importantly, that this variation is similar in the three languages. Note also that there is a significant effect neither of Nasal Consonant Duration nor Nasal Intensity of the target consonant, suggesting that the temporal extent of anticipatory coarticulation in our data varies independently of the particulars of the realization of the target nasal stop.

For time-normalized values, the statistical result is the same. For a model with time normalized divergence point as the dependent variable and the fixed factors Language, Nasal Intensity of the nasal Target Consonant and Number of Syllables, only Language is retained in model comparison. The post-hoc test gives a significant difference between English and French (p < 0.001) as well as English and German (p = 0.02), but not between German and French (p = 0.12). Note though that the ROI does not define a particular segmental or prosodic unit, in contrast to other studies which have focused on the pre-nasal vowel specifically. Rather, the main interest in our study lies in the whether there would be an interaction between ROI duration and the divergence point. Our statistical model in absolute time did not confirm this possibility, showing instead, by virtue of the significant main effect, that ROI duration affects divergence point to a similar degree across our three languages, such that earlier divergence points occur with longer ROI durations. Fig. 7 plots divergence point as a function of ROI duration by language.

Since the previous literature has focused mostly on nasal anticipation during a preceding vowel, we additionally express the divergence point (i.e., anticipation interval) as a proportion of preceding vowel duration in Fig. 8; here, values between [−1, 0] represent divergence points that fall within the preceding vowel and values <−1 represent divergence points that even precede the onset of the preceding vowel. Again, we see that American English anticipates an upcoming nasal considerably earlier than the other two languages with many tokens having a proportion extending beyond −1 (mean for English is −1.36). French and German are fairly similar (mean for French: −0.90; mean for German: −0.84). This leads us to conclude two things: First, we confirm that the absence of a nasal vowel contrast does not predict the extent of anticipatory coarticulation in our data, in that English and German are markedly different, while German and French are the same. Nonetheless, the extent of anticipation is, *relative to English*, constrained in French, which, at first glance, is consistent with the contrast hypothesis. Yet contextual nasalization in French and German can be described as ‘constrained’ here only in relation to English – we would like to emphasize that, in German and French, on average by 84% and 90% of the pre-nasal vowel is nasalized, respectively. This is at odds with the contrast hypothesis which assumes that the constrained nature of coarticulation is rooted in perceptual factors. Importantly, the presence of a contrast does not in principle limit anticipatory coarticulation to the preceding vowel: For all languages we observe proportional values smaller than −1 for some of the data, where anticipatory coarticulation spreads beyond the onset of the pre-nasal vowel.

Our divergent point analyses so far have exclusively focused on the temporal extent of coarticulation, but have not considered the magnitude of nasality differences. In order to formally assess the integrated time and magnitude nasal intensity difference over the anticipatory window (ROI) between the languages, we computed the area under the difference curve (AUC) on a by-trial basis over the interval from the divergence point to the zero point (the onset of the target consonant). Fig. 9 displays the AUC values by language. English has greater AUC values compared to French and German. While this may simply be due to the overall earlier onset of coarticulation in English (since AUC is the integrated time/magnitude difference), Fig. 10 suggests that even at comparable divergence points, English has a greater nasal intensity difference between the oral and nasal conditions (and thus possibly a larger velic opening). This is apparent in Fig. 10 from English having higher AUC values compared to the other two languages across almost all divergence point values.

A statistical model with AUC values as the dependent variable and an interaction between Language and Divergence Point was a significantly better fit than a model without an interaction (i.e., Language and Divergence Point as independent

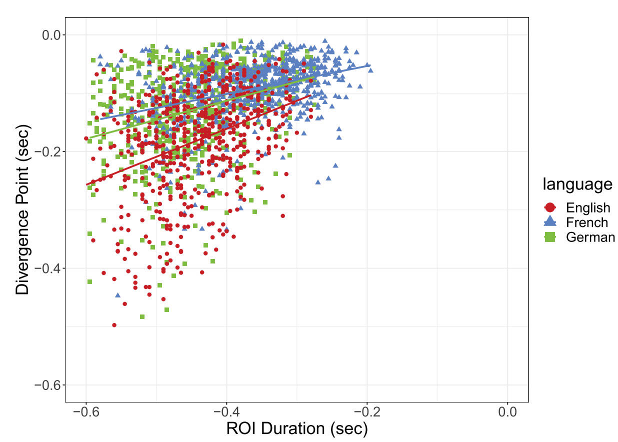

Fig. 7. Divergence point as a function of ROI duration for the non-initial condition. Both axes are in seconds with the onset of the target consonant as zero point. Smaller values mean longer duration and earlier onset of coarticulation, respectively.

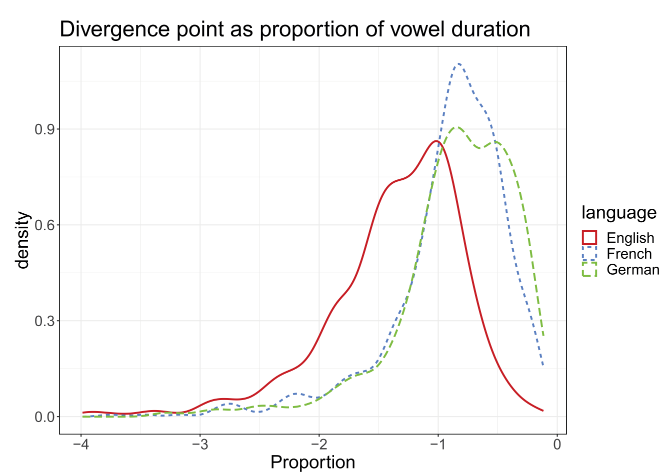

Fig. 8. Divergence point as a proportion of pre-nasal vowel duration. Values between 0 and −1 fall within the pre-nasal vowel, values <−1 precede the pre-nasal vowel.

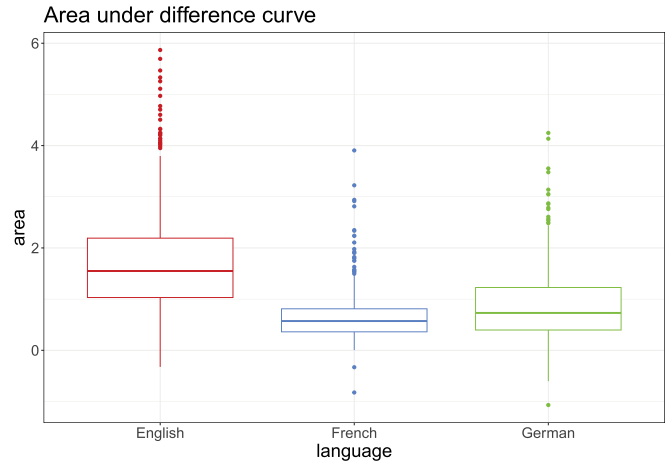

Fig. 9. Area under the difference curve (AUC) by language.

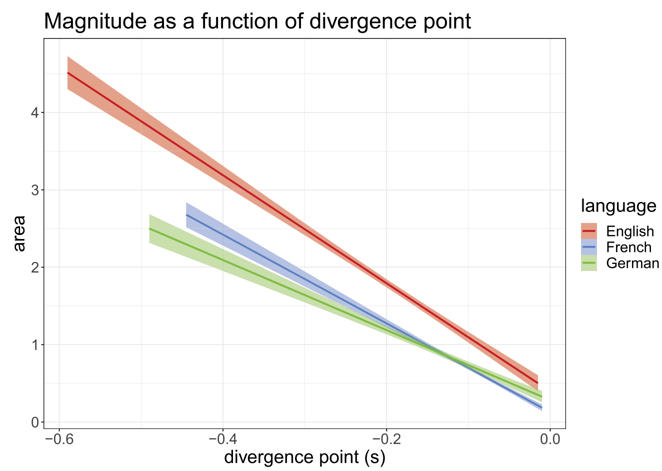

Fig. 10. AUC (integral of the nasal intensity difference curve between divergence point and target onset) as a function of divergence point by language. The zero-point is the onset of the nasal target consonant.

main factors, model comparison: $\chi^2(2) = 12.8$; $p = 0.002$). No other fixed effects were included in the models (except for gender as a nuisance variable). The fixed effects account for 54% of the variance out of a total of 75%. The interaction is visualized in Fig. 10; it arises due to German having a smaller increase in the AUC with longer anticipatory intervals. Most striking though is the overall difference in AUC and, again, in time in English compared to the other languages. Fig. 10 displays, using a linear smooth, AUC as a function of divergence point per language.

Summarizing our results thus far, we find that English has a significantly earlier onset of coarticulation compared to French and German, with the latter two not differing from each other. While English displays the most extensive coarticulation, even the relatively more constrained nasalization of German and French covers on average 84–90% of the pre-nasal vowel and may spread beyond the pre-nasal vowel for all languages. In addition to an earlier onset of nasal coarticulation, English shows a greater nasal intensity difference (higher AUC values) during the coarticulated segments than German and French. Fig. 10 suggests that this is not just due to the larger time-span of coarticulation in English, but may possibly be caused by a larger velic opening.

3.2.2. Individual variation

In the previous section, we consistently observed a between-language effect, driven by the extremely extensive anticipatory nasalization particular to English. We were able to statistically confirm this effect with a relatively high number of speakers, putting our understanding of between-language differences in anticipatory coarticulation on firmer footing. Even when speaker and item variability is accounted for by the random effects structure, language is consistently a statistically significant predictor for our results. At the same time, it was also apparent that the random effects explained a sizable portion of the variance. Our next step of the analysis is to take a closer look at levels of within-individual variation between the three languages. To that effect, we computed, for each speaker, the coefficient of variation across all their divergence points and plotted it against the speaker-specific mean divergence point in Fig. 11. The coefficient of variation (i.e., the mean-normalized standard deviation) is a relative measure that allows us to assess variability independently of its temporal extent, since larger intervals are inherently more variable. In Fig. 11, the more variable a speaker is, the higher their value on the y-axis. By visual impression, for German (green squares) there are fewer speakers in the lower variability range.

To test for differences between languages in within-speaker variability,[4] a Kruskal-Wallis test with the coefficient of variation as the dependent variable and language as a predictor was significant ($\chi^2(2) = 9.78$, $p = 0.0075$). Post-hoc pairwise comparisons using a Wilcoxon rank sum test revealed German to be significantly more variable than both English and French, with the latter two not differing from each other (English – German: $p = 0.02$; French – German: $p = 0.016$; English – French: $p = 0.32$). This result means that English and French speakers are equally variable despite their difference in the temporal domain of anticipation, while German speakers display a significantly higher level of within-speaker variability.

We also plot in Fig. 12 the speaker coefficients of the statistical model we ran in Section 3.2.1 on the divergence points in absolute time as a function of Language and ROI Duration. The plot gives each speaker's deviation from the model intercept ($\beta = -2.53$) and allows us to gain a picture of the levels of between-speaker variation within each language. German is by far the most variable and, interestingly, it is not the French, but the English speakers that show the tightest distribution. This means that overall, German displays the highest level of variability between and within speakers.

4. Discussion

The goal of our paper was to compare anticipatory nasal coarticulation in American English, French, and German, which differ in the role of nasality in their phonology. While French contrasts oral-nasal vowels, for American English contextual vowel nasalization has been described as phonologized with the pre-nasal vowel being planned as nasal (Solé, 1992). For German, contextual nasality has not been ascribed

[4] For this study we cannot meaningfully compute token-to-token variability since we only have three repetitions per item. The coefficient of variation was therefore computed across all divergence point values of a given speaker and thus mostly represents individual variability across items.

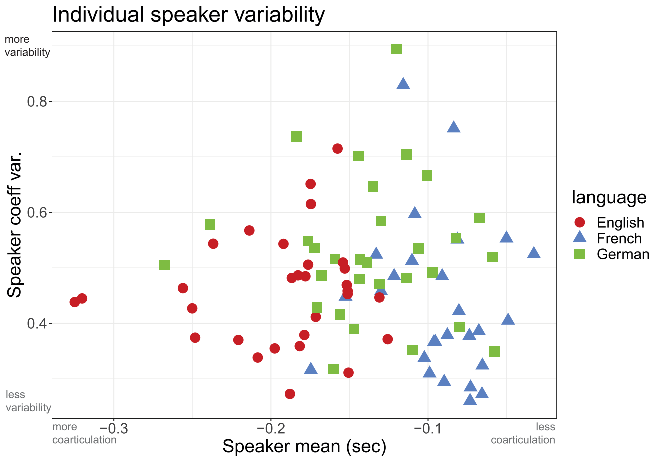

Fig. 11. Coefficient of variation and mean divergence point by speaker and language. Each data point represents a speaker.

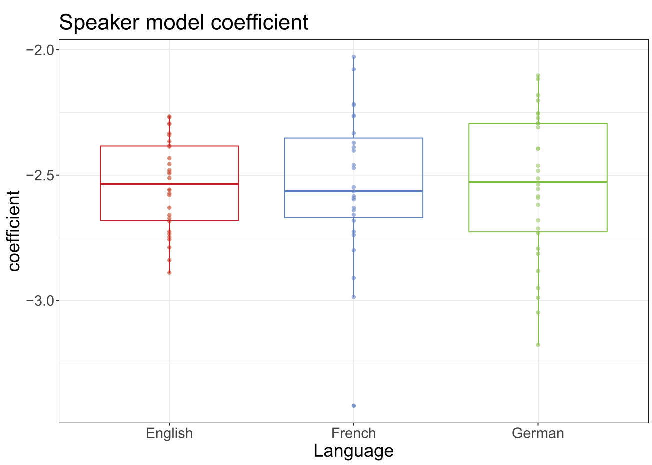

Fig. 12. Speaker deviation from model intercept by language.

any specific phonological status. Our stimuli allow for coarticulation to spread over a window of several segments preceding the target consonant (termed region of interest or ROI, see Table 1) in all three languages; this design principle was chosen to get a clearer picture of possible (language-specific) control structures underlying anticipatory coarticulation. A nasal-initial condition served to ascertain whether nasality would spread over a word boundary for all three languages, notably keeping the prosodic differences between the languages in mind. While German and English are so-called head-prominence languages with lexical stress, French has been classified as a head-edge prominence language. Moreover, in French the target word is canonically realized as its own accentual phrase (Jun, 2014 Jun & Fougeron, 2002), whereas in German and English the target word is its own prosodic word. The weak language-specific effects that emerged in the initial condition were only apparent in absolute time; in proportional time the ROI interval in the initial condition was nasalized to an equal extent for the three languages. The word boundary may thus have attenuated any language-specific effects.

As to the non-initial condition, the focus of our current study, language consistently emerged as a significant predictor for the temporal extent of anticipatory coarticulation (divergence point, Section 3.2.1), confirming its language-specific nature. English had the greatest temporal extent of anticipatory nasality, while German and French speakers anticipated nasality to a lesser degree and did not differ significantly from each other (Fig. 6). Note that this result does not group the languages according to prosodic typology, which would predict a grouping of English and German vs. French. We therefore believe that prosodic typology is not the main conditioning factor for cross-linguistic differences in our study. Instead, our results are in agreement with previous observations in the literature about extensive nasal coarticulation in English and limited coarticulation in French (Cohn, 1990; Delvaux et al., 2008; Solé, 1992). For German, no comparative previous work exists to our knowledge (cf. Carignan et al., 2021; Kunay, 2021 for work on German). For all three languages, the onset of coarticulation preceded the pre-nasal vowel for a noticeable proportion of the data (Fig. 8), which underscores that anticipatory nasal coarticulation is not necessarily confined to nor planned relative to the pre-nasal vowel. Neither nasal intensity during the target consonant nor nasal target consonant duration was a significant predictor of onset of coarticulation, meaning that the between-language differences in the scope of anticipation are not driven by production differences in the nasal target consonant itself. ROI duration was a significant predictor of divergence point in addition to Language. Therefore, the onset of coarticulation varies systematically with the available anticipatory window for coarticulation, such that the longer the ROI, the longer the nasalized portion of the vowel. The three languages vary similarly in this way, since there was no significant interaction between Language and ROI duration. In contrast to the temporal analysis which aligned German and French, German speakers were significantly more variable within-speaker compared to English and French and also have the most between-speaker variability.

4.1. Coarticulation and contrast

It has been argued previously that anticipatory velum opening may be purely mechanistic in some languages (Bongiovanni, 2020; Dow, 2020; Solé, 1992), in that anticipatory coarticulation may occur only due to the transition time necessary for the velum opening movement. Mechanistic velum opening has also been argued to be invariant in the face of durational variation of the context segment (Solé, 1992). Low-level anticipation is by hypothesis confined to a comparatively constant, minimal time window immediately preceding the nasal consonant. According to this view, if anticipation were low-level mechanistic in one of the languages investigated here, it should occur over a short, constant time window, irrespective of durational variation of the context segment preceding the nasal consonant. Yet in the current study ROI duration was a predictor of divergence point for all three languages, irrespective of whether coarticulation is relatively more (English) or less (French, German) extensive: The statistical analyses revealed independent main effects of Language and ROI duration, but no interaction. Such an interaction would have been expected if nasality were mechanistic in some but not all of our languages.

Besides variability, a small temporal extent of coarticulation in absolute time has been used in some studies as a diagnostic for a low-level origin of coarticulation. It is quite difficult to know what a physiologically minimally required interval of anticipatory velum opening would be. Basset, Amelot, Vaissière, and Roubeau (2001, p. 87) assume an opening-closing cycle of the velum to take 50 ms, citing Ohala (1975). Stevens (1998, p. 44), based on acoustic data, says that a time of 50 ms is required to create a velopharyngeal port area of 0.5 cm^2. He further estimates the peak opening value of the velar port during an intervocalic nasal consonant to be 0.2 cm^2 (p. 487), though he notes that this is his own estimate rather than an empirically derived number. Following this, we would arrive at about 25 ms needed minimally to arrive at peak opening (for more discussion of the speed of velum opening and closing, see Kollia, Gracco, and Harris (1995) and Birkholz and Kleiner (2021)). For our results, anticipatory coarticulation is in most cases substantially longer than these estimates (cf. Table 4, Fig. 6 left). The main effect of ROI duration in our data across the three languages, as well as the comparatively large spread of anticipatory nasality apparent in some of the data, speaks against a straightforward mechanistic interpretation of anticipatory velar lowering for any of our languages.

One particular focus of our study was on whether phonological contrast would predict language-specific effects in the data either in terms of the temporal domain of anticipation or in terms of variability levels between languages. In the simplest version of the contrast hypothesis, in which the presence of an oral-nasal vowel contrast globally constrains or blocks anticipatory coarticulation, we would expect French to show the comparatively least amount of anticipation and nasalize a pre-nasal vowel only to a limited temporal extent, while English and German could be expected to coarticulate more compared to French. English nasal coarticulation, as already found in previous work, extends for most of the pre-nasal vowel and, in many cases, considerably beyond. This is in clear contrast to German which is, in terms of the temporal domain of anticipatory coarticulation, more constrained compared to English and not different from French. This could mean that the presence, but not the absence, of a contrast has predictive power for the coarticulatory span: While a language without a nasal vowel contrast may have *any* range of nasal anticipation and may arbitrarily show relatively more or less coarticulation, a language with a nasal-oral contrast would always have constrained coarticulation. Such a statement is, in our view, too strong for the following reasons. For one, as Fig. 8 underscores, the range of coarticulation in French can strongly be assumed to exceed what is physiologically necessary. Just as Scarborough et al. (2015) found for Lakota and Brkan (2018) for French and Urdu, a sizable portion of the vowel is subject to anticipatory nasalization in our data: Recall that we find the vowel in French to be contextually nasalized for an average of 90%. This is more constrained *relative to English*, but not constrained in absolute terms. Moreover, French speakers coarticulate in a window larger than the preceding vowel for a noticeable portion of the data. This could be uncovered in our study because our stimuli do not force a closed velum in the segment preceding the pre-nasal vowel. Thus, while coarticulation is *relatively* more constrained in French, it can systematically exceed what is deemed physiologically necessary and varies with ROI duration to a similar degree as it does in English and German. While it may seem counterintuitive from a perceptual perspective that French oral vowels are nasalized to such a high proportion, it is important to keep in mind for one, that the dynamics of nasalization may still be different between contextually nasalized and phonologically nasal vowels (Delvaux et al., 2008), and secondly, that the oral-nasal vowel contrast is signaled by multiple cues, notably vowel and voice quality differences (Carignan, Shosted, Fu, Liang, & Sutton, 2015, Carignan, 2017). It is thus far from clear whether contextual nasalization causes perceptual confusion at all; instead, the temporal spreading of cues by coarticulation may be perceptually advantageous in any case.

4.2. The special case of American English

The work of Solé (1992, 1995) and Beddor (2009; Beddor et al., 2018) aptly reminds us that our considerations of the role of contrast in coarticulatory vowel nasalization should go beyond the vowel: There is a nasal-oral contrast on the source of the coarticulation, i.e., the nasal consonant itself. This is particularly relevant for American English for which a trade-off between nasal consonant duration and contextual nasality has been observed. Beddor presented evidence (2007, 2009; Beddor et al., 2018) that in American English, variation in contextual nasalization may, at least in the $VNC_{obstruent}$ context, be in a trading relationship with the nasal consonant itself. Even though a systematic relationship between the production characteristics of the consonant and vowel nasality is not apparent in our data, the variability results (Section 3.2.2.) do support an argument that both Solé and Beddor have brought forward from different angles: Contextual vowel nasality in American English seems to be phonologized in a way that it is not in German. This is evident in the differences we found between English and German, in terms of both temporal extent of coarticulation and within- and between-speaker variability. In particular, English had the lowest between-speaker variability and the within-speaker variability turned out to be as low as in French.

Before considering how a phonological role of nasality may relate to speaker variability, we will first turn to the question of how to account for the large temporal domain of English anticipatory nasality. It has been shown for labial coarticulation (e.g., Lo et al., 2023; Lubker & Gay, 1982; Redford, Kallay, Bogdanov, & Vatikiotis-Bateson, 2018) that rounding can be anticipated for hundreds of milliseconds, whereas for velic coarticulation comparable observations have to our knowledge not been made. Of course, this may be due to a lack of comparative data, and nasal coarticulation in English may simply spread over longer distances. Yet another possibility we have already considered in the Introduction is Solé's hypothesis that English, due to a sound change, has a phonologically nasal vowel in VN contexts (i.e., allophony). If we take this seriously, this would imply that the pre-nasal vowel itself would be a *source* of anticipatory coarticulation. To our knowledge, this possibility has not been considered or tested before – in Solé's study, as in many others, the stimuli had an initial voiceless obstruent, and she would not have been able to observe any anticipatory spreading beyond the vowel. It is by virtue of the particular design of our study that anticipatory coarticulation is allowed to spread beyond the pre-nasal vowel, and this is indeed what we observe: There is a significantly and substantially earlier onset of coarticulation in English compared to the other two languages. The greater integrated time/magnitude difference (AUC) of English lends further credibility to such an interpretation: If the vowel is produced with a nasal target in its own right in English but not the other languages, we can expect such a large difference as is apparent in Fig. 10. Indeed, it is noticeable from Fig. 6 and Fig. 8 that the English distribution not only has a longer tail due to more extensive coarticulation, but the entire distribution is shifted to the left compared to French and German. While the latter languages are comparatively close to the hard boundary at zero (the onset of the nasal consonant), this is not the case for English. In Fig. 8 in particular, the shape of the distribution of the English data points is not very different from the other two languages; rather, it appears to simply cover a different range. The coarticulatory time domain of the three languages might in the end not be different at all if the English distribution were corrected, so to speak, for the fact that the alignment point is a different one.

Our results thus support Solé's argument that American English contextual vowel nasality is better described as allophony rather than coarticulation due to a following nasal consonant. Such a view has clear consequences: Pre-nasal vowel nasality for American English would in effect be thoroughly uninformative about the mechanisms of coarticulation and this variety of English should not be compared under this viewpoint to other languages. The source of anticipatory nasal spreading in English would in this view be the pre-nasal vowel itself (plus the nasal consonant).

Our view that the English pre-nasal vowel is the source, rather than the target, of anticipatory nasal coarticulation, cannot be tested independently of a nasal consonant, of course, since vowel nasality in English only occurs in prenasal position. This means that there are inevitably two co-occurring sources of nasality. Comparing English to other languages that have nasal vowel allophony in this way would be required. Taking all of our results together, we follow Solé's hypothesis that the comparatively large temporal spread that we observe for English is particular to the diachronically dynamic state of vowel nasality in English.

4.3. Implications for models of speech production

We would further like to discuss our results in the context of models of speech production. For all of our languages, the anticipatory domain may extend beyond the pre-nasal vowel (Fig. 8), a scenario observed in several studies before, but not very well accounted for in models of speech production. Moll and Daniloff (1971) were among the first to show that in English, nasal coarticulation may occur across multiple segments and cross word boundaries (see relatedly Clumeck (1976) and Ushijima and Hirose (1974) for similar results in other languages). They proposed a feature-spreading or *look-ahead* model of coarticulation (similar to Henke (1966)) in which the temporal extent of anticipation is limited by the featural specification of the neighboring segments. Anticipation will occur as long as there is no antagonistic feature specification. In this model nasality would be anticipated to the extent that it is not blocked by a [-nasal] specification, e.g., of an obstruent. This makes coarticulation equivalent to a phonological feature-spreading process and places it clearly in the domain of speech planning. As it has become clear that a feature-spreading account, in which coarticulation can easily span several segments and is in principle unbounded, overpredicts the temporal extent of coarticulation in many cases (and underpredicts in others), theoretical modelling has focused on local interactions between neighboring segments based on their temporal orchestration. Coarticulation then arises from the temporal overlap of adjacent gestures or gestures which are coordinated relative to one another (Browman & Goldstein, 1989; Fowler, 1980; Recasens, Pallarès, & Fontdevila, 1997; Tilsen, 2016; Bell-Berti, Krakow, Gelfer, & Boyce, 1995). This shift in focus in the theoretical modeling of coarticulation from the maximal extent to local interactions was, as we would argue, also possible because Öhman's (1966) ground-breaking work paved the way for treating seemingly non-local effects of V-to-V coarticulation across an intervening consonant as local. Long-distance effects have since been theoretically neglected or even denied, with a few exceptions.

For instance, Bell-Berti and Krakow (1991) explicitly argued against the existence of long-distance effects. They provided evidence for seemingly long-distance effects being really due to additive effects of intrinsic articulatory specifications for segments. Actual anticipatory velar opening due to the nasal consonant is, they proposed, only relatively late in the pre-nasal vowel, similarly to what Solé (1992) later described for Spanish. Our results highlight once more that such a view is too limiting. Our difference curve method takes into account any inherent segmental velum positions due to the stimulus material, and still the temporal window over which coarticulation occurs is not easily reconciled with a mechanistic interpretation (Fig. 6 left), if one follows the argument that a mechanistic velum can be identified on the basis of a brief, constant time window. Yet another view would allow for arbitrary coarticulatory variation between languages as part of a language-specific phonetic grammar which is separate from phonology. Cho and Ladefoged (1999), in their study on cross-linguistic VOT differences, argue that languages may arbitrarily differ in the phonetic numeric range onto which a given phonological category is mapped, which they call language-specific phonetic grammar. Even though in our case there is no mapping process of categories onto phonetic targets in the way that a phonological feature [- voiced] is 'mapped' onto VOT, extending this view to coarticulation would imply that coarticulation is, while certainly in some way a physiological necessity, different in 'numeric range' between languages as just-so stories without a principled connection to a language's phonology. Yet whether there is such a connection is precisely the context in which our study is placed.[5] Our variability results speak for such a connection, but ultimately studies comprising more languages with and without a nasal vowel contrast will be needed to answer this question. Moreover, it will be important to study

[5] In the context of consonant clusters there have been several proposals for a principled connection between language-specific coarticulation and phonology (phonotactics) (e.g., Chitoran, Crouch, & Katsika, 2023; Pouplier, Marin, Hoole, & Kochetov, 2017; Wright, 1996).

how factors which affect lexical access, such as neighborhood density and neighborhood frequency, affect the range of coarticulation. That lexical factors do in principle impact coarticulation is known (cf. e.g., Scarborough (2013)), but there is currently, we would argue, too little knowledge in the field to gain predictive power over the circumstances under which more or less coarticulation may be observed for a given language, context, or speaker.

4.4. Within- and between-speaker variability

Finally, another source of variability in coarticulation to be considered is the individual speaker. In our data, German has a significantly higher level of within- and noticeably higher between-speaker variability compared to the other two languages. While this is can intuitively be connected to the lack of a phonological role of vowel nasality in German, it is worth considering briefly how exactly such a link could be formulated in models of speech production. Recently it has been suggested that individual variability in coarticulation may be rooted in the variability of cognitive representations between speakers. Harper (2021), using dynamic field theory (Erlhagen & Schöner, 2002), proposed that individuals' cognitive representations may differ in the size of the target space for individual phonemes (given a model where each phoneme has a target region of possible production values). This, according to her model simulations, not only gives rise to different levels of token-to-token variability in the production of individual sounds but may also give rise to greater context-conditioned coarticulatory variability. In an experience-based model of the lexicon view, high within-speaker variability would also condition higher between-speaker variability, since the exposure to more production variability would induce broader representations. Note that Harper's work is the first to sketch the possibility of a relationship between lexical representation and coarticulatory variability. This necessarily predicts a principled relationship between variability in the production of the nasal consonant itself and variability in the extent of coarticulation. For our analyses, no relationship between the details of nasal consonant production and divergence point was found, but more fine-grained analyses, using experimental designs targeting this question specifically, might lead to more nuanced findings. Harper's work thus provides an interesting avenue for considering the individual structure of lexical representations as source of coarticulatory variability in an exemplar approach.

In sum, our experiment testing for differences in the temporal extent of anticipatory coarticulation in English, French, and German supports the hypothesis that English contextual vowel nasality should be considered allophonic, meaning that the pre-nasal vowel is, instead of being contextually nasalized, itself a source of coarticulation. Anticipatory vowel nasality in French and German is relatively less extensive than in English, but nonetheless covers on average 80–90% of the pre-nasal vowel and may spread beyond the pre-nasal vowel. Our results thus speak against the notion that phonological contrast is a predictor of the temporal extent of anticipatory coarticulation. Between- and within-speaker variability is, however, higher in German compared to English French. This is consistent with the notion that phonologically specified nasality in English and French constrains the production variability within speakers to a higher degree compared to a language that does not phonologically specify velum position for vowels.

CRediT authorship contribution statement

Marianne Pouplier: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Francesco Rodriquez:** Writing – review & editing, Methodology. **Justin J.H. Lo:** Writing – review & editing, Visualization, Software, Investigation. **Roy Alderton:** Writing – review & editing, Software, Methodology, Formal analysis. **Bronwen G. Evans:** Writing – review & editing, Conceptualization. **Eva Reinisch:** Writing – review & editing, Conceptualization. **Christopher Carignan:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Acknowledgements

We are very much indebted to our research assistants Katharina Neubert, Catherine Lewis, and Andrea García-Covelo for tirelessly recruiting speakers and running the experiments. We also thank our experiment participants for their interest in our work and their contribution to this project.

Work funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 448242388 and the UK Arts and Humanities Research Council (AHRC).

Appendix. Stimuli

Tables 5–7 give our stimulus minimal pairs in orthography and broad transcription. Two non-initial stimulus pairs fewer than for the other languages were recorded for German due to human error in the programming of the experiment presentation software.

Table 5
German stimuli.

Word-initial	Non-initial
Macht, Pacht /maxt, paxt/	Leine, leite /laɪnə, laɪtə/
Nadel, Tadel /naːdl, taːdl/	Laune, Laute /laʊnə, laʊtə/
Not, Tod /noːt, toːt/	Löhne, löte /løːnə, løːtə/
Naht, Tat /naːt, taːt/	Lang, Lack /laŋ, lak/
Meter, Peter /meːtɐ – peːtɐ/	Lohn, Lot /loːn, loːt/
	Lahm, lag /laːm, laːk/
	Leim, Laib /laɪm, laɪp/
	jung, juck /jʊŋ, jʊk/

Table 6
French stimuli.

Word-initial	Non-initial
né – thé /ne, te/	l'année – l'athée /lane, late/
mot – peau /mo, po/	l'aîné – l'été /lene, lete/
noix – toit /nwa, twa/	l'anis – lapis /lani, lapi/
nœud – queue /nø, kø/	ligneur – liqueur /liɲœʀ, likœʀ/
mère – père /mɛʀ, pɛʀ/	l'émis – l'épi /lemi, lepi/
	l'âne – latte /lan, lat/
	Yann – yack /jan, jak/
	l'homme – lotte /lɔm, lɔt/
	l'aune – l'hôte /lon, lot/
	l'âme – lac /lam, lak/

Table 7
English stimuli.

Word-initial	Non-initial
knocks, pox /nɑks, pɑks/	rammer, rapper /ɹæmɚ, ɹæpɚ/
mat, pat /mæt, pæt/	Leonard, leopard /lɛnɚd, lɛpɚd/
night, tight /naɪt, taɪt/	Ronnie, rocky /ɹɑni, ɹɑki/
met, pet /mɛt, pɛt/	ringer, ripper /ɹɪŋɚ, ɹɪpɚ/
moat, coat /moʊt, koʊt/	rhymer, riper /ɹaɪmɚ, ɹaɪpɚ/
	ran, rat /ɹæn, ɹæt/
	line, light /laɪn, laɪt/
	own, oat /oʊn, oʊt/
	lamb, lap /læm, læp/
	lung, luck /lʌŋ, lʌk/

References

Bartoń, K. (2022). *MuMIn: Multi-Model Inference*. R package version 1.47.1. Retrieved from https://CRAN.R-project.org/package=MuMIn.

Basset, P., Amelot, A., Vaissière, J., & Roubeau, B. (2001). Nasal airflow in French spontaneous speech. *Journal of the International Phonetic Association, 31*(1), 87–99. https://doi.org/10.1017/S0025100301001074.

Bates, D. M., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 667*(1), 1–48.

Beddor, P. S. (2007). Nasals and nasalization: the relation between segmental and coarticulatory timing. In *Proceedings of the 16th International Congress of Phonetic Sciences* (pp. 249–254).

Beddor, P. S. (2009). A coarticulatory path to sound change. *Language, 85*(4), 785–821. https://doi.org/10.1353/lan.0.0165.

Beddor, P. S., Coetzee, A. W., Styler, W., McGowan, K. G., & Boland, J. E. (2018). The time course of individuals' perception of coarticulatory information is linked to their production: Implications for sound change. *Language, 94*(4), 931–968. https://doi.org/10.1353/lan.2018.0051.

Beddor, P. S., Harnsberger, J. D., & Lindemann, S. (2002). Language-specific patterns of vowel-to-vowel coarticulation: Acoustic structures and their perceptual correlates. *Journal of Phonetics, 30*, 591–627.

Bell-Berti, F., & Krakow, R. A. (1991). Anticipatory velar lowering: A coproduction account. *The Journal of the Acoustical Society of America, 90*(1), 112–123. https://doi.org/10.1121/1.401304.

Birkholz, P., & Kleiner, C. (rkholz and Kleiner 2021). Velocity differences between velum raising and lowering movements. In A. Karpov & R. Potapova (Eds.), *Speech and Computer. SPECOM 2021. Lecture Notes in Computer Science* (pp. 70–80). Cham: Springer International Publishing.

Bell-Berti, F., Krakow, R. A., Gelfer, C. E., & Boyce, S. E. (1995). Anticipatory and carryover effects: Implications for models of speech production. In F. Bell-Berti & L. J. Raphael (Eds.), *Producing Speech: Contemporary Issues. For Katherine Safford Harris* (pp. 77–97). New York: American Institute of Physics.

Boersma, P., & Weenink, D. (2022). *Praat: doing phonetics by computer* [Computer program]. http://www.praat.org.

Bongiovanni, S. (2020). Acoustic investigation of anticipatory vowel nasalization in a Caribbean and a non-Caribbean dialect of Spanish. *Linguistics Vanguard, 7*(1). https://doi.org/10.1515/lingvan-2020-0008.

Bongiovanni, S. (2021). On covariation between nasal consonant weakening and anticipatory vowel nasalization: Evidence from a Caribbean and a non-Caribbean dialect of Spanish. *Laboratory Phonology, 12*(1). https://doi.org/10.16995/labphon.6444.

Brkan, A. (2018). *Étude comparative des phénomènes de coarticulation nasale en Anglais Américain, Bosnien, Français, Norvégien et Ourdou*. Paris: Université Sorbonne Nouvelle, Paris 3.

Brkan, A., Amelot, A., & Vassière, J. (2014). Anticipatory nasalization in four languages: American English, French, Bosnian and Norwegian. In *Proceedings of the 10th International Seminar on Speech Production, Cologne, Germany, 5–8 May 2014* (pp. 57–60).

Browman, C., & Goldstein, L. (1989). Articulatory gestures as phonological units. *Phonology, 6*(2), 201–251.

Butcher, A. (1999). What speakers of Australian Aboriginal languages do with their velums and why: the phonetics of the oral/nasal contrast. In *Proceedings of the XIVth International Congress of the Phonetic Sciences, San Francisco*, 479-482.

Butcher, A., & Loakes, D. (2008). Enhancing the left edge: The phonetics of prestopped sonorants in Australian languages. *Journal of the Acoustical Society of America, 124*, 2527. https://doi.org/10.1121/1.4782973.

Caglar, M. U., Teufel, A. I., & Wilke, C. O. (2018). Sicegar: R package for sigmoidal and double-sigmoidal curve fitting. *PeerJ, 6*, e4251.

Carignan, C. (2014). An acoustic and articulatory examination of the "oral" in "nasal": The oral articulations of French nasal vowels are not arbitrary. *Journal of Phonetics, 46*, 23–33. https://doi.org/10.1016/j.wocn.2014.05.001.

Carignan, C. (2017). Covariation of nasalization, tongue height, and breathiness in the realization of F1 of Southern French nasal vowels. *Journal of Phonetics, 63*, 87–105. https://doi.org/10.1016/j.wocn.2017.04.005.

Carignan, C., Coretta, S., Frahm, J., Harrington, J., Hoole, P., Joseph, A., & Voit, D. (2021). Planting the seed for sound change: Evidence from real-time MRI of velum kinematics in German. *Language, 97*(2), 333–364. https://doi.org/10.1353/lan.2021.0020.

Carignan, C., Shosted, R. K., Fu, M., Liang, Z.-P., & Sutton, B. P. (2015). A real-time MRI investigation of the role of lingual and pharyngeal articulation in the production of the nasal vowel system of French. *Journal of Phonetics, 50*, 34–51.

Chitoran, I., Crouch, C., & Katsika, A. (2023). Sonority sequencing and its relationship to articulatory timing in Georgian. *Journal of the International Phonetic Association, 53* (3), 1049–1072. https://doi.org/10.1017/S0025100323000026.

Cho, T., Kim, D., & Kim, S. (2017). Prosodically-conditioned fine-tuning of coarticulatory vowel nasalization in English. *Journal of Phonetics, 64*, 71–89. https://doi.org/10.1016/j.wocn.2016.12.003.

Cho, T., & Ladefoged, P. (1999). Variation and universals in VOT: Evidence from 18 languages. *Journal of Phonetics, 27*(2), 207–229. https://doi.org/10.1006/jpho.1999.0094.

Clumeck, H. (1976). Patterns of soft palate movements in six languages. *Journal of Phonetics, 4*, 337–351.

Cohn, A. (1990). Phonetic and phonological rules of nasalization. *UCLA Working Papers in Phonetics, 76*.

Delvaux, V., Demolin, D., Harmegnies, B., & Soquet, A. (2008). The aerodynamics of nasalization in French. *Journal of Phonetics, 36*(4), 578–606. https://doi.org/10.1016/j.wocn.2008.02.002.

Desmeules-Trudel, F., & Brunelle, M. (2018). Phonotactic restrictions condition the realization of vowel nasality and nasal coarticulation: Duration and airflow measurements in Québécois French and Brazilian Portuguese. *Journal of Phonetics, 69*, 43–61. https://doi.org/10.1016/j.wocn.2018.05.001.

Dow, M. (2020). A phonetic-phonological study of vowel height and nasal coarticulation in French. *Journal of French Language Studies, 30*(3), 239–274. https://doi.org/10.1017/S0959269520000083.

Draxler, C., & Jänsch, K. (2004). SpeechRecorder – a universal platform independent multi-channel audio recording software. *Proceedings of LREC, Lisbon 2004* (2004, pp. 559–562). .

Erlhagen, W., & Schöner, G. (2002). Dynamic field theory of movement preparation. *Psychological Review, 109*(3), 545–572. https://doi.org/10.1037/0033-295X.109.3.545.

Farnetani, E., & Recasens, D. (2010). Coarticulation and connected speech processes. In W. J. Hardcastle, J. Laver, & F. E. Gibbon (Eds.), *The Handbook of Phonetic Sciences* (2nd. ed., pp. 316–352). Wiley-Blackwell.

Fowler, C. (1980). Coarticulation and theories of extrinsic timing. *Journal of Phonetics, 8*, 113–133.

Harper, S. (2021). Individual differences in phonetic variability and phonological representation PhD dissertation. Los Angeles, CA: University of SouthernCalifornia.

Hauser, I. (2021). Contrast implementation affects phonetic variability: A case study of Hindi and English stops. *Laboratory Phonology, 12*(1). https://doi.org/10.16995/labphon.6465.

Henke, W. L. (1966). *Dynamic articulatory model of speech production using computer simulation* PhD dissertation. Boston, MIT.

Huffman, M. (1990). Implementation of nasal: Timing and articulatory landmarks. *UCLA Working Papers in Phonetics, 75*.

Jang, J., Kim, S., & Cho, T. (2018). Focus and boundary effects on coarticulatory vowel nasalization in Korean with implications for cross-linguistic similarities and differences. *The Journal of the Acoustical Society of America, 144*(1), EL33-EL39. https://doi.org/10.1121/1.5044641.

Jang, J., Kim, S., & Cho, T. (2023). Prosodic structural effects on non-contrastive coarticulatory vowel nasalization in L2 English by Korean learners. *Language and Speech, 66*(2), 381–411. https://doi.org/10.1177/00238309221108657.

Jun, S. A. (2014). Prosodic typology: By prominence type, word prosody, and macro-rhythm. In S. A. Jun (Ed.), *Prosodic typology II: The phonology of intonation and phrasing* (pp. 520–539). Oxford: Oxford University Press.

Jun, S.-A., & Fougeron, C. (2000). A phonological model of French intonation. In A. Botinis (Ed.), *Intonation: Analysis, modelling and technology* (pp. 209–242). Dordrecht: Kluwer.

Jun, S.-A., & Fougeron, C. (2002). The realizations of the accentual phrase in French intonation. *Probus, 14*, 147–172.

Kollia, B., Gracco, V. L., & Harris, K. (1995). Articulatory organization of mandibular, labial and velar movements during speech. *Journal of the Acoustical Society of America, 98*(3), 1313–1324.

Kunay, E. (2021). Vowel nasalization in German. PhD Dissertation, München, LMU. Retrieved from http://nbn-resolving.de/urn:nbn:de:bvb:19-293408.

Kunay, E., Hoole, P., Gubian, M., Harrington, J., Jospeh, A., Voit, D., & Frahm, J. (2022). Vowel height and velum position in German: Insights from a real-time magnetic resonance imaging study. *The Journal of the Acoustical Society of America, 152*(6), 3483–3501. https://doi.org/10.1121/10.0016366.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software, 82*(13), 1–26. https://doi.org/10.18637/jss.v082.i13.

Lenth, R. V. (2022). *emmeans: Estimated Marginal Means, aka Least-Squares Means*. Retrieved from https://CRAN.R-project.org/package=emmeans.

Li, H., Kim, S., & Cho, T. (2020). Prosodic structurally conditioned variation of coarticulatory vowel nasalization in Mandarin Chinese: Its language specificity and cross-linguistic generalizability. *The Journal of the Acoustical Society of America, 148*(3), EL240–EL246. https://doi.org/10.1121/10.0001743.

Lo, J. J. H., Carignan, C., Pouplier, M., Alderton, R., Rodriquez, F., Evans, B. G., & Reinisch, E. (2023). Language specificity vs speaker variability of anticipatory labial coarticulation in German and English. In R. Skarnitzl & J. Volín (Eds.), In *Proceedings of the 20th International Conference of the Phonetic Sciences, Prague* (pp. 2105-2109).

Lubker, J., & Gay, T. (1982). Anticipatory labial coarticulation: Experimental, biological, and linguistic variables. *The Journal of the Acoustical Society of America, 71*(2), 437–448. https://doi.org/10.1121/1.387447.

Manuel, S. (1990). The role of contrast in limiting vowel-to-vowel coarticulation in different languages. *Journal of the Acoustical Society of America, 88*(3), 1286–1298.

Manuel, S. (1999). Cross-language studies: relating language-particular coordination patterns to other language-particular facts. In W. J. Hardcastle & N. Hewlett (Eds.), *Coarticulation. Theory, data and techniques* (pp. 179–198). Cambridge: Cambridge University Press.

Mok, P. (2012). Does vowel inventory density affect vowel-to-vowel coarticulation? *Language and Speech, 56*(2), 191–209.

Moll, K. L., & Daniloff, R. G. (1971). Investigation of the Timing of Velar Movements during Speech. *The Journal of the Acoustical Society of America, 50*(2B), 678–684. https://doi.org/10.1121/1.1912683.

Noiray, A., Cathiard, M.-A., Ménard, L., & Abry, C. (2011). Test of the movement expansion model: Anticipatory vowel lip protrusion and constriction in French and English speakers. *The Journal of the Acoustical Society of America, 129*(1), 340–349. https://doi.org/10.1121/1.3518452.

Noiray, A., Wieling, M., Abakarova, D., Rubertus, E., & Tiede, M. (2019). Back from the future: Nonlinear anticipation in adults' and children's speech. *Journal of Speech, Language, and Hearing Research, 62*(8S), 3033–3054. https://doi.org/10.1044/2019_JSLHR-S-CSMC7-18-0208.

Oh, E. (2008). Coarticulation in non-native speakers of English and French: An acoustic study. *Journal of Phonetics, 36*(2), 361–384. https://doi.org/10.1016/j.wocn.2007.12.001.

Ohala, J. (1975). Phonetic explanations for nasal sound patterns. In C. A. Ferguson, L. Hyman, & J. Ohala (Eds.), *Nasalfest: Papers from a symposium on nasals and nasalization* (pp. 289–316). Stanford: Language Universals Project.

Öhman, S. E. (1966). Coarticulation in VCV utterances: Spectrographic measurements. *Journal of the Acoustical Society of America, 39*(1), 151–168.

Pouplier, M., Marin, S., Hoole, P., & Kochetov, A. (2017). Speech rate effects in Russian onset clusters are modulated by frequency, but not auditory cue robustness. *Journal of Phonetics, 64*, 108–126.

Pouplier, M., Pastätter, M., Hoole, P., Marin, S., Chitoran, I., Lentz, T. O., & Kochetov, A. (2022). Language and cluster-specific effects in the timing of onset consonant sequences in seven languages. *Journal of Phonetics, 93*. https://doi.org/10.1016/j.wocn.2022.101153 101153.

Puggaard-Rode, R. (2024). *praatpicture: 'Praat Picture' Style Plots of Acoustic Data*. R package version 1.0.0. Retrieved from https://CRAN.R-project.org/package=praatpicture.

Recasens, D., Pallarès, M. D., & Fontdevila, J. (1997). A model of lingual coarticulation based on articulatory constraints. *Journal of the Acoustical Society of America, 102*(1), 544–561.

Redford, M., Kallay, J., Bogdanov, S., & Vatikiotis-Bateson, E. (2018). Leveraging audiovisual speech perception to measure anticipatory coarticulation. *The Journal of the Acoustical Society of America, 144*(4), 2447–2461. https://doi.org/10.1121/1.5064783.

Scarborough, R. A. (2013). Neighborhood-conditioned patterns in phonetic detail: Relating coarticulation and hyperarticulation. *Journal of Phonetics, 41*, 491–508.

Scarborough, R. A., Zellou, G., Mirzayan, A., & Rood, D. S. (2015). Phonetic and phonological patterns of nasality in Lakota vowels. *Journal of the International Phonetic Association, 45*(3), 289–309. https://doi.org/10.1017/S0025100315000171.

Solé, M.-J. (1992). Phonetic and phonological processes: The case of nasalization. *Language and Speech, 35*(1–2), 29–43. https://doi.org/10.1177/002383099203500204.

Solé, M.-J. (1995). Spatio-temporal patterns of velopharyngeal action in phonetic and phonological nasalization. *Language and Speech, 38*, 1–23.

Steinlen, A. (2005). *A cross-linguistic comparison of the effects of consonantal contexts on vowels produced by native and non-native speakers*. Tübingen: Gunther Narr.

Stevens, K. N. (1998). *Acoustic phonetics*. Cambridge, MA: MIT Press.

Stoakes, H. M., Fletcher, J. M., & Butcher, A. R. (2020). Nasal coarticulation in Bininj Kunwok: An aerodynamic analysis. *Journal of the International Phonetic Association, 50*(3), 305–332. https://doi.org/10.1017/S0025100318000282.

Tilsen, S. (2016). Selection and coordination: The articulatory basis for the emergence of phonological structure. *Journal of Phonetics, 55*, 53–77.

Ushijima, T., & Hirose, H. (1974). Electromyographic study of the velum during speech. *Journal of Phonetics, 2*(4), 315–326. https://doi.org/10.1016/S0095-4470(19)31301-4.

Whalen, D. H. (1990). Coarticulation is largely planned. *Journal of Phonetics, 18*, 3–35.

Wright, R.A. (1996). Consonant clusters and cue preservation in Tsou. Dissertation. Los Angeles, CA: UCLA.

Zellou, G. (2017). Individual differences in the production of nasal coarticulation and perceptual compensation. *Journal of Phonetics, 61*, 13–29. https://doi.org/10.1016/j.wocn.2016.12.002.